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> *"The goal of a scientist is to uncover new ideas, concepts and tools, practical or theoretical, that extend our understanding of the world around us and enable us to do new things. One must believe in what one is doing and stay the course. Now of course, in science one can ultimately prove the correctness of one's work by appeal to experiment and established theory. But even with this buttressing of one's ideas, acceptance can be a long and difficult road."*
>
> **Richard F.W. Bader (1931 – 2012)**

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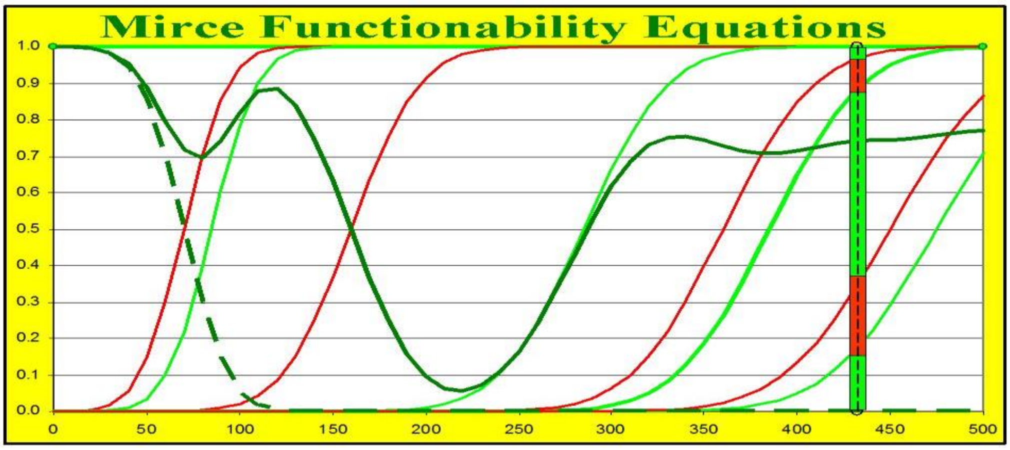
Mirce Science in brief

The philosophy of MIRCE Science is based on the premise that the purpose of existence of any functionable system[1] *is to do expected work, which is considered to be done when the expected measurable function is performed through time, like miles travelled, units produced, energy supplied and similar. However, experience teaches us that at any instant of in-service life there is a probability of work being interrupted by occurrences of negative functionability events, resulting from failures of consisting components, natural causes, human actions or their interactions. For the work to be continued, humans undertake appropriate positive functionability actions, like: maintenance tasks, change of the mode of operation and similar must be performed. Thus, the life of functionable systems is a motion through functionability states, in respect to time. Typically, functionability performance (the amount of work done and resources consumed to support operation and maintenance) becomes known through the end of the life statistics*[2]*, which certainly could be change at that stage.*

After five decades of systematic studies (practical and observational) of functionability of functionable systems and their performance Knezevic [1] has generated a body of knowledge, named Mirce Science, which describes the motion of functionable systems through Mirce Space[3]*. Its axioms, equations and computational methods enable predictions of expected performance to be done, well before the design has been finalised, for each of physically feasible alternative. It is based on the scientific understanding of the physical mechanisms that generates the occurrences of functionability events, considered within a physical scale between* 10^{-10} *m (atomic scale) and* 10^{10} *m (solar system scale). These mechanisms, together with the human imposed rules, quantitatively define the expected functionability performance, by making use of Mirce Functionability Equations and methods.*



Reference: [1] Knezevic, J., The Origin of MIRCE Science, pp. 232, MIRCE Science, Exeter, UK, 2017, ISBN 978-1-904848-06-6

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[1] Functionable system is a set of natural and human resources arranged to deliver at least one measurable function. [1]

[2] Pan Am's Boeing 747, registration number N747PA, during the 22 years of in-service life, has delivered: $80x10^3$ hours of flying, transported $4x10^6$ passengers, burned $1.03x10^9$ litres of fuel, while receiving $8.06x\ 10^5$ maintenance man-hours, using: 2,100 tyres, 350 brake systems, 125 engines..

[3] Mirce Space**:** a conceptual 3-dimentional space containing MIRCE Functionability Field, which is an infinite but countable set of all possible functionability states that a functionable system could be found in at any instance of calendar time and the corresponding probability of being in those states. [1]

Content

Pre-Determined Debris Avoidance Maneuvers (PDAMs) as Mechanism of Motion of International Space Station through MIRCE Space

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Abstract

MIRCE Science is a theory of the motion of working system through MIRCE Space caused by any action whatsoever. The International Space Station is orbiting the Earth since 1998. At its orbit of 400 km there is huge concentration of orbital debris resulting from accidents, failures or, in some cases, deliberate destruction of human sent spacecraft. Due to their speed the debris present a serious treat to the safety of the station and its crew. Hence, the main objective of this paper is to present the accurate available record of the pre-determined debris avoidance maneuvers taken by the International Space Station thus far, through the perspective of MIRCE Science. The information regarding 24 functionability actions have been identified and presented in paper of out 38 recorded. Identifications of the tractable orbital debris that constituted negative functionability actions threatening the safety of ISS are cited. The cost of the resources used for the execution of avoiding functionability actions has been presented together with the estimated costs of the fuel consumed. Finally, this paper clearly confirms the fourth axiom of MIRCE Science that states "The probability that a functionable (working) system type will move to a negative functionability state at any instant of time is greater than zero", regarding possible collisions of ISS with orbiting orbital debris.

Key words: MIRCE Science, functionability actions, International Space Station, space debris, orbital debris, Pre-Determined Debris Avoidance Maneuvers

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1. Introduction

The philosophy of MIRCE Science[4] is based on the premise that the purpose of the existence of any human created working system is to do a work. The work is considered to be done when the expected measurable function is performed. At any instant of calendar time, a working system could be in one of the following two macro states:

- Positive Functionability State (PFS), a generic name for a state in which a working system is able to deliver the expected measurable function(s),

- Negative Functionability State (NFS), a generic name for a state in which a working system is unable to deliver the expected measurable function(s).

In MIRCE Science, work done by a working system is uniquely defined by the trajectory generated by its motion through MIRCE Space[5.] That motion is driven by occurrences of functionability events generated by the following functionability actions:

- Positive Functionability Action (PFA) is a generic name for any natural process or human activity that compels a system to move to a PFS.
- Negative Functionability Action (NFA) is a generic name for any natural process or human activity that compels a system to move to a NFS.

The time evolution of a working system through MIRCE Space is physically manifested through the occurrences of functionability events, which are classified as:

- Positive Functionability Event (PFE) that is a physically observable occurrence at which a working system moves to a PFS,
- Negative Functionability Event (NFE) that is physically observable occurrence at which a working system moves to a NFS.

To scientifically understand the mechanisms that generate functionability actions, positive and negative, analysis of the in-service behaviour of several thousands of items, modules, assemblies and whole systems in aerospace, nuclear, transportation, motorsport, communication, defence and other industries have been conducted at the MIRCE Akademy[6]. The minimum sufficient "physical scale" which enables scientific understanding of relationships between physical phenomena that take place in the natural environment and the physical mechanisms that govern functionability events has to be based with the following range:

- the "bottom end" of the physical world, which is at the level of the atoms and molecules that exists in the region of 10^{-10} of a metre.
- the "top end" of the physical world, which is at the level of the solar system that stretches in the physical scale around 10^{+10} of a metre.

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[4] Knezevic, J., The Origin of MIRCE Science, pp. 232, MIRCE Science, Exeter, UK, 2017, ISBN 978-1-904848-06-6

[5] MIRCE Space is a conceptual 3-dimensional coordinate system depicting a probabilistic trajectory of the motion of a working system through MIRCE functionability field. Knezevic (2017)

[6] http://www.mirceakademy.com/news/2/15/MIRCE-Functionability-Actions/

The main objective of this paper is to present the Pre-Determined Debris Avoidance Maneuvers (PDAM) as a mechanism of the motion of the International Space Station (ISS) through MIRCE Space. Thus, the dates, circumstances and brief descriptions of 24 functionability events that were generated by of the detection of tractable orbital debris that were threatening the safety of ISS are cited. The cost of the resources used for the execution of avoiding functionability actions has been presented together with the estimated costs of the fuel consumed.

2. The International Space Station

The International Space Station came into existence on 6th December 1998, when the USA module Unity was deployed from space shuttle Endeavour was joined with Russia's Zarya module. Despite the fact that these two very different hardware pieces were run by computers that have never talked to each other and software that's only been tested in models, when assembled together it worked.

The whole process took a full orbit of Earth and it was completed 160 miles over China. The space station began hosting crews in November 2000. As of today, the ISS is the largest orbiting laboratory ever built. It is an international, technological, and political achievement by United States, Russia, Europe, Japan, and Canada.

The ISS orbits about 400 km above Earth. An international crew of seven astronauts resides and works while orbiting Earth at speed of 8 km/sec, about every 90 minutes.

3. Space Debris and Orbital Debris

Spacecrafts are vulnerable to micrometeoroid and orbital debris (MMOD) impact. Each of these impacts has the potential to degrade performance, shorten the mission, or result in loss of the spacecraft. [18] Since 1957 humans have sent over 10,000 tonnes into orbit in total. Some of it became the debris in space as the result of accidents, failures or, in some cases, deliberate destruction. Also, many satellites also become obsolete, stop functioning, or were accompanied into space with detachable items, like rocket boosters, which are designed to stay in space. Consequently, space debris is generic name for any piece of equipment or debris left by humans in space.

NASA defines space debris as both natural meteoroid and artificial (human-made) orbital debris. Meteoroids are in orbit about the Sun, while most artificial debris is in orbit about the Earth (hence the term "orbital" debris). Orbital debris is the term for any object in Earth orbit that no longer serves a useful function. It includes non-operational spacecraft, derelict launch vehicle stages, mission-related debris, and fragmentation debris.

3.1 Size and quantity of debris

Based on statistical models produced by ESA's space debris office[7], it is estimated that in 2022 there were 36,500 objects larger than 10 cm, 1 million objects between 1-10 cm, and an extraordinary 130 million objects between 1 mm to 1 cm. These tiny objects could be anything from paint flecks from rockets or small fragments created from in-orbit impacts.

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[7] https://sdup.esoc.esa.int/discosweb/statistics/

However, despite their physical size, they can still cause an incredible amount of damage to spacecraft and satellites due to their travelling speed.

3.2 International identifiers for artificial objects in space

The Committee on Space Research (COSPAR) of the International Science Council (ISC) has created the international designator for identifying artificial objects in space, known as COSPAR ID. It consists of the launch year, a three-digit incrementing launch number of that year and up to a three-letter code representing the sequential identifier of a piece in a launch.

The United States Space Command (USSPACECOM) created North American Aerospace Defense Catalogue Number, NORAD ID in the order of launch or discovery to all artificial objects in the orbits of Earth and those that left Earth's orbit.

3.3. ISS as a source of orbital debris

During its operational life the ISS itself has become a source of orbital debris, both large and small. Most large debris were released during Extravehicular Activities (EVA), although manly by accidents.

By the 10th anniversary of the ISS, the U.S. Space Surveillance Network (SSN) had detected and catalogued 65 debris from the outpost, not including operational spacecraft releases, like the TNS-0 small satellite in March 2005.

Inadvertent losses ranged from a camera to a variety of tools to a complete tool bag to a foot restraint. Intentional debris releases included towels, equipment covers and carriers, hardware too large or too dangerous to return to Earth in a logistics vehicle, and an old space suit. Most of these objects fell harmlessly back to Earth in less than two months. The cumulative number of debris object-years is almost exactly 10, the equivalent of one piece of debris remaining in orbit for 10 years.

4. Pre-determined Debris Avoidance Maneuvers of ISS as Functionability Action

NASA's long-standing guidelines require the ISS to maneuver if any satellite comes within a "pizza box"-shaped area of space surrounding the orbit of the station. The box is roughly 4 by 50 by 50 km with the ISS at the centre, according to agency officials. Tractable pieces in that orbital plane are roughly 5 cm in diameter, but even paint flecks can cause issues given the high velocities involved with objects in orbit.

When predictions indicate that any tracked object will pass close enough for concern and the quality of the tracking data is deemed sufficiently accurate, Mission Control centers in Houston and Moscow work together to develop a prudent functionability action for its avoidance. The collision risk is calculated many hours in advance of a potential collision based on the orbital elements of the debris object and potential target.

Successfully operated and finished pre-determined ISS debris avoidance maneuver PDAM and passing of orbital debris on the safe distance, will mark the moment in time when the ISS negative functionability action is finished, and ISS starting the positive functionability action to return to positive functionability state – normal operation mode.

4.1 ISS negative functionability actions between 1999 – 2003

During this period of operation the ISS performed 7 PDAMs, all of which are noted below:

27th October 1999: ISS performed collision avoidance action to prevent conjunction with Pegasus Rocket Body[8] (COSPAR ID: 1998-046K, NORAD ID: 25422). [1]

30th September 2000: ISS collision avoidance action to escape conjunction with Vostok Rocket Body[9] (COSPAR ID: 1971-031B, NORAD ID 5143). [1]

10th February 2001[10]: ISS/Space Shuttle collision avoidance action to prevent the conjunction with Electron 1 Debris (COSPAR ID: 1964-006, NORAD ID 87618). [1]

14th March 2001: ISS/Space Shuttle collision avoidance action avoiding conjunction with ISS/Shuttle Debris (COSPAR ID: 2001-010B, NORAD ID 26723) and Cosmos Rocket Body (COSPAR ID: 1990-078B, NORAD ID 20775). [1]

15th December 2001: ISS executed collision avoidance action to avoid conjunction with Cosmos Rocket Body (COSPAR ID: 1971-119B, NORAD ID 5730). Space Shuttle conducted action prior to undocking and conjunction. [1]

16th May 2002: ISS collision avoidance action avoiding conjunction with Cosmos Rocket Body (COSPAR ID: 1994-061B, NORAD ID 23279). [1]

30th May 2003: ISS collision avoidance action avoiding conjunction with MegSat (COSPAR ID: 1999-022B, NORAD ID 25722). [1]

4.2 ISS negative functionability actions between 2008 – 2015

There were no pre-determined debris avoidance maneuvers between 2004-2008. However, there were 18 PDAMs between 2008-2015. Those known to the authors are presented below:

27th August 2008: The ISS collision avoidance action occurred when a fragment from the Cosmos 2421[11] spacecraft was projected to pose a collision risk of 1 in 72. ESA's Automated Transfer Vehicle, the Jules Verne, performed the collision avoidance maneuver. [2]

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[8] Pegasus Rocket Body was launched on 2 August 1998. Flight ended-decayed on 15 December 2000. Launch site: Eastern Range Airspace, United States.

[9] Vostok Rocket Body SL-3 R/B. Launch date: 17 April 1971. Flight ended-decayed on 18 April 2001. Launch site: Plesetsk Missile and Space Complex, Russia, former USSR.

[10] Electron 1 (COSPAR ID: 1964-006A, NORAD ID 746) non-operational spacecraft with a cylindrical body 0.75 m in diameter and 1.3 m length from which antennas and six solar cell panels were extended. It was placed into an eccentric orbit to study the internal zone of the radiation belt. It was equipped with micrometeorite detectors, a proton detector, a mass spectrometer and instruments for recording the corpuscular emission and energy spectrum of electrons. It was launched on 30th January 1964 from Tyuratam (Baikonur Cosmodrome), USSR. Mass: 350kg. Electron 1 is still in orbit with minimum altitude-perigee of 418.1 km and peak altitude-apogee of 6272.7.

[11] This was one of more than 500 catalogued debris released from Cosmos 2421 during three major fragmentation events from March to June 2008, that took place only about 60 km above the orbit of the ISS. As these fragments decayed down towards the ISS orbit, the number of potentially threatening conjunctions each month increased by a factor of three.

October, 2010: The ISS was forced to action to avoid a potential collision with a piece of debris which had come off a 19-year-old NASA scientific spacecraft[12] only one month earlier. The collision avoidance action was successfully performed by the Progress M-07M logistics vehicle that docked at the aft port of the ISS Zvezda module on 12 September. [3]

2nd April 2011: The ISS performed collision avoidance action regarding a fragment from Cosmos 2251[13]. A small evasive maneuver action was done by the European Automated Transfer Vehicle 2 (ATV-2), which was docked at the aft end of the ISS complex on 24 February. The burn, which lasted 3 minutes and 18 seconds, was executed early 2 April (GMT), imparting a change in velocity to ISS of only 0.5 meters per second. [4]

29th September 2011: International Space Station dodging of orbital debris from the Russian Tsyklon rocket body. [17]

13th January 2012: International Space Station dodging of orbital debris. Avoiding conjunction with fragmentation debris from Iridium 33. [17]

28th January 2012: To avoid a possible conjunction with fragmentation debris from Fengyun-1C the ISS performed a required maneuver. [17]

12th November 2014: The ISS avoided satellite debris by activating engines of “Georges Lemaitre” Automated Transfer Vehicle for 3 minutes, 25 seconds. This pre-determined debris avoidance maneuver (PDAM) was done to move well away from a small piece of debris from a spent Chinese satellite (Yaogan 12) launched in November 2011. It was coordinated with Russian and European flight controllers, and raised the station’s altitude by 9/10 of a mile at apogee and 2/10 of a mile at perigee and left the station in an orbit of 262.3 x 252.0 statute miles. [5]

4.3 ISS negative functionability actions between 2020 – 2023

During this period 13 pre-determined debris avoidance maneuvers have been performed by ISS to protect it from identified orbital debris. Majority of them are listed below:

22nd September 2020: The ISS conducted PDAM by Progress 75 thrusters, with a 150-second reboost to avoid a possible conjunction with an unknown piece of space debris. Due to the late notification of the possible conjunction, the three Expedition 63 crew members were directed to move to the Russian segment of the station to be closer to their Soyuz MS-16 spacecraft as part of the safe haven procedure out of an abundance of caution. This functionability action raised the station’s orbit out of the predicted path of the debris at the estimated distance of 1.39 km. [6]

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[12] Since its decommissioning in late 2005, NASA’s Upper Atmosphere Research Satellite (UARS) had been gradually falling back to Earth. By September 2010 the 5.7-metric-ton spacecraft was in an orbit of 335 km by 415 km with an inclination of 57.0 degrees, when the U.S. Space Surveillance Network (SSN) discovered that a fragment had separated from the vehicle.

[13] Russian communications satellite which had accidentally collided with the U.S. Iridium 33 communications satellite in February 2009, producing more than 2000 large debris. Designated as Satellite Number 34443 in the U.S. Satellite Catalogue (COSPAR ID: 1993-036SL), the fragment had an apparent size of 10-15 cm.

3rd December 2021: The ISS orbit adjusted to dodge debris from old U.S. Pegasus[14] rocket (object 39915) rocket. Russian Progress 79, attached to the space station, fired its thrusters for 2 minutes and 41 seconds to lower the station's orbit. This action generated a safe margin of separation from a fragment tracked by ballistics specialists. The Expedition 66 crew aboard the station was not in any additional danger. [7]

16th June 2022: The ISS conducted a collision avoidance action to escape a large fragment (COSPAR ID[15]: 1982-92BYX, NORAD ID: 52590). This was the first time the risk of a collision exceeded the requirements for an avoidance maneuver. [8]

24th October 2022: The ISS conducted a second collision avoidance action for the year to avoid a potential high-risk collision with a large debris fragment (COSPAR ID: 1982-092BMN, NORAD ID: 51561). [9]

21st December 2022: The tracking data showed a close approach of a fragment of Russian Fregat-SB upper stage debris to the ISS. The consequential functionability action was the Roscosmos Progress 81 thrusters firing for 10 minutes and 21 seconds to avoid the estimated passing of the debris as closed as less than a half of kilometre from the station. This functionability action resulted in a postponement of the planned spacewalk by two NASA astronauts. [10]

6th March 2023: The ISS fired thrusters to avoid collision with an Earth observation satellite. The power came from the docked ISS re-supply ship Progress 83 and lasted just over six minutes slightly raising the station's orbit to avoid the approaching satellite. The new orbital trajectory did not impact the upcoming departure of the Crew-5 mission. [11]

14th March 2023: To provide extra distance from a fragment of Russian Cosmos 1408 satellite debris the ISS Progress 83 thrusters fired for a 2-minute and 35-seconds. NASA and Russian flight controllers worked together to conduct the maneuver to prevent the fragment potentially passing within 200 metres from the station. [12]

6th August 2023: The ISS taken PDAM to mitigate a projected high-risk conjunction with Cosmos 1408 debris (COSPAR ID: 1982-092BZV, NORAD ID: 52808). The 83P Progress vehicle thrusters were used to raise perigee altitudes by 0.73 km and 0.40 km, respectively. [13]

24th August 2023: Using the Zvezda Service Module's main engines as thrusters the ISS completed a PDAM to avoid a high-risk conjunction with Fengyun-1C[16] (FY-1C) debris (COSPAR ID: 1999-025DPV, NORAD ID: 35213). This action lowered the ISS apogee and perigee altitudes by 0.18 km and 1.34 km, respectively. Both the timing of the action and its retrograde direction were chosen to minimise the impact of the PDAM upon Progress 85P, the SpaceX Crew-7 vehicle, and the Soyuz 69S departure and 70S launch operations. [13]

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[14] Object 39915 was a piece of debris generated during the break-up of object 23106 (Pegasus R/B) that was launched on 19th May 1994. The rocket's upper stage break-up occurred on 3rd June 1996. [7]

[15] It was generated on 15 November 2021 as result of the antisatellite (ASAT) test on Cosmos 1408 by the Russian Federation. Since then, the ISS has experienced many conjunctions with its remaining tracked fragments.

[16] This debris was created by anti-satellite test on FY-1C conducted by the People's Republic of China in January 2007.

10th November 2023: The International Space Station (ISS) performed a Predetermined Debris Avoidance Maneuver (PDAM) at 15:07 GMT to mitigate a projected high risk conjunction with SL-16 debris (COSPAR ID: 1992-093KT, NORAD ID: 39841). This fragment was created during one of four known breakup events; the first event occurred on 26 December 1992, within 26 hours of the 25 December launch, and the last event occurring on 30 December 1992. The breakup parent was the Cosmos 2227 rocket body, a Zenit-2/SL-16 second stage. [14]

4.4 Summary of ISS avoiding actions

In summary during the 25 years of orbiting Earth the ISS has performed 38 functionability actions to preserve its safe operation. Annual and cumulative number of PDAMs executed thus far has been present in Figure 1.

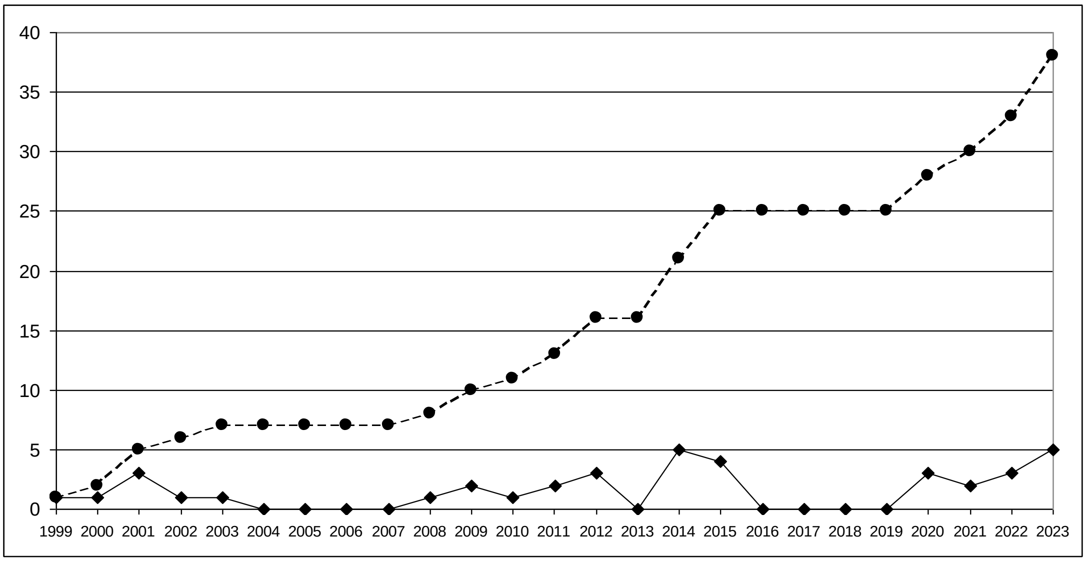

Figure 1. History of the ISS collision avoidance actions.

5. Resources Used by Pre-Determined Debris Avoidance Maneuver PDAM

The NASA “Cost and Benefit Analysis of Orbital Debris Remediation” report about addressing orbital debris released on March 10, 2023 estimates the costs and complications of maneuvering the ISS in case of trouble. [15] Costs associated with pre-determined debris avoidance maneuver are briefly present below.

5.1 Risk analysis per warning

Based on numerous public information sources, the report says that each maneuver requires two person-hours of risk analysis.

5.2 Labor per maneuver

That said, changing the ISS orbit would only be needed in a small minority of possible messages about "conjunctions" or close encounters with orbital debris (about 2%, the authors estimate with 100 person hours of effort charged at the standard labor rate).

5.3 Propellant per maneuver (cost of propellant).

Approximately 70 kg of propellant are required to boost the station and then another 70 kg would be required to lower it. Most PDAMs would also contribute to routine orbit-raising requirements that represent 90% of maneuvers with zero wasting propellant. Debris avoidance maneuvers that consumes propellant represent about 10%. To lower and then re-raise the ISS it would require 140 kg of propellant. Based on the cost of cargo being $70,000 per kilogram and that 10% of maneuvers consuming 140 kg of propellant, there is an average of 14 kg[17] of propellant used per maneuver making the cost per PDAM of one million dollars.

5.4 Lost work per maneuver (suspension of all activities of the ISS crew).

Suspension of all activities of the ISS crew during the orbital debris avoidance maneuver. The crew must be each time prepared for the potential immediate evacuation using Soyuz spacecraft. There may eventually be potential costs associated with interruption and potential cancellation of microgravity experiments.

5.5 Hardware cost of collision.

The above mentioned report assumes an impact would be from an object between 1 cm and 10 cm in diameter. The cost to repair such a debris puncture would be at least $200 million, as a spacecraft would need to go to the ISS bearing necessary materials for repair. However, the cost is likely much higher when taking into account numerous factors like crew time and lost science time, or potential repairs to non-core ISS elements like docked spaceships.

5.6 Lost operations due to collision.

The report indicates that a lost operations value per one ISS element out of service would be about $160 million per year. Given that there is no information how long the struck element would be in negative functionability state, it is assumed that the damaged ISS element would be minimum two years out of operations, leading to lost operations cost of about $300 million in total.

5.7 Contamination and mechanical erosion on exposed ISS surfaces by hypergolic components.

The bipropellant thrusters used by ISS (for reboost and attitude control) and other visiting spacecraft produce contamination and mechanical erosion on exposed surfaces which can impact optical properties and performance of systems such as the ISS solar arrays and robotic cameras, as well as introduce hazards to Extra-Vehicular Activity (EVA).
They are hypergolic components, either monomethylhydrazine (MMH) or unsymmetrical dimethylhydrazine (UDMH) as the fuel and nitrogen tetroxide (N_2O_4, or NTO) as the oxidizer. [16]

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[17] 0.9×0 [kg] + 0.1×140 [kg] = 14 kg

Table 1. Costs associated with debris avoidance.

Cost Element	Value	Cost
Risk Analysis	$200	Per Warning
Propellant	$1 million [a]	Per Maneuver
Labor	$8,000	Per Maneuver
Lost Work	$0	Per Maneuver
Lost Vehicles	$200 million [b]	Per Collision
Lost Operations	$300 million [b]	Per Collision
Contamination and Mechanical Erosion of ISS Surfaces	Unknown	Per Maneuver

[a] Most maneuvers will not cause a waste of propellant, only a small portion. The average cost of waste propellant is presented.

[b] Estimation for damage of single module, not the entire ISS.

6. Summary

MIRCE Science is a theory of the motion of working system through MIRCE Space caused by any action whatsoever. Consequently, the main objective of this paper was to present the pre-determined debris avoidance maneuvers of the International Space Station as a functionability action.

When predictions indicate that any tracked object will pass close enough for concern and the quality of the tracking data is deemed sufficiently accurate, a prudent functionability action for its avoidance is created by relevant mission control centres. The risk of each potential collision is calculated many hours in advance in accordance to the orbital elements of the debris object and potential target.

Calendar dates regarding 24 functionability actions have been identified and presented in paper of out 38 recorded. Identifications of the tractable orbital debris that constituted negative functionability actions threatening the safety of ISS are cited in accordance to the Committee on Space Research (COSPAR) of the International Science Council (ISC), (COSPAR ID) and North American Aerospace Defense Catalogue Number, (NORAD ID).

The paper clearly confirms the fourth axiom of MIRCE Science that states: The probability that a functionable (working) system type will move to a negative functionability state at any instant of time is greater than zero, regarding possible collisions of ISS with orbiting orbital debris. The randomness of occurrences of PDAM related functionability events during in-service life of ISS are presented in graphical form.

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Space Weather as a Mechanism of Motion of Autonomous Trains in MIRCE Science

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Abstract

The main objective of this paper is to draw attention to the scientific approach to reliability and safety of autonomous trains, promoted by MIRCE Science, as guidance for the design engineers and operational managers of the future driverless rail transportation systems. Hence, scientific understandings of the mechanisms that cause undesirable events during their operation by surrounding natural environment are required. This paper focuses on already experienced negative impacts of space weather on reliability and safety of technological systems like power networks, aviation, ships, pipelines, digital control systems and similar. The events presented in this paper should be served as the lessons learned that must be considered during the development of the operational concepts of the future autonomous trains and technologies used. Then and only then, accurate and meaningful reliability and safety actions could be taken by design engineers and operational managers that should be able to deal with potentially harmful consequences of the space weather on the working effectiveness of autonomous trains.

Key words: MIRCE Science, functionability actions, space weather, autonomous trains

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1. Introduction

The philosophy of MIRCE Science is based on the premise that the purpose of the existence of any working system is to do work. The work is considered to be done when the expected measurable function is performed through time. MIRCE Science focuses on the scientific understanding and description of the physical phenomena and human rules that govern the motion of working systems through MIRCE Space[18]. A full understanding of the mechanisms that generate this motion is essential for the accurate predictions of the expected work done by a given working system type using the mathematical scheme of MIRCE Science. [1]

An autonomous train, like all other autonomous systems, is equipped with advanced technology that enables artificial intelligence to "think" and move by itself. This is achieved with sensors and software that identify its exact position, review its speed at any time, detect obstacles on the track, monitor its surroundings and many other relevant issues. They are becoming more and more common, from the metros and trams in city centres to the 2 kilometres long freight train, pioneered by Hitachi Rail. It has no driver, but it has a range of AI enabled cameras and machine learning algorithms that tell it what to do when it 'sees' a kangaroo, encounters a level crossing, or needs to adjust its speed to the gradient of the terrain, at Rio Tinto mine in Australia. [2]

On 27th February 2023 a powerful solar storm delayed the SpaceX rocket launch as a huge amount of charged solar particles reach Earth. In February 2022 SpaceX lost a batch of 40 satellites after launching them right into a relatively mild geomagnetic storm. The interactions of these particles with the upper atmosphere caused the atmosphere to swell as the density of gases at higher altitude increases and spacecraft experience more drag. Since SpaceX launches Starlink craft into very low altitudes and then uses the onboard propulsion of satellites to raise their orbit, this additional drag was too much and satellites were lost. [3]

Even more, the same solar storm temporarily disrupted work of multiple oil rigs in Canada, as GPS signals were too inaccurate. The electronics in the tool that determines which direction and inclination the drill bit should be going was receiving so much interference from the storm that its readings were unreliable. [4]

The railway transport system heavily depends on the availability of other critical infrastructures such as power, signalling, communications, and navigation systems for operations. Many research studies have shown that these technologies were and could be disrupted by impacts of space weather generated phenomena.

Consequently, the main objective of this paper is to draw the attention of the railway industry to the MIRCE Science approach to reliability and safety of the future autonomous trains whose working performance could be significantly affected by the space weather. Impact of the space weather on in-service reliability of avionics is discussed in the paper, as they were the first earthly systems to be affected. It is essential to understand the potential impacts of space weather on the operation of the technologies and sensors used that are "nerves" of the operation of the autonomous trains in the future. Only then, meaningful reliability and safety engineering actions could be taken towards reduction of

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[18] MIRCE Space is a conceptual 3-dimensional coordinate system containing a sequential motion of a working system through quantised functionability states in time and probability of being in them. [1]

the probability of occurrences of the damaging effects of space weather on autonomous trains during their working lives.

2. The Concept of Autonomous Train

In 1968, London Underground opened the Victoria Line that had the first fully automated trains running on it. A driver was still present in the cabin, and there were still manual controls which could override the automation in an emergency, but the main job was opening and closing the doors, something that could not be safely done remotely.

It wasn’t until the arrival of the Port Liner in Kobe, Japan, in 1981 that the world had a fully autonomous public railway. A few years later a similar system was built in Lille, Northern France. Today there are many autonomous public transportation systems around the world, with a higher degree of automation than ever, on inter-city high speed train services. However, there is still always a driver or engineer on board, with various levels of control, as well as overall management of the train, equivalent to a ship’s captain.

2.1 Levels of autonomous trains

While full driverless autonomy is certainly technically possible, and is applied on various routes world-wide, it still accounts for a small percentage of trains running today. New trains are still being designed and built with fully equipped driver cabins. However, looking to the future the industry has a categorised the Grades of Automation (GoA) for trains, as follows:

- GoA0: All driving done by a human, no autonomy.
- GoA1: A human starts and stops the train, but it can automatically travel in between, with the driver able to intervene in an emergency.
- GoA2: The driver remains in the train to override the transportation system if necessary and to perform procedures like checking the platform is clear of passengers before initiating the start sequence, but the train drives from stop to stop automatically.
- GoA3: A person, who can take over the controls if needed, is always on board, but not necessary in the cabin, while checking tickets, making announcements, opening and closing doors and so forth. However, the train can, and does, drive itself.
- GoA4: Neither driver nor any staffs are required to be in the train, at any time, as the full automation manage all passenger safety and driving activities.

Although reliability and safety are a paramount for rail transportation, nowadays there is a push towards automation that is facilitated by remote monitoring, on-train sensors, fail-safe computer based algorithms for vehicles and networks, all of which are considered sufficiently adequate to provide the expected level of railway services.

The natural ability of drivers to notice, interpret and take action on-track hazards, including other trains, requires several hundred metres distance between most trains. However, on automated trains with modern hazard management that reaction and decision time is not required, which means that they can travel closer to each other and still stop safely in an emergency, enabling higher throughput.

The 23 June 2023 the 1st stage of Honolulu Rail Transit system was opened, which is the first fully autonomous system in the US. Hitachi Rail launched a driverless metro system in Copenhagen, a safe, fast and comfortable metro system that pioneers autonomous train operation. The final giant leap will be to apply GoA4 to high-speed intercity passenger trains, although there are few signs of that happening in the experimental projects. The technology certainly exists, but the cost of re-engineering large networks and their infrastructures might prove decisive.

3. MIRCE Science Fundamentals

MIRCE Science is a theory of the motion of working systems through MIRCE Space resulting from any functionability actions whatsoever and the actions required to produce functionability related motions. According to MIRCE Science, at any instant of calendar time, a given working system could be in one of the following two macro states [1]:

Positive Functionability State (PFS), a generic name for a state in which a working system is able to deliver the expected measurable function(s),

Negative Functionability State (NFS), a generic name for a state in which a working system is unable to deliver the expected measurable function(s), resulting from any reason whatsoever.

In MIRCE Science, work done by a working system is uniquely defined by the trajectory generated by its motion through MIRCE Space. That motion is driven by functionability actions, which are classified as:

- Negative Functionability Action (NFA), is a generic name for any natural process or human activity that compels a system to move to a NFS. Typical examples are: thermal ageing, actinic degradation, acid reaction, bird strike, warping, abrasive wear, suncups formation on the blue ice runway, fatigue, pitting, thermal buckling, photo-oxidation, production errors, strong wind, maintenance error, hail damage, lightening strike, COVID-19, quality problems in production or installation, tsunami, sand storm and so forth.

- Positive Functionability Action (PFA), is a generic name for any natural process or human activity that compels a system to move to a PFS. Typical examples are: servicing, lubrication, visual inspection, repair, replacement, final repair, examination, partial restoration, inspection, change of operational mode, postponed operation, modification, cannibalisation, refurbishment, condition monitoring, packaging, diagnostics and similar

The main objective of MIRCE Science is the scientific understanding of mechanisms that govern positive and negative functionability events. That represents a real challenge, as the answers to the question “what are the natural and human processes that lead to the occurrence of given functionability events” have to be determined. Without accurate answers to those questions the prediction of their future occurrences is not possible, and without the ability to predict the future, the use of the word science becomes inappropriate.

Research studies conducted at MIRCE Akademy[19] by staff and students had shown that any serious studies of the functionability mechanisms have to be based between the following two boundaries [1, 13,15]:

- the "bottom end" of the physical world, which is at the level of the atoms and molecules that exists in the region of 10^{-10} of a metre.
- the "top end" of the physical world, which is at the level of the solar system that stretches in the physical scale around 10^{+10} of a metre.

This range is the minimum sufficient "physical scale" which enables scientific understanding of relationships between physical phenomena that take place in the natural environment and the physical mechanisms that govern functionability events during the life of working systems.

Space weather is a phenomenon of the natural world that directly impacts the reliability of working systems in general and potentially autonomous trains in particular. This paper therefore considers major properties of space weather that impacts the amount of work done by autonomous trains.

3.1 Space weather as a negative functionability action in MIRCE Science

Negative functionability action is a generic name for any natural process or human action that compels a working system to move to a NFS, some of which are mentioned earlier in the paper. Space weather is one of the numerous natural actions that have a negative impact on the work done by an autonomously working system. Their physical occurrences are manifested through occurrences of negative functionability events. These are observable instances of time at which working systems stops delivering expected measurable function(s). [1]

Space weather events have always occurred, but as the biggest impacts are arguably on technology driven systems, it is only in modern times that our attention is drawn toward their susceptible threats. Different systems across the globe are exposed to varying levels of risk depending on their technical design, location and the type of space weather they are susceptible to. It is a reliability and safety engineering challenge to ensure that future systems are designed with appropriate provisions to minimise the risk posed by space weather. [7]

Until the early 1980s the space weather phenomena was only observed in orbiting satellites. Then they began to be noticeable in electronic devices related primarily to radiation concern for avionics, a term derived from the expression "aviation electronics", concerned with the development and production of electronic instruments used in aircraft and spacecraft. [8]

A Single Event Effects, SEEs, is the principal space weather phenomena affecting avionics devices. The Single Event Upset, SEU, is a NFE that is occurring when a sole incident particle creates a charge disturbance of sufficient magnitude in a memory cell, flip-flop, latch or register to reverse or flip its currently stored data state. Alternatively, in logic or

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[19] for more information follow the link: http://www.mirceakademy.com/news/2/15/MIRCE-Functionability-Actions/

support circuitry a transient voltage pulse can be generated that, on the right conditions, can propagate through the logic of the device and become latched into a memory cell. Voltage spikes on power supply lines and noise can also cause transient errors. However, appropriate shielding and filtering design measures can suppress these types of disturbances. [12, 14]

Space weather generated radiation can affect electronic devices as the consequence of a single energetic particle strike, termed 'single event' or as multiple strikes over an extended period of time. The effects due to multiple events, Total Ionisation Dose, TID, and displacement damage manifest gradually in electronic components as damage is accumulated over time. These total dose effects and hard SEEs whilst relevant to electronic systems operating in the harsher space environment have a negligible effect on current semiconductor devices used in the terrestrial environment.

Multiple Bit Upset, MBU, is the second most prevalent SEE that occurs when a single particle causes the upset of two or more memory cells. Fortunately MBUs only form a fraction of the total number of SEUs, thus they have little significance except for memory architectures employing Error Detection and Correction, EDAC, techniques. In these circumstances, dependent on the type of error correction technique employed, multiple bit errors could have significant consequences if the protected memory is used for flight or mission critical applications. MBUs are generally assumed to attribute 3% of the total upset rate. [12]

The following two negative functionability events account for the majority of the remaining proportion of SEEs affecting avionics devices, thus:

Single Event Functional Interrupt, SEFI, that occurs when an upset initiates an Integrated Circuit, IC, test mode or reset mode that causes the device to temporary loose functionality.

Single Event Latch ups, SELs, arise when an incident particle creates a charge disruption sufficient enough to effectively short circuit the device resulting in its permanent change of state or in some circumstances permanent damage if excessive current flows as a result of the latch-up.

The last SEE of avionics relevance that can generate soft errors in the core logic of microprocessors and microcontrollers is the Single Event Transient, SET. They are transient and non-destructive in nature and are capable of producing a soft error, (i.e. the storage of an erroneous data value in registers, memories or latches) only if it is propagated through the logic pathways of the device. [9]

4. Placing Space Weather in MIRCE Functionability Equation

MIRCE Functionability Equation is a mathematical description of the motion of the working systems through MIRCE Space, caused by any action whatsoever, is defined as following expression [1]:

$$y(t) = 1 - \sum_{i=1}^{\infty} F_S^i(t) + \sum_{i=1}^{\infty} O_S^i(t), \quad t \geq 0 \qquad (1)$$

In the above equation $F_S^i(t)$ is a cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the sequential negative functionability event, $TNE_S^i(t)$ of a system considered. In MIRCE Science it is defined by a following convolution integral:

$$F_S^i(t) = \int_0^t O_S^{i-1}(x)dF_{S,i}(t-x), \qquad i = 1, \infty \qquad (2)$$

where: $F_{S,i}(t)$ is a cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the i_{th} negative functionability event, $TNE_{S,i}(t)$ of a working system considered. The number of these functions is equal to the number of NFA that generate NFE occurring during the in-service life of working systems, briefly mentioned above. In the case that this random variable is governed by the impact of space weather it is denoted as $TNE_{S,i,SW}$, and it is defined by the following expression:

$$F_{S,i}(t) = P(TNE_{S,i,SW} \leq t) = \int_0^t f_{S,i,SW}(t)dt \qquad (3)$$

where; $f_{S,i,sw}(t)$ is a probability density function of the random variable that defines the time to the occurrence of i_{th} negative functionability event, which in this specific example is a space weather. The above equation is in the most generic form and as such covers all possible variations and impacts of space weather, which means each specific generating NFA has its own mathematical expressions for each occurring event.

In the equation (1) $O_S^i(t)$ is a convoluted form of cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the consecutive positive functionability event, $TPE_S^i(t)$ of a system considered. In MIRCE Science it is defined by the following convolution integral:

$$O_S^i(t) = \int_0^t F_S^i(x)dO_{S,i}(t-x), \qquad i = 1, \infty \qquad (4)$$

where: $O_{S,i}(t)$ is a cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the i_{th} positive functionability event, $TPE_{S,i}(t)$ of a system considered. The number of these functions is equal to the number of NFA that generate NFE occurring during the in-service life of working systems, briefly mentioned above. In the case that this random variable is governed by the impact of a positive action taken in response to the occurred space weather generated NFE on the autonomously working system. It is denoted as $TPE_{S,i,SW}$, and it is defined by the following expression:

$$O_{S,i}(t) = P(TPE_{S,i,SW} \leq t) = \int_0^t o_{S,i,SW}(t)dt \qquad (5)$$

where; $o_{S,i,sw}(t)$ is a probability density function of the random variable that defines the time to the occurrence of i_{th} positive functionability event, which in this specific example is a space weather responding action. The above equation is in the most generic form and as such covers all possible variations and impacts PFA that could be taken to return a system to PFS after impacts of space weather generated NFA, which means that each action has its own mathematical expressions for each specific application.

Possible space weather generated actions that could cause occurrences of NFEs and thus impact the motion of autonomous trains through MIRCE Space are addressed in the remaining part of the paper.

5. The Concept of Space Weather

Space weather term refers to the environmental conditions in Earth's magnetosphere, ionosphere and thermosphere due to the Sun and the solar wind that can influence the functioning and reliability of space-borne and ground-based systems and services or endanger property or human health. Space weather deals with phenomena involving ambient plasma, magnetic fields, radiation, particle flows in space. In addition to the Sun, non-solar sources such as galactic cosmic rays can be considered as a part of space weather since they alter space environment conditions near the Earth. [5]

Space weather science is a developing field and its impacts upon modern society have only recently come in to the fore as results of dependencies on technologies vulnerable to solar phenomena increases. Therefore, significant research efforts are made to better understand potential impacts of severe space weather events.

The sun is a dynamic star. Its surface boils at over 5,500 degrees Celsius, with complex electric and magnetic fields twisting, winding and plunging in and out of the depths. This intricate relationship between the superheated plasma of the sun and its own magnetic fields creates the conditions for solar storms. These events, including flares, eruptions and coronal mass ejections, release tremendous amounts of energy into the solar system. Sometimes the releases take the form of pure radiation, whereas sometimes entire blobs of sun stuff launch from the surface, moving slowly toward the planets. Often, the sun launches storms of tiny, charged particles known as solar energetic particles, SEPs, electrons and protons travelling at nearly the speed of light.

During periods of intense solar activity, SEPs can slam into Earth, penetrating its magnetic field and even punching through the atmosphere, raining deadly radiation onto the surface causing electronics to get scrambled, and sensors to get damaged.

The three constituent elements of a solar storm and their resultant space weather manifestations are:

- Solar flares: magnetically initiated explosions that occur at or near the surface of the Sun that release intense bursts of electromagnetic radiation in the form of x-rays, ultraviolet and radio emissions, which can cause disruptions to the Earth's ionosphere leading to radio and communications interference.

- Geomagnetic storms: large disturbances in the Earth's magnetic field caused by changes in the solar wind and interplanetary magnetic field, IMF structure.

- Coronal mass ejections, CMEs: a result of the twisting and realignment of the sun's magnetic field. As magnetic field lines "tangle" they produce strong localised magnetic fields that can break through the surface of the sun at active regions.

To provide an appreciation of the temporal characteristics of the Sun’s effects on the radiation environment, the arrival times of each solar storm component are very briefly stated below:

- X-Rays and radio waves travel from the Sun at the same speed as visible light, hence they take approximately 8 minutes to reach Earth.

- The speed of protons during solar particle ejections is dependent on energy level and therefore typically takes between 15 minutes to a few hours to generate atmospheric and ground level particle enhancements.

- The solar plasma cloud of CMEs takes between 2 and 4 days to impact the Earth’s geomagnetic field and generate a geomagnetic storm that may take several days or even weeks to recover.

6. Impact of Space Weather on Functionability of Autonomous trains

The amount of work done by autonomous trains during a stated time, W(Tst), is not driven by their functionality performance, it is driven by their functionability performance, defined by equation (1). Hence, the expected amount of work done by a working system could be determined by making use of the following:

$$(6) \qquad W(Tst) = \int_{0}^{Tst} y(t)dt$$

To do the work an autonomous train has to be in PFS and for that to happen its supporting infrastructure like, power provisioning, signalling,communications, navigation, positioning and similar systems must be also in PFS. However, the digital technologies used within supporting systems have increased the risk of adverse effects caused by the space weather on their functionability.

For example, the power-grid is critical for train’s functionality because of its immediate impact on the railway network, as well as potential affects on other systems within railway stations. From a safety criticality standpoint, the most significant systems that may be affected by geomagnetically induced current, GIC, are signalling and traffic control systems. This problem exists due to the increase in lengths of track-circuit and longer length of trains. Other train supporting equipment such as heating systems, switching actions can also be possibly susceptible to GIC are wayside cables, telecom and line-side circuits, backup systems, batteries, condition monitoring systems, point circuits in switching, crossings and location devices. [11]

Autonomous trains control systems used for communications are relying on mobile phones and wireless technology, which is also susceptible to interference from solar radio bursts. The same applies to the speed and position controlling systems that communicate movement of trains. Interference from radio bursts could cause the transition of the functional train to NFS stopping it from doing the expected work. [6]

A research project that investigated the effect of solar storms on railway signals has shown that fluctuations in space weather are disrupting train signals and causing significant delays. To track the location of trains, a railway line is split into small, consecutive segments called 'blocks' with an average length of 1-2 km. Each block is tied to a signal that indicates the presence of a train in that block. The signals are controlled by relays that detect currents in the system, which turn signal to green if the block is empty and a current is detected or to red if the block is occupied and no current is detected. [5]

According to [16] solar storms can off-set the balance of currents controlling the light signals on train lines, causing lights to show clear sections as occupied with a red light. Evidence shows that stronger solar storm cause more signals to malfunction, thus increasing the amount of time the train is delayed. A team of researchers at the University of Lancaster has modelled the impacts of solar storms on two segments of the UK railway network, namely a South-North line from Preston to Lancaster and a West-East line from Glasgow to Edinburgh. One of the objectives of this research is to determine how strong a storm needs to be to turn a red signal back to green, which is very hazardous scenario potentially leading to crashes. Solar storms can off-set the balance of currents controlling the light signals on train lines, causing lights to show clear sections as occupied with a red light. Evidence shows that stronger solar storm cause more signals to malfunction, thus increasing the amount time the train is delayed. Technological problems can occur as a result of solar storms with a range of strengths: from medium storms with electric field strengths of 2V/km to strong storms at 4V/km. In the past, values of higher than 7 V/km have been detected along railways in Sweden. Estimates of extreme solar storms have predicted events with strengths of up to 20 V/km. Interestingly, the results suggest that signalling failures can occur even with moderate storms. So, while these estimates are unsettling, there is still cause for concern without these extreme storms. The continuation of this research is expected to provide the answer to the question, how strong a storm needs to be to turn a red signal back to green, which is a hazardous scenario potentially leading to crashes. [16]

7. Space Weather Forecasting

As almost all aspects of human life on Earth become ever more dependent on technology and systems such as satellites, Global Navigation Satellite System, Global Positioning System, power and radio communications, the threats of a severe space weather event are increasing in importance. Therefore, space weather prediction is of crucial importance to power companies, satellite operators and all modes of transport.

For example, a severe space weather event service was added to the United Kingdom's National Risk Register of Civil Emergencies in 2011. The Met Office, the national meteorological service for the UK, was given ownership of that task in 2013 and set up the Met Office Space Weather Operations Centre[20], MOSWOC, to provide space weather alerts, warnings, and guidance to the UK government and general public. The centre was officially opened in 2014 October, although 24/7 operational services commenced in 2014

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[20] https://www.metoffice.gov.uk/weather/learn-about/space-weather/what-is-space-weather

April. MOSWOC provides flare forecasts to users multiple times daily as part of their space weather service. [10]

To address the potential dangers of solar activities on humans and technology on Earth, in 2023 NASA provided five years' worth of funding for CLEAR, a space weather forecasting centre at the University of Michigan. It will bring together astronomers and astrophysicists with a wide variety of specialities, ranging from observers to theorists, to address the challenge of SEP prediction. They will use theoretical models of the solar surface to predict when solar flares and coronal mass ejections, which launch SEPs, are likely to erupt.

8. Engineering Mitigation for the Impacts of Space Weather on Autonomous Trains

The main objective of this paper was to draw the attention of design engineers of autonomous trains to the impact of the space weather on their in-service reliability and safety. These impacts have been determined by applying principles of MIRCE Science to the process of the motion of autonomous trains through MIRCE Space.

Mitigation of the impacts of space weather on in-service reliability and safety of autonomous trains boils down to the following two opportunities:

- engineering out as much risk as is reasonably possible during the conceptual stage of the design of the future autonomous trains

- selecting operational strategies to deal with the residual risk during the in-service operation of autonomous trains

The impacts of both approaches could be quantitatively evaluated by making use of MIRCE Functionability Equation, given that all necessary information is available.

Needless to say, that is a real challenge, but it is essential to understand that functionability of autonomous trains is affected by the impacts of space weather driven functionability actions, on one hand and the impact of contemporary technologies used to control and manage their functionality, on the other. [13]

9. Conclusion

In summary, this paper states that reliability and safety considerations of autonomous trains must include the full understanding of the impact of space weather on their functionability performance. Then and only then, accurate and meaningful reliability and safety engineering predictions can become possible. These predictions are enabling design teams and operational managers to focus on the ultimate goal, which is the reduction of the probability of the occurrence of undesirable impacts of naturally occurring space weather phenomena on day to day operations of autonomous trains. It is necessary to point out that these phenomena impact all modern technological working systems like, power networks, aviation, satellite services, pipelines, digital controls and many others.

Further more, this paper advocates that the MIRCE Science physical scale from 10^{-10} metre to 10^{+10} metre must be used in order for the functionability events generating space weather mechanisms to be understood. Then and only then accurate predictions of functionability performance of autonomous trains could be obtained by making use of MIRCE Functionability Equation.

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Optical Observations of Orbital Debris on Uncontrolled Reentry Path

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Abstract

The main objective of this paper is to draw attention to the uncontrolled reentry of orbital debris (non-operational spacecrafts and derelict launch vehicle stages-rocket bodies). Uncontrolled reentry of orbital debris poses a risk to the Earth population and the environment. The following paper will present the results of ground-based optical observations of orbital debris on uncontrolled reentry path. This paper is the continuation of the previously published research paper on Optical Observations of Large Orbital Debris in Low Earth Orbit. The following objects were tracked and observed: ERS-2 non-operational spacecraft (SATCAT: 23560, COSPAR ID: 1995-021A), SL-27 R/B Rocket Body (SATCAT: 40354, COSPAR ID: 2014-084B) derelict launch vehicle stages type of orbital debris, CZ-2C R/B Rocket Body (SATCAT: 39364, COSPAR ID: 2013-059B) derelict launch vehicle stages type of orbital debris and GSLV R/B Rocket Body (SATCAT: 56082, COSPAR ID: 2023-043AN) derelict launch vehicle stages type of orbital debris.

Key words: rocket body, orbital debris, space debris, uncontrolled reentry, optical observations

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1. Introduction

Orbital debris can be presented as man-made/technological hazard and thus all disaster risk reduction techniques that are applied in the case of other natural and man-made/technological hazards can be also applied in the case of orbital debris reentry hazard. One of the core techniques for dealing with imposed risk on population and the environment is the remote sensing of orbital debris or in this case ground-based optical observations of orbital debris environment. The main orbital debris types that pose a great risk during the uncontrolled reentries are the non-operational spacecrafts and derelict launch vehicle stages-rocket bodies. [1]

Approximately 70% of the reentries of intact orbital objects are uncontrolled, corresponding to about 50% of the returning mass, i.e. ∼100 metric tons per year. On average, there is one spacecraft or rocket body uncontrolled reentry every week, with an average mass around 2000 kg. [2] Derelict launch vehicle stages-rocket bodies poses a great risk to the International Space Station (ISS) and forced the ISS to conduct pre-determined debris avoidance maneuver (PDAM) few times in operational history from 1999 to 2024. [3] Uncontrolled reentries of non-operational spacecrafts and derelict launch vehicle stages-rocket bodies can spread hazardous substances over a large area in the atmosphere during the reentry and on the ground as surviving orbital debris.

Figure 1. Recovered debris of Falcon 9 second stage, Brazil (December 2014). [4]

Figure 2. Recovered debris of Atlas V second stage (Centaur), Spain (November 2015). [4]

2. Observations

To track and observe the uncontrolled reentry of orbital debris of interest, the following statements must be fulfilled:

- the chosen object is in Very Low Earth Orbit (VLEO) below 400 km mean altitude
- on uncontrolled reentry path
- represent one of the two types of orbital debris: non-operational spacecrafts or derelict launch vehicle stages-rocket bodies

Complete orbital debris observations were done from non-permanent observatory, Novi Sad metropolitan area, Serbia. Orbital debris images and videos were taken using the custom made Full-spectrum Nikon D7000 camera with 50 mm lens. [5] [7]

Observations of orbital debris currently involve an interest in following objects:

- orbital debris from McKnight Top 50 - the 50 statistically most concerning derelict objects in LEO (old and new list)
- orbital debris on uncontrolled reentry path
- orbital debris involved in conjunction and fragmentation events

2.1 Observations of ERS-2 (SATCAT: 23560, COSPAR ID: 1995-021A) non-operational spacecraft

ERS-2 was an ESA earth resources spacecraft launched by an Ariane rocket from the Kourou Space Center in French Guiana on April 21, 1995. The 2,516 kg spacecraft carried a synthetic aperture radar for topographic studies, a wide beam radar (both in the C-band), a radar altimeter for measuring ocean surface and waves, a radiometer for measuring ocean surface temperatures, and an optical Global Ozone Monitor (GOME) that will monitor ozone and ozone-destroying gases and carried reflectors for laser tracking. It has a 6.5 gigabyte tape recorder to record data from a full orbit. [6] On February 21, 2024. ESA confirmed the atmospheric reentry of ERS-2 at 17:17 UTC (18:17 CET) over the North Pacific Ocean between Alaska and Hawaii. [12]

Observation dates:

day.month.year.	recording format
16.01.2024.	video
21.01.2024.	**video**
06.02.2024.	video
21.02.2024.	**video**

The ERS-2 overpasses were continuously tracked and observed from 16.01.2024. to the final reentry date which was on 21.02.2024. It was observed in Full HD 1080p video format using Nikon D7000 custom made Full-spectrum camera. [5]

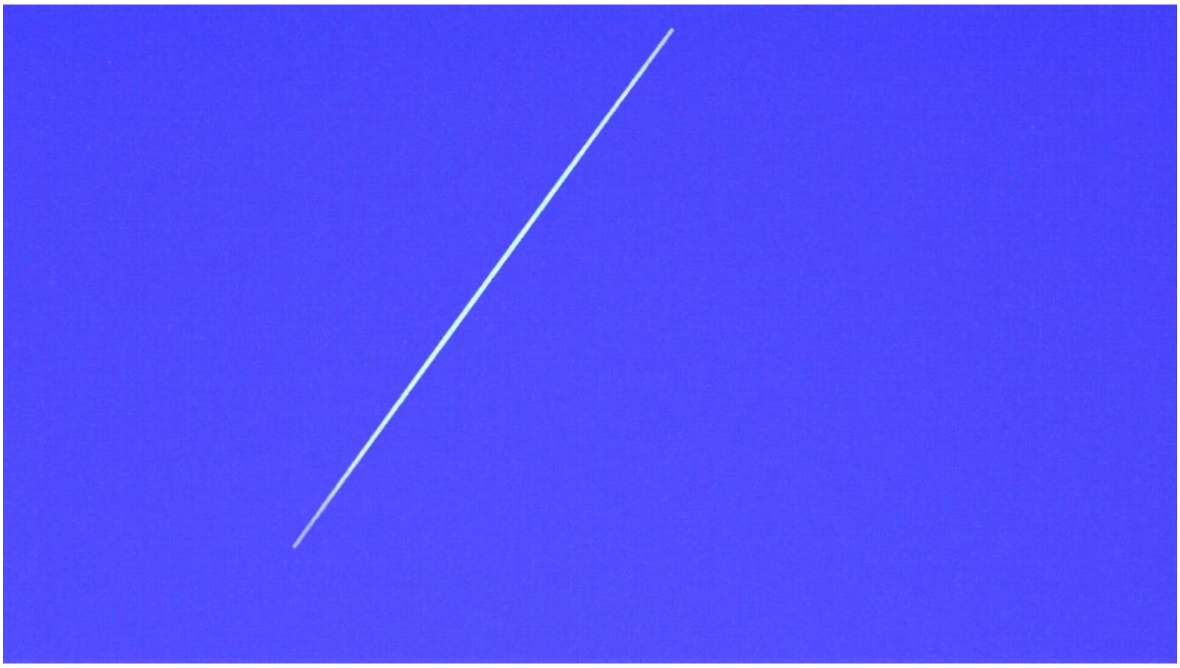

Figure 3. ERS-2 non-operational spacecraft overpass on 21.01.2024. The final image of overpass is produced by images sequencing from video file and then the sequenced images are composed into one final image. [7] Overpass direction from south to north. Mean altitude: 336 km. [9]

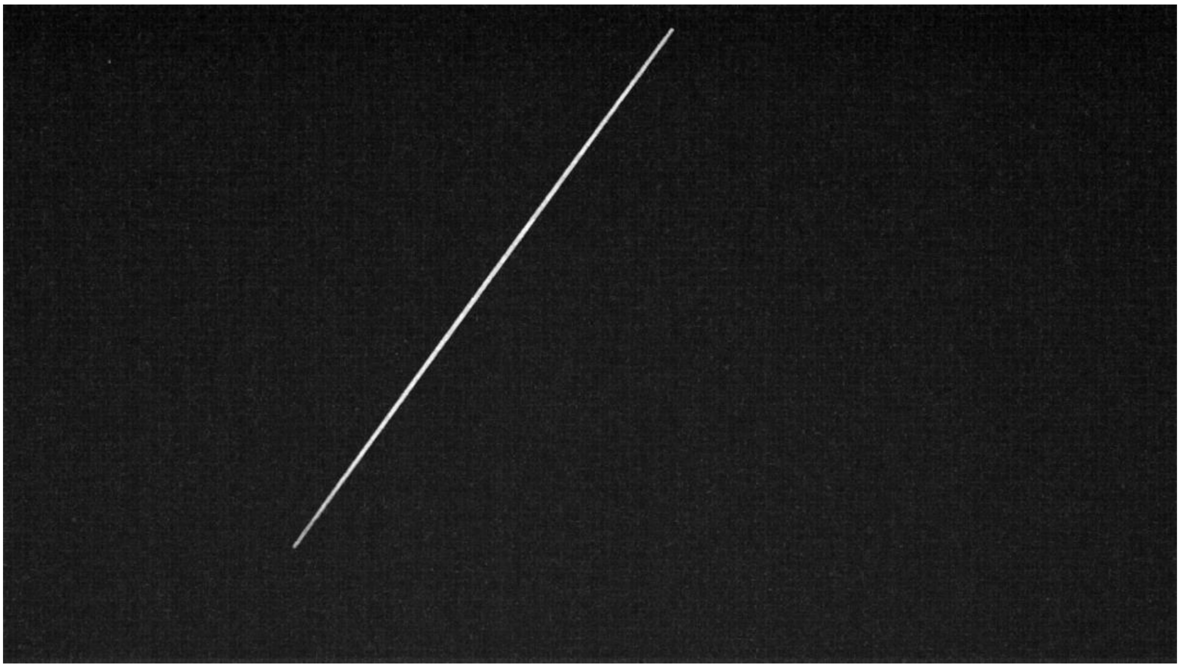

Figure 4. Extracted infrared channel image of ERS-2 non-operational spacecraft overpass on 21.01.2024. The final image of overpass is produced by images sequencing from video file and then the sequenced images are composed into one final image. [7]

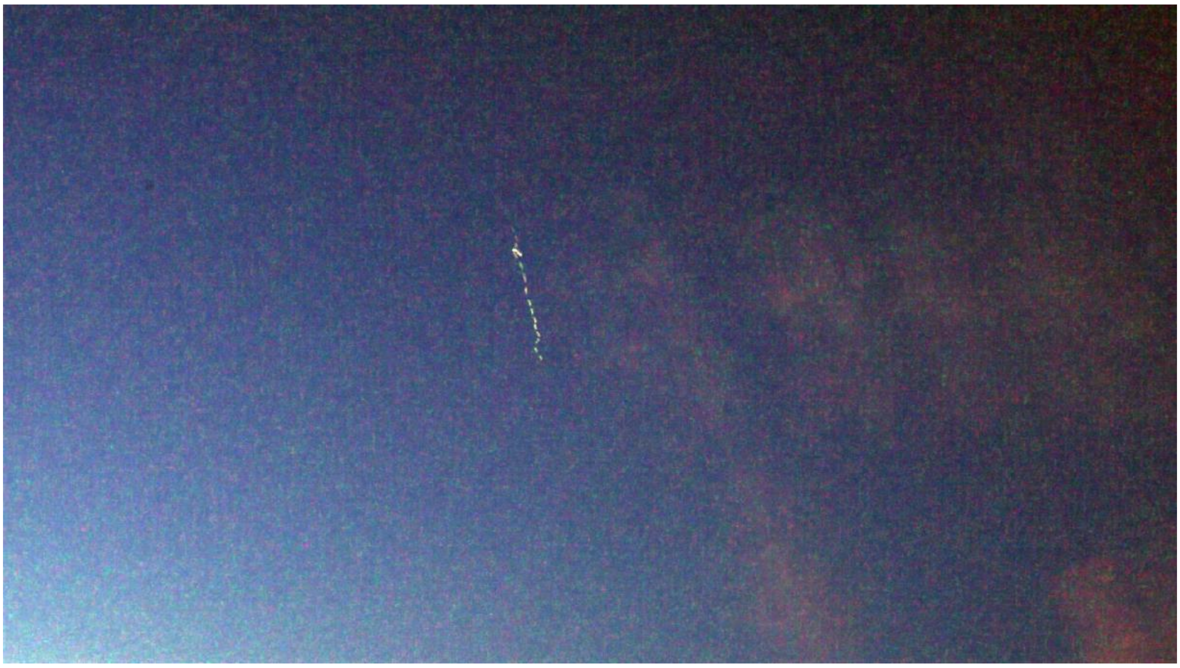

Figure 5. First part of ERS-2 non-operational spacecraft overpass on 21.02.2024. Time 5:53 PM CET west of Novi Sad, Serbia. Overpass from south to north with camera pointed to the north during recording. The final image of overpass is produced by images sequencing from video file and then the sequenced images are composed into one final enhanced image. The overpass track is an irregular line because of camera shaking during fast pointing. Clouds can be seen on the right.

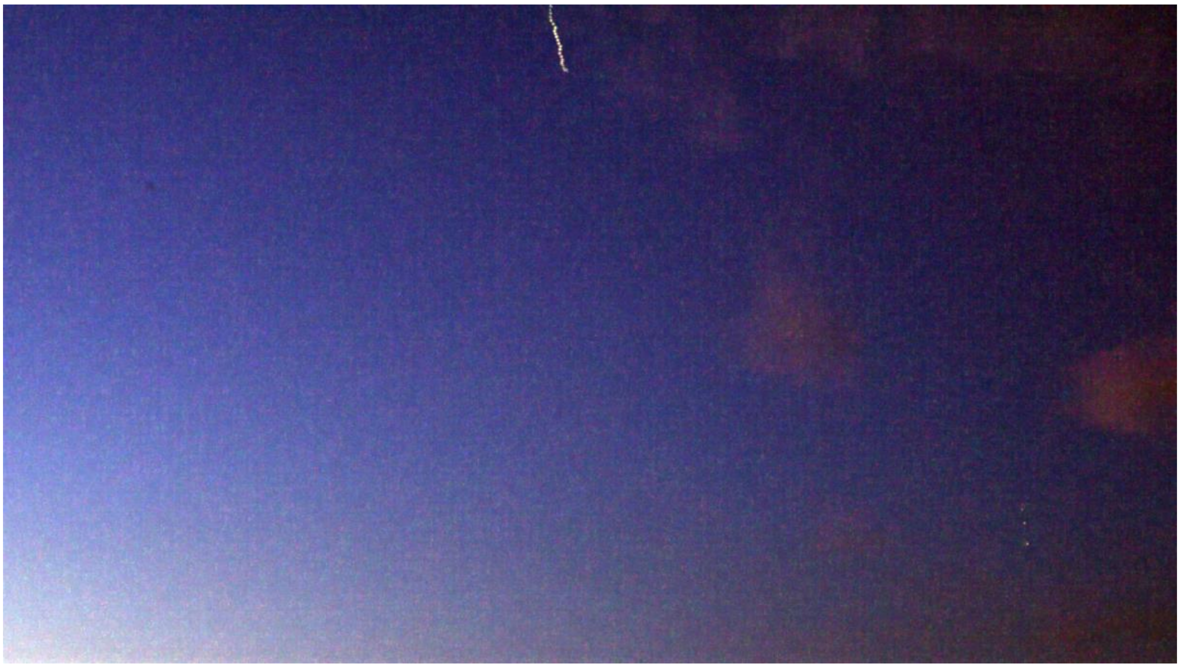

Figure 6. Second part of ERS-2 non-operational spacecraft overpass on 21.02.2024. reentry date with same properties as previous image.

2.2 Observations of SL-27 R/B Rocket Body (SATCAT: 40354, COSPAR ID: 2014-084B) derelict launch vehicle stages

According to the available data this rocket body was a part of Strela launch vehicle [8] and was launched with Kondor-E (SATCAT: 40353, COSPAR ID: 2014-084A) small radar Earth observation satellite. [9]

Observation dates:

day.month.year. recording format
04.03.2024. video
14.04.2024. image
19.04.2024. video

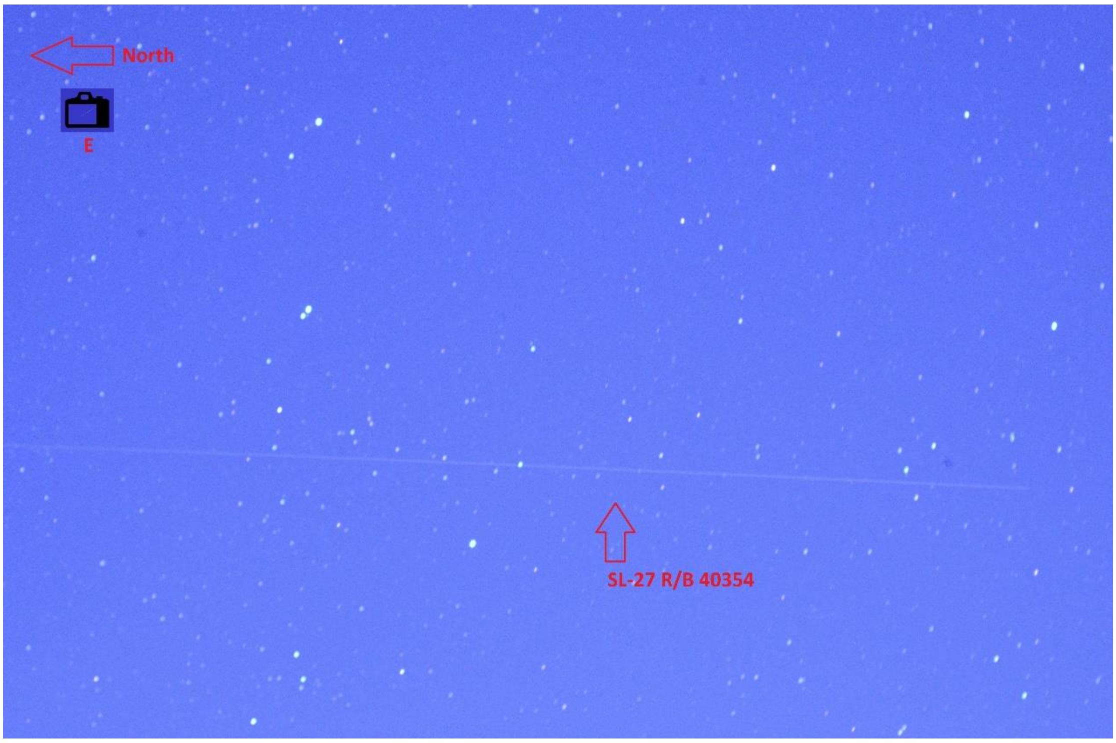

Figure 7. SL-27 R/B Rocket Body (SATCAT: 40354, COSPAR ID: 2014-084B) orbital debris overpass. Type of orbital debris: derelict launch vehicle stages. Original non-enhanced image. Observation date 14.04.2024. Camera pointed towards east. Overpass direction from north to south. Mean altitude: 359.25 km. [11]

Figure 8. Enhanced image of SL-27 R/B Rocket Body (SATCAT: 40354, COSPAR ID: 2014-084B) orbital debris overpass. Type of orbital debris: derelict launch vehicle stages. Observation date 14.04.2024. Overpass direction from north to south.

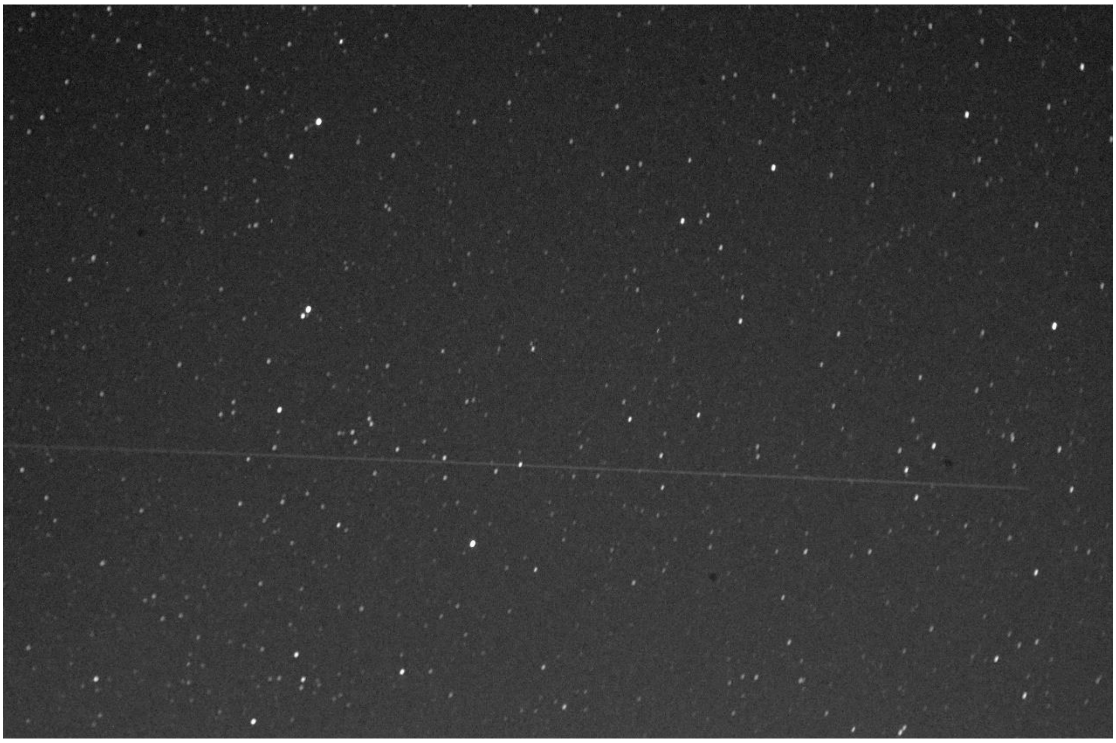

Figure 9. Extracted infrared channel image of SL-27 R/B Rocket Body orbital debris overpass.

2.3 Observations of CZ-2C R/B Rocket Body (SATCAT: 39364, COSPAR ID: 2013-059B) derelict launch vehicle stages

Long March 2C second stage. Dry mass: 3200 kg. According to the available data this rocket body was launched on October 29, 2013. alongside Yaogan 18 (JB-7 3) (SATCAT: 39363, COSPAR ID: 2013-059A) remote sensing satellite. [10] Four type of orbital debris were associated with this mission: CZ-2C DEB 39365, CZ-2C DEB 39366, CZ-2C DEB 39367 and CZ-2C DEB 39368. [9]

Observation dates:

day.month.year. recording format
27.04.2024. video
28.04 2024. image
04.05.2024. image
12.05.2024. image
13.05.2024. image
14.05.2024. image
20.05.2024. image

Figure 10. CZ-2C R/B Rocket Body (SATCAT: 39364, COSPAR ID: 2013-059B) orbital debris overpass. Type of orbital debris: derelict launch vehicle stages. Original non-enhanced image. Observation date 12.05.2024. Camera pointed towards east. Overpass direction from south to north. Mean altitude: 317.70 km. [11]

Figure 11. Enhanced image of CZ-2C R/B Rocket Body (SATCAT: 39364, COSPAR ID: 2013-059B) orbital debris overpass. Type of orbital debris: derelict launch vehicle stages. Observation date 12.05.2024. Camera pointed towards east. Overpass direction from south to north.

Figure 12. Extracted infrared channel image of CZ-2C R/B orbital debris overpass.

Figure 13. CZ-2C R/B Rocket Body (SATCAT: 39364, COSPAR ID: 2013-059B) orbital debris overpass. Type of orbital debris: derelict launch vehicle stages. Original non-enhanced image. Observation date 14.05.2024. Camera pointed towards west. Overpass direction from south to north. Mean altitude: 314.86 km. [11]

Figure 14. Enhanced image of CZ-2C R/B orbital debris overpass.

2.4 Observations of GSLV R/B Rocket Body (SATCAT: 56082, COSPAR ID: 2023-043AN) derelict launch vehicle stages

GSLV R/B Rocket Body (SATCAT: 56082, COSPAR ID: 2023-043AN) derelict launch vehicle stages. Launched on March 26, 2023. alongside 36 OneWeb satellites from Satish Dhawan Space Centre. [9] Geosynchronous Satellite Launch Vehicle (GSLV) is a class of expendable launch systems operated by the Indian Space Research Organisation (ISRO).

Observation dates:

day.month.year. recording format
05.05.2024. image
10.05.2024. image

Figure 15. GSLV R/B Rocket Body (SATCAT: 56082, COSPAR ID: 2023-043AN) orbital debris overpass. Type of orbital debris: derelict launch vehicle stages. Original non-enhanced image. Observation date 05.05.2024. Camera pointed towards west. Overpass direction from north to south. Mean altitude: 319.69 km. [11]

Figure 16. Enhanced image of GSLV R/B Rocket Body orbital debris overpass.

Figure 17. Extracted infrared channel image of GSLV R/B Rocket Body orbital debris overpass.

3. Conclusion

From the following tracked and observed objects, only the ERS-2 non-operational spacecraft reentered on 21.02.2024. The rest of the tracked and observed objects are still on their reentry path. The changes in orbital debris overpass track and time, bad weather and prolonged day hours makes the observations more challenging but not unattainable. The main result of this paper was to improve the development of techniques and sensors for orbital debris observations and contribute to the monitoring of sustainable and safe use of Earth's orbital environment for well-being of all humanity. Future work will bring focus on environmental protection from orbital debris.

Cusat 2 & Falcon 9 R/B Rocket Body orbital debris overpass.

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MIRCE Science: Shark Bite as a Mechanism of Motion of Submarine Cables through MIRCE Space

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Abstract

Sharks represent a serious, but still not fully understood, threat to modern communication systems connected through submarine cables. While the vast majority of sharks do not cause any damage to cables, some shark bites have led to serious consequences to submarine cables used for the worldwide internet connection, generating high repair costs and long outages. Thus, this paper addresses shark bites from the MIRCE Science point of view, which means that it is considered as a mechanism that generates a negative functionability event that causes the motion of a system from a positive to negative functionability state. Therefore, this paper briefly examines the shark species to understand the capabilities and strength of shark bites as mechanisms that could generate undesirable negative consequences the in-service life of affected working systems. The method for predicting impacts of potential protective actions taken by design and operational decisions on in-service reliability, cost and effectiveness of submarine cables can be calculated by making use of MIRCE Functionability Equation are presented in the paper.

Key words: MIRCE Science, submarine cables, shark bites, protection actions, MIRCE Functionability Equation

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1. Introduction

Sharks have been around for over four millions years, survived five mass extinctions and recently shown an inexplicable taste for the submarine cables laid along the ocean floor, as a part of the infrastructure for provision of around 99% of all data transmission requirements. [1] The ocean floors of the world are covered by around 1 million kilometres of cables enabling human's luxuries and conveniences like Netflix or Google. Millions of people, in all types of transport, navigate the physical world using data transmitted by submarine cables, as well as WhatsApp or Signal users to make and change plans in real time. Even further, hospitals, electricity grids, emergency services, public transport, the aerospace and even international politics diplomacy are deeply depend on the internet to run safely and smoothly. [2]

Although submarine cables are a highly reliable means for information transmission, their in-service reliability is affected by external actions. They result from a variety of factors, like the impacts of fishing boats, the interactions of cable landing sites with busy harbours, waterways and associated anchorages and the length of the continental shelf and the system's routing to deep water. Also, natural occurrences such as earthquakes and landslides have damaged cables; together with the corrosive saltwater, extreme temperature fluctuations and marine life all threaten marine cables.

The first recorded shark bites of a deep-ocean fibre-optic cable occurred off the Canary Islands around 1985 to 1987. On four occasions these pioneering systems were damaged by small sharks biting through cable's polyethylene sheath. Testing by Bell Laboratory scientists [7] showed that it was the deep-dwelling, crocodile shark (Pseudocarcharias kamoharai), which occupied water depths between 1000 and 1900 meters.

As in-service reliability, cost and effectiveness of submarine cables are essential for the provisioning of the global data transmission their design process and specifications must be able to ensure delivery of these targets. Thus, the main objective of this paper is to highlight the shark bite as one of many treats that impact in-service performance of submarine cables directly and many other worldwide systems that are consequentially affected. Therefore, this paper briefly examines the shark species to understand the capabilities and strength of shark bites as mechanisms that could generate undesirable negative consequences the in-service life of affected working systems. The method for assessing the impact of potential protective actions, design and operational, on in-service reliability, cost and effectiveness of submarine cables by making use of MIRCE Functionability Equation has been presented in the paper.

2. The Philosophy of MIRCE Science

The philosophy of MIRCE Science [3] is based on the premise that the purpose of the existence of any human created working system is to do a work. The work is considered to be done when the expected measurable function is performed through time. At any instant of calendar time, a working system could be in one of the following two macro states:

- Positive Functionability State (PFS), a generic name for a state in which a working system is able to deliver the expected measurable function(s),

- Negative Functionability State (NFS), a generic name for a state in which a working system is unable to deliver the expected measurable function(s).

In MIRCE Science, the work done by a working system is uniquely defined by the trajectory generated by its motion through MIRCE Space[21]. That motion is driven by functionability actions, which are classified as:

- Positive Functionability Action (PFA) that compels a system to move to a PFS,
- Negative Functionability Action (NFA) that compels a system to move to a NFS.

To scientifically understand the mechanisms that generate functionability actions, positive and negative, analysis of the in-service behaviour of several thousands of items, modules, assemblies and whole systems in aerospace, nuclear, transportation, motorsport, communication, defence and other industries have been conducted at the MIRCE Akademy. The minimum sufficient "physical scale" which enables scientific understanding of relationships between physical phenomena that take place in the natural environment and the physical mechanisms that govern functionability events has to be based with the following range:

- the "bottom end" of the physical world, which is at the level of the atoms and molecules that exists in the region of 10^{-10} of a metre.
- the "top end" of the physical world, which is at the level of the solar system that stretches in the physical scale around 10^{+10} of a metre.

The time evolution of a working system through MIRCE Space is physically manifested through the occurrences of functionability events, which are classified as:

- Positive Functionability Event (PFE) that is a physically observable occurrence at which a working system moves a PFS,
- Negative Functionability Event (NFE) that is physically observable occurrence at which a working system moves to a NFS.

The MIRCE Functionability Equation is a mathematical description of the motion of the working systems through MIRCE Space, caused by any action whatsoever, is defined by the following expression [3]:

$$y(t) = 1 - \sum_{i=1}^{\infty} F_S^i(t) + \sum_{i=1}^{\infty} O_S^i(t), \quad t \geq 0 \qquad (1)$$

In the above equation $F_S^i(t)$ is a cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the sequential negative functionability event, $TNE_S^i(t)$ of a system considered. In MIRCE Science it is defined by a following convolution integral:

$$F_S^i(t) = \int_0^t O_S^{i-1}(x) dF_{S,i}(t-x), \qquad i = 1, \infty \qquad (2)$$

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[21] MIRCE Space is a conceptual 3-dimensional coordinate system depicting a probabilistic trajectory of the motion of a working system type through MIRCE Functionability Field. Knezevic (2017)

where: $F_{S,i}(t)$ denotes a cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the i_{th} negative functionability event, $TNE_{S,i}(t)$ of a working system type considered.

In Eq.1 $O_S^i(t)$ is a convoluted form of cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the consecutive positive functionability event, $TPE_S^i(t)$ of a system considered. In MIRCE Science it is defined by the following convolution integral:

$$O_S^i(t) = \int_0^t F_S^i(x) dO_{S,i}(t-x), \qquad i = 1, \infty \qquad (3)$$

where: $O_{S,i}(t)$ is a cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the i_{th} positive functionability event, $TPE_{S,i}(t)$ of a system consider

The remaining part of the paper focuses on the shark bite as one of many negative functionability actions generated by the natural world that directly impacts the in-service reliability, cost and effectiveness of submarine cables and associated systems, from MIRCE Science perspective.

3. Submarine Cables

Submarine cables are not one-size-fits-all solutions. Different applications require cables with unique characteristics. Particular submarine cable specifications are needed to meet their demands. Thus, the main categories of submarine cables are:

- Submarine communication cables are the backbone of global telecommunications and data transfer.
- Underwater Power Cables that transmit electrical power from offshore wind farms to tidal energy installations and oil and gas platforms to the mainland.
- Submarine research cables are used for various scientific purposes, like: collection of oceanographic data and underwater monitoring.
- Specialised submersible vehicles cables that provide power supply, control, and data transmission for remotely operated vehicles and autonomous underwater vehicles.

3.1 Submarine design driven decisions

In-service performance of submarine cables, like all other working systems, is ensured by the decision made at the initial stages of the design process. Major design concerns regarding in-service performance of submarine cables are:

- Conductor materials which determines portion of their performance and longevity.
- Insulation and jacketing materials that are responsible for protecting and maintaining signal strength.
- Armour and Sheathing that provides resistance against mechanical damage, including crushing and abrasion.
- Voltage ratings, which depends on the usage, as it must assure that the cable can safely transmit electrical power, while avoid overheating or breaking down.

- Current carrying capacity that determines the maximum amount of electrical current the cable can safely carry without overheating.
- Installation specifications that cover factors such as laying depth, burial methods, and the use of protective equipment, which is essential to prevent costly cable damage and ensure the safety of installation crews, which could be cost significant.
- Inspection and maintenance policies which are key for their inspection intervals and methods to detecting water ingress, physical damage, or insulation degradation.
- Repairs and splicing of submarine cables due to damage or faults are complex and challenging tasks, which often require specialised equipment and expertise.

Understanding submarine cable specifications, characteristics and maintenance policies is important for successfully deploying and operating undersea communication and power transmission systems, as safety of the global society is reliant on these cables. As technology advances and our reliance on undersea infrastructure grow, the importance of rigorous cable specifications becomes the norm.

3.2 Copper cables vs. fibber-optics cables

American Telephone & Telegraph Company had laid thousands and thousands of miles of copper made undersea cable all over the world with no problem. There had not been a single case of a shark biting one of the old cables, although they have found shark teeth mark[22]. They took the teeth marks from the cables surrounding to a shark dentist for identification. However, experts disagree on which type of shark was responsible for the attack.

Modern, fibber-optic cables look essentially the same as copper cables, except that they are around 2 cm in diameter, while the older ones are over 10 cm thick. Inside each of the new cables, however, are six hair-like strands of glass that can carry as many as 40,000 separate conversations traveling as staccato pulses of laser light. In contrast, the first trans-Atlantic telephone cable, whereas a “fat” copper line laid between Newfoundland and Scotland in 1956, could carry only 36 conversations. Even the newest copper cable, laid in 1983, has a maximum capacity of only 9,000 calls.

National and international regulatory bodies often mandate submarine cable specifications together with various industry standards organizations. Compliance with these specifications is essential for obtaining necessary approvals and certifications for design and operation of submarine projects.

4. Shark species (Selachimorpha)

Sharks have been in the sea waters on the Earth for more than 400 million years, which means they evolved nearly 200 million years earlier than the first dinosaurs. During all this time, sharks have either shared or solely owned the position of the top predators in the marine food chain. Scientist identified more than 400 different shark species, the vast majority of which can be found in every ocean of the world, with some species also inhabiting rivers.

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[22] https://www.nytimes.com/1987/06/11/us/phone-company-finds-sharks-cutting-in.html

Sharks are a remarkably diverse group of fish. The largest species, the whale shark, can grow up to 12 m in length, whereas the smallest species, the dwarf lantern-shark, reaches a size of 17 cm only.

Sharks have seven senses, the five that they share with humans, plus an electrical sense (small pores detect minute electrical currents in the water) and a lateral line (pressure sensitive cells beneath their skin) both of which help them detect prey and avoid predators. A shark's brain shows the importance of smell to sharks, due to the fact that over 60% of their brain's total weight is taken up with processing the olfactory sense.

Sharks belong to a group of creatures known as cartilaginous fishes, because most of their skeleton is made from cartilage rather than bone. The only part of their skeleton not made from this soft, flexible tissue is their teeth. As they are made from a material known as dentin that is harder and denser even than bone, sharks have a powerful bite. Even further, rather than having just a few sets of teeth that last all their life, sharks are continually producing new teeth. As an older one breaks or wears down, it simply falls out of the front of the mouth and onto the sea floor, as a new tooth takes its place. Depending on species and diet, a shark can produce between 20,000 and 40,000 teeth, over its entire lifetime. This means that there is a much greater chance that a shark tooth will be preserved and turned into a fossil. Not only are the teeth the most common part of sharks to be found, they're one of the most common fossils of any organism.

Measuring the bite force of a shark is no easy task, while some of these numbers have been recorded in scientific studies; others are estimates or have only been recorded once. To investigate the power of the shark, scientist built a custom the "bite-meter" attached to the end of a long rod that measures the force. This was the first time that such a measurement had ever been attempted for this shark. When one specimen spotted the device the bites were relatively weak, but they quickly grew in strength and final measurement was staggering 13 kN. On the same test the bull shark has a bite force of 6,000 N, the white shark has 10 kN bite force. The strongest bite force ever measured for any animal on earth is the saltwater crocodile at 17 kN. [4]

According to scientists there is no single reason for sharks survival of all five major extinction events on Earth, all of which had different causes and different groups of sharks pulled through each one. [5] However, the shark diversity may also have played an important role, as they are able to exploit different parts of the water column, from deep dark oceans to shallow seas, and even river systems. The wide variety of food, such as plankton, fish, crabs, seals and whales enabled sharks as a group to survive all changes in the oceans during hundreds of millions of years. Perhaps, that led them to develop the taste submarine cables!

A recent significant discovery in marine science [2] led to the conclusion that there are some properties of the electrical current in the fiber-optic lines that attracts sharks, which may trigger an automatic feeding reflex. They are supersensitive to electrical signals, and are able to detect electric fields as faint as a few millionths of a volt per centimeter in water. Thus, a faint field near the cable activates their natural instinct, programmed in their genes, and they attack.

5. Shark Bite as a Negative Functionability Action

Submarine cables are an integral part of the internet's physical infrastructure, with many funded in recent years by internet giants like Microsoft, Google, Amazon and Facebook parent Meta. Damage to these subsea networks can cause widespread internet outages and all other dependent working systems worldwide.

According to the International Cable Protection Committee (ICPC), the world's leading organisation promoting submarine cable protection and resilience, negative functionability actions related to submarine cables are proportional as following:

- 65-75 % are caused by ships' anchoring and fishing activities.
- 10% are generated by natural phenomena, such as subsea landslides and ocean currents, are responsible for up to 10 per cent of faults.
- 5% of NFEs are caused by cable component failure.
- 10-20 % of in-service failures cannot be determined.
- 1 % is attributable to shark bites, which leave evidence in the form of teeth imprints or actual teeth embedded in a cable's sheathing.

Evidence shows that between 1901 and 1957, which is a period dominated by subsea telegraphic cables, at least 28 cables were damaged by fish bites, including sharks.
Sharks do have a history of dining on ocean cables, but although they have bitten fibre-optic cables, they do not appear to have developed a taste for them.
There were around 11 cables that needed repair caused by shark bites during 1959 to 2006, the period that encompasses coaxial cables, which were replaced by fibre-optic systems in 1988.

The latest analysis, covering 2007 to 2014, recorded no cable faults attributable to sharks. Due to increased shipping and fishing activities on the continental shelf, fibre-optic cables are now protected by the addition of steel wire "armour" to the cable's exterior, as well as burial up to 3m below the seabed.

6. Positive Functionability Action

Although submarine cables are very reliable regarding their own design and manufacturing processes there are occasions when a repair to a cable becomes necessary due to the any of the above mentioned, human or natural, negative functionability actions.

Generally speaking, each repair process could be considered as unique, but the following sequence of tasks could be presented as generalised process, thus:

- Fault detection of undersea cable from the one or even both shore ends, which could be include a signal injector, that could help in locating the actual cable fault location.
- Determination of maintenance resources (people, material, equipment, tools, etc,).
- Travel to damage the cable several miles before the fault to lift its working end up to the surface and cut it off.
- Then go several miles to the other side of the damaged cable to cut and lift that end.
- Splice a new cable section in, and then lower the cable in a loop, so that it does not kink going down.

Personnel involved with submarine cable repairs express feeling uneasy regarding swimming around them.

7. Placing Shark Bite in MIRCE Functionability Equation

To benefit from the ability to predict expected work done by underwater cable types in respect to the frequencies and durations of outage of submarine cables caused by shark bites through in-service lives, it is necessary to place it in MIRCE Functionability Equation.

A cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the i_{th} negative functionability event, $TNE_{S,i}(t)$ of a working system considered is generically defined by Eq.2. Hence, in the case that this random variable is governed by the impact of a shark bite, it is denoted as, $TNE_{S,i,SBite}$, and it is defined by the following expression:

$$F_{S,i=SBite}(t) = P(TNE_{S,i=SBite} \le t) = \int_0^t f_{S,i=SBite}(t)dt \qquad (4)$$

where: $f_{S,i=SBite}(t)$ is a probability density function of the random variable that defines the time to the occurrence of i_{th} negative functionability event, which in this specific example is a shark bite. The above equation is in the most generic form and as such covers all possible variations and impacts of shark bite, which means each specific manifestation will have its own, most appropriate, mathematical expression. However, based on author's experience, the most likely the exponential probability distribution will be applicable to represent the shark bite which caused a NFE.

A cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the consecutive positive functionability event, $TPE_S^i(t)$ of a system considered is defined by Eq.3. In MIRCE Science it is defined by the following convolution integral

$$O_S^i(t) = \int_0^t F_S^i(x)dO_{S,i}(t-x), \qquad i = 1,\infty \qquad (5)$$

where: $O_{S,i}(t)$ is a cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the i_{th} positive functionability event, $TPE_{S,i}(t)$ of a working system type considered. The number of these functions is equal to the number of NFAs that generate NFEs occurring during the in-service life of working systems. In the case that this random variable is governed by the impact of a positive functionability action taken in response to the occurred shark bite it is denoted as $TPE_{S,i,SBite}$, and it is defined by the following expression:

$$O_{S,i,SBite}(t) = P(TPE_{S,i,SBite} \le t) = \int_0^t o_{S,i,SBite}(t)dt \qquad (6)$$

where: $o_{S,i,SBite}(t)$ is a probability density function of the random variable that defines the time to the occurrence of i_{th} positive functionability event, which in this specific example is a shark bite action. The above equation is in the most generic form and as such covers all possible variations and impacts PFA that could be taken to return a system to PFS after impacts of any generated NFA, which means that each shark bite related action, has its own mathematical expressions. In general, Eq. 4 could be represented as a sum of all positive functionability actions, denoted as *npa*, which should be completed to return a submarine cable to PFS, as speedily and efficiently as possible, thus

$$O_{S,i,SBite}(t) = P(TPE_{S,i,SBite} \le t) = P\left(\sum_{j=1}^{npa} TPT_{SBite,j} \le t\right) = \int_0^t O_{SBite}^{j-1}(x)\,dO_{SBite,j}(t-x), \quad j = 1, npa$$

The above expression is a sum of several independent convolution integrals, which could be very challenging task for the provision of the analytical solution, unless all of the maintenance tasks are modelled by the normal probability distribution.

8. Mitigations of the Impacts of Shark Bites on the Functionability of Submarine cables

The main objective of this paper was to draw the attention of design engineers of submarine cables to the impact of shark bites on their in-service reliability and safety. These impacts have been determined by applying the principles of MIRCE Science to the process of the motion of submarine cables through MIRCE Space. Having concluded that a shark bite is detected and observed mechanism that impacts in-service reliability, cost and effectiveness of submarine cables, the obvious question is – What could be done to reduce the frequencies and consequences of these functionability events?

According to [6] the global digital giant Google makes great efforts to protect their fibber-optic cables against shark attacks. They are made of fragile fiber glass that is covered in a plastic coating of in different colours, so that maintainers can follow the path of each strand and finally all is enclosed by an outer polyurethane jacket, a protective layer (made from a material like Kevlar),

By making use of the MIRCE Functionability Equation, it is possible to assess the impact of each feasible design decision on in-service reliability, cost and effectiveness of the future working system, on a life time scale. It means that each category of functionability driven design decisions, presented in part 3.1, could be numerically evaluated and then made the final and justifiable decision in accordance to the criteria chosen.

9. Conclusion

Since sharks and submarine cables share the same physical space it is inevitable that interactions between them are possible. Using principles of MIRCE Science, in this paper a shark bite is considered as a mechanism that generate sufficient mechanical energy to cause the occurrence of a negative functionability event that cause the transition of submarine cables from a positive to a negative functionability state.

The results of the research conducted by the author, at the MIRCE Akademy, has shown that there are physical evidences of the sharks damaging submarine cables by biting them with very powerful jaws. These bites negatively affected the performance of cables, which had to be restored by the execution of adequate repair actions. These repair actions take a long time and required specific resources and complex logistics support, as the cables are deep into water and often far from the shores.

To benefit from the ability to predict expected frequencies and durations of outage of submarine cables caused by shark bites through in-service lives, by making use of MIRCE Functionability Equation, it is necessary to “translate” physical reality of related negative and positive functionability actions into their “mathematical reality”. However, mathematics does not teach the user how to select the most appropriate distributions, but requires that to be done. It means that engineers and managers need to use their experience, knowledge and assumptions made to describe those mechanisms accurately before they apply mathematics to make expected predictions. Descriptions of mechanisms of functionability actions present a huge challenge, but not for mathematicians, it is a challenge for MIRCE Science users.

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MIRCE Science: Lightning as an Imposing Functionability Action

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Abstract

MIRCE Science is a theory of the motion of working systems through Mirce Space compelled by imposing functionability actions, which is used for predicting expected functionability performance for a working system type. For accurate predictions to be made it is essential a scientific understanding of the mechanisms that govern imposing functionability actions, the occurrences of negative functionability events before engineering, technological, business and economical decisions are made. Lightning strikes are not uncommon physical mechanisms that completed the motion of working systems through Mirce Space. For example, airliners in the worldwide fleet average at least one strike per year. Hence, the main objective of this paper is to understand physical mechanisms that generate the occurrences of lightening events and assesses their impacts on the work done by working systems in general and an aircraft in particular. The available methods for dealing with them in respect to the provision of safety by detection, protection and design are also addressed in the paper.

Key words: MIRCE Science, lightening strikes, discharge mechanism**,** impact of lightening on aviation

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1. Introduction

Every day, an average, around 8 million lightning strikes discharge across the planet Earth, which is the equivalent of about 100 lightning strikes every second. For example, airliners in the worldwide fleet average at least one lightning strike per year. Although meteorologists may forecast the general conditions that cause lightning, but the exact location and time of future lightning strikes cannot be predicted. However, for successful management of in-service performance of working systems lightning detection and monitoring are very important as they have impact on the public safety, potential wildfires, protection of electrical supply and so forth.

The main objective of this paper is to address lightening as an imposing functionability action driven by a natural physical phenomenon and to assess its impact on the functionability performance of working systems types, in general with some specific examples related to commercial aviation, as well as to outline existing lightening protection methods and approaches.

2. Brief Overview of MIRCE Science

The philosophy of MIRCE Science is based on the premise that the purpose of the existence of any working system is to do work. The work is considered to be done when the expected measurable function is performed through time. MIRCE Science focuses on the scientific understanding and description of the physical phenomena and human rules that govern the motion of working systems through MIRCE Space[23]. A full understanding of the mechanisms that generate this motion is essential for the accurate predictions of the expected work done by a given working system type using the mathematical scheme of MIRCE Science. [1]

In accordance to MIRCE Science philosophy a working system type could be in one of the following two functionability states:

- Positive Functionability State (PFS), a generic name for a state in which a working system type is able to deliver a measurable function(s)
- Negative Functionability State (NFS), a generic name for a state in which a working system type is unable to deliver a measurable function(s), resulting from any reason whatsoever.

Being in one of these two functionability states is a physical manifestation of the motion of a working system type through in-service time.

The motion of a working system type through the functionability states, in the direction of in-service time, is caused by imposing functionability actions. MIRCE Science philosophy classifies all functionability actions whatsoever as following:

- Positive Functionability Action (PFA), a generic name for any natural process or human activity that compels a working system type to move to a PFS

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[23] MIRCE Space is a conceptual 3-dimensional coordinate system containing a sequential motion of a working system through quantised functionability states in time and probability of being in them. [1]

- Negative Functionability Action (NFA), a generic name for any natural process or human activity that compels a working system type to move to a NFS.

The mechanisms, nature, frequency and complexity of functionability actions, positive and negative, is specific to each working system type, but the consequential movements to corresponding functionability state is common for all of them.

The motion of a working system type through the functionability states is manifested through the occurrences of functionability events, which in MIRCE Science philosophy are classified as following:

- Positive Functionability Event (PFE), a generic name for any physically observable occurrence in time that signifies the transition of a working system type from a NFS to a PFS
- Negative Functionability Event (NFE), a generic name for any physically observable occurrence in time that signifies the transition of a working system type from a PFS to a NFS.

In essence functionability events, positive and negative, are physically observable occurrences that are taking place during the in-service life of working systems. These events are measurable physically properties for each individual working system that contributes to the formations of the trajectory of the motion of the whole population type through in-service time.

Research studies conducted at MIRCE Akademy[24] by staff and students had shown that any serious studies of the functionability mechanisms have to be based between the following two boundaries [1]:

- the “bottom end” of the physical world, which is at the level of the atoms and molecules that exists in the region of 10^{-10} of a metre.

- the “top end” of the physical world, which is at the level of the solar system that stretches in the physical scale around 10^{+10} of a metre.

This range is the minimum sufficient “physical scale” which enables scientific understanding of relationships between physical phenomena that take place in the natural environment and the physical mechanisms that govern functionability events during the life of working systems.

2. Lightening as Functionability Action

Lightning is an atmospheric discharge of electricity. Being the most visible form of electricity and a widely recognised natural phenomenon, lightning remains relatively poorly understood. Even the most basic questions of how lightning is initiated inside thunderclouds and how it then propagates for many tens of kilometers have only begun to be addressed. In the past, progress was hampered by the unpredictable and transient nature

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[24] for more information follow the link: http://www.mirceakademy.com/news/2/15/MIRCE-Functionability-Actions/

of lightning and the difficulties in making direct measurements inside thunderstorms. However, the advances in technology enable creation of remote sensing methods, instrumentation and rocket-triggered lightning experiments that are now providing new insights into the mechanisms of lightning.

Proper understanding of lightning phenomena involves the synthesis of many branches of physics, from atmospheric physics to plasma physics to quantum electrodynamics, and provides a plethora of challenging unsolved problems. However, in this paper only an elementary review of the scientific understanding of lightning as an imposing functionability action is provided.

Generally speaking lightning is the dissipation of static energy stored in cloud clusters. Scientists believe that the static energy stored in clouds comes from the relative motion of precipitation within the clouds that generate free electrons resulting in stored charges collected within the cloud. Positive charge in the cloud will seek negative charges on the Earths' surface. While in the same manner, negative charges in the cloud will seek positive charges on the ground. Lightning begins to move away from the cloud filled with static energy through what is known as leaders. Leaders are electrical energy moving out to seek ground or an object of opposite charge. Leaders stem from what is called a lightning channel. Lightning energy moves from the lightning channel in leader streams. If the leaders do not find anywhere of an opposite charge or "ground" to transfer the energy in an opposite charge or "ground" the leader, the leader is pull back into the channel and the channel stores the leader charge which increases the energy in the leader channel. This process continues as leader stream away from the lightning channel seeking an opposite charge, constantly growing energy in the lightning channel until a leader finds an oppositely charged object, which could be cloud or ground[25], creating an electrical circuit and quickly discharges the energy built up in the channel. This transfer of channel energy can be dramatic since the stored plasma often reaches levels of electrical power beyond a million volts and reach temperatures of over 25,000°C! When lightening flashes, it finds the faster path down to Earth and then it follows the same route back up to the cloud again. A downward flash of lightening leader travels at up to 1,600 km/s, while the return speed is up to 140,000 km/s. [3]

The research performed has shown that lightening makes the air inside a cloud nearly 6 times hotter than the surface of the Sun! The hot air inside a thundercloud expands and vibrates which makes the loud rumbling crash that is commonly called a thunder. Thunder and lightening happen at the same time but there is always a gap between the flash of light and the crash of a thunderclap. That is because light travels many times faster than sound[26]. Rough rule of thumb says if the number of seconds between the flash of lightening and the bang of thunder are counted and divided by 3, the results obtain would represent the approximate distance of the storm in kilometres. [3]

Thunderstorms are most common near the equator. This is because it's hotter, so there is more hot air (energy) to rise and create more thunderclouds and lighting. Hence, geographical areas like South America, Central Africa and Indonesia have on average 100-200 thunderstorms a year. [3]

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[25] In a given geographic area, there can be as many as 10 times more cloud-to-cloud as cloud-to-ground strikes. Furthermore, discharges can also occur within individual clouds.

[26] The speed of light is 299,792,458 ms^{-1} whereas the speed of sound in air is between 331 ms^{-1} at 0ºC and 360 ms^{-1} at 50 ºC

The main types of lightening observed are listed below:

- Ball lengthening that is manifested as a slow moving ball of the fire that can sometimes appear inside structures[27]
- Zig-zag lightening that is a giant spark that “zig-zags” its way to the ground
- Forked lightening that looks like the letter Y upside down
- Sheet lightening that makes a white light that fills a wide area of the sky
- St Elmo’s fire that is a faint flickering glow around trees, buildings or ships masts.

Lightning doesn't strike the ocean as much as land, but when it does; it spreads out over the water, which acts as a conductor. In existing literature, various different estimates have been given for the distance over which it would dissipate, to the point where it would no longer be a harmful to a person. Fish, which usually move around at greater depths, are safer than human swimmers. Protruding heads or even entire bodies, such as those presented by surfers or paddle boarders, could put people in greater danger. Boats can be fitted with lightning conductors, which direct the charge into the sea, while avoiding their most vulnerable parts, such as passenger areas or equipment rooms.

Lightening also hits deserts and sandy beaches that are high in silica or quartz. As the temperature in the affected areas reaches more than 1800° C, the lighting can fuse the sand into silica glass. The blast of a billion Joules of energy radiates through the ground making fulgurites[28].

3. Lightening Strike as Functionability Event

Lightning strike is not only spectacular functionability event; it is a rather dangerous natural phenomenon. Each year around 2,000 people are killed worldwide by lightning [2]. Although hundreds more survive strikes, they suffer from a variety of lasting symptoms, including memory loss, dizziness, weakness, numbness, and other life-altering ailments. Strikes can cause cardiac arrest and severe burns, but 9 of every 10 people survive. The average USA citizen has about a 1 in 5,000 chance of being struck by lightning during a lifetime. [3]

Many houses are grounded by rods and other protection that conduct a lightning bolt's electricity harmlessly to the ground. Homes may also be inadvertently grounded by plumbing, gutters, or other materials. Grounded buildings offer protection, but occupants who touch running water or use a landline phone may receive a shock by conducted electricity.

Lightning may also occur in Volcanic Ash clouds formed in the immediate vicinity of eruptions because the vertical movement and collision between solid particles within the cloud generates static charges.

In June 2006 a total of 17,000 lightening strikes hit Alaska, starting hundreds of fires, which by the end of June destroyed an area twice of the size of London. [3]

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[27] In 1984, Russian airline passengers were surprised to see a blob of ball lightening floating over their heads inside the plane. No one was hurt however the plane’s radar was damaged.

[28] **F**ulgurites, from the Latin fulgur, meaning "lightning", are natural tubes, clumps, or masses of sintered, vitrified, and/or fused soil, sand, rock, organic debris and other sediments that can form when lightning discharges into ground.

It is worth pointing out that flashes of lightening have been observed on Venus and Jupiter. Lightening on Jupiter is thought to be more powerful than on Earth, but happens less frequently.

4. The Impact of Lightening on Aviation

Through history of aviation there have been cases of aircraft being brought down by lightning strikes that started electrical fires or arced into unprotected fuel tanks, significant damage to aircraft today is a rare functionability event. However, in the early years of jet transport, the in-flight breakup of a Pan American World Airways Boeing 707-121 over Elkton, Maryland, in 1963 while on approach to Philadelphia, killed 81 people on board. The incident was attributed to lightning and became a watershed event in advancing aircraft protection. It was later determined that the breakup resulted from an explosion in a fuel tank due to a lightning strike. Subsequently, in USA the nascent Federal Aviation Administration (FAA) required that lightning safety devices be installed on all commercial aircraft, including the now familiar static “wicks” or dissipaters on the trailing edges of wings and control surfaces.

A few examples of accidents and incidents that have been reported with lightning being attributed as a principal contributing factor:

- In 1969 the US Apollo 12 spacecraft was hit by lightening as it took off for the Moon. It survived. However, in 1987, a rocket launched from Florida crashed after lightening damaged its on-board computer. US shuttle launches were postponed when lightening was around.

- On February 8, 1988 a flight from Hanover to Düsseldorf, Germany, a Fairchild Metro III commuter turboprop crashed on approach to Dusseldorf after a lightning strike resulting in “disconnection of all batteries and generators from the aircraft's electrical system” including the termination of the cockpit voice recorder record". Twenty-one people died (19 passengers and 2 crew).

- On 25 September 2001, an Embraer 145 in descent to Manchester (UK) sustained a low power lightning strike which was followed, within a few seconds, by the left engine stopping without indicating a failure. A successful single engine landing followed. The Investigation concluded that the cause of failure of the FADEC-controlled AE3007 engine (which has no surge recovery logic) was the aero-thermal effects of the strike to which all aircraft with relatively small diameter fuselages and close mounted engines are vulnerable. It was considered that there was a risk of simultaneous double engine flameout in such circumstances which was impossible to quantify.

- On 4 December 2007, while approaching Bodø (Norway) the crew of a Dornier 228-200 (LN-HTA) lost control of their aircraft resulting from a powerful lightning strike, which temporarily blinded both pilots and damaged the aircraft such that they lost elevator control. After regaining partial pitch control using pitch trim, a second attempt at a landing resulted in a semi-controlled crash that seriously injured both pilots and damaged the aircraft beyond repair. The Investigation concluded that the energy in the lightning had probably exceeded certification resilience requirements and that up to 30% of the bonding wiring in the tail may have been defective before lightning struck.[29]

- An Airbus A330-200 was struck by lightning just after arriving to Perth WA Australia, on 26 November 2014. It was allocated a stand following a one hour post-landing delay after suspension of ramp operations due to an overhead thunderstorm. Adjacent ground services operatives were subject to electrical discharge from the strike and one who was connected to the aircraft flight deck intercom was rendered unconscious. The investigation found that the equipment and procedures for mitigation of risk from lightning strikes were not wholly effective and also that perceived operational pressure had contributed to a resumption of ground operations which hindsight indicated had been premature.

5. Mechanics of the Motion of Lightning through the Aircraft Structure

An aircraft flying in an electrically charged area may also complete the circuit and receive a strike that will continue from the aircraft to the ground or another cloud. These strikes on aircraft commonly occur within 1,500 m of the freezing level[30].

A lightning strike is accompanied by a brilliant flash of light and often by the smell of burning, as well as noise, which can be very distressing to passengers and crew. However, significant physical damage to an aircraft is rare nowadays and the safety of an aircraft in flight is not usually affected. Damage is usually confined to aerials, compasses, avionics, and the burning of small holes in the fuselage. Of greater concern is the potential for the transient airflow disturbance associated with lightning to cause engine shutdown on both: a FADEC[31] control and non-FADEC engines with close-spaced engine pairs.

A strike at the aircraft’s radome will travel along the outer skin and exit at an extremity like a wingtip, the tail or a control surface. The entry point will vary from pitting to a small hole; at the exit point however, the charge may burn a larger hole. Meanwhile, the path of the charge along the airframe can produce scorching, often at rivets as the charge arcs across the miniscule gaps between rivet heads and adjacent skin.

If the charge exits from a control surface, hinge bushings and bearings may be spalled and require replacement. Strikes can also affect avionics, antennae and, especially, compasses. In any case, after a lightning strike, the airframe will require a thorough inspection and any serious damage repaired, meaning that the most tangible negative result of the lightning encounter will probably be downtime and repair, as necessary. Reportedly, airlines spend millions of dollars annually returning struck aircraft to service.

6. Lightning Compelled Flameouts

FADECs programmed with surge-protection logic can respond to flow disruption temperature spikes by automatically shutting down the engines. This aircraft configuration

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[29] https://www.skybrary.aero/index.php/D228,_vicinity_Bod%C3%B8_Norway,_2003

[30] The freezing level, or 0 °C (zero-degree) isotherm, represents the altitude in which the temperature is at 0 °C (the freezing point of water) in a free atmosphere.

[31] FADEC: full authority digital engine (or electronics) control a system consisting of a digital computer, called an "electronic engine controller" (EEC) or "engine control unit" (ECU), and its related accessories that control all aspects of aircraft engine performance.

has proven to be vulnerable to engine flameouts as a lightning strike charge travels longitudinally down the sides of the fuselage seeking an exit point. In the case of closely spaced fuselage-mounted engines, the strike's "aero-thermal effects" can disrupt intake flows of both powerplants. FADECs programmed with surge-protection logic can respond to such disruption temperature spikes by automatically shutting down the engines. On the other hand, hydro-mechanically controlled engines, as an indirect result of lightning strikes, will tend to experience transient over-temperature conditions while continuing to operate, as shutdown protocols are manually controlled by the flight crew.

In 2001, an Embraer ERJ 145 regional airliner received a lightning strike while descending for an approach to Manchester International Airport in England, followed by the left Rolls-Royce AE3007 turbofan flaming out without any fault indication or audible warning in the cockpit. The crew was on top of the situation and immediately transitioned to a successful single-engine landing. A post-incident investigation concluded that the failure of the FADEC-equipped engine was due to the aero-thermal effects of the strike characteristic of aircraft with small-diameter fuselages and aft-mounted engines. It further considered that a risk existed for loss of both engines, but investigators were unable to quantify that.

As a precautionary measure when entering areas of electrical activity in aircraft with FADEC-equipped engines, experts recommend that, if within operating limits, flight crews fire up the APUs[32] so that, in the event of a double engine failure, electrical power and hydraulics will be maintained while emergency relights of the engines can be attempted. It is worth saying that it is possible that APUs can be affected by lightning strikes, too. It's also recommended that flight crews review memory items for a dual engine relight before venturing into areas of known lightning activity.

7. Lightning Protected Aircraft Structures

To survive multiple lightning strikes an aircraft has to be designed as "Faraday cage." Back in the 18th century electricity pioneer Michael Faraday created a metal-lattice contraption that conducted high-voltage electricity harmlessly around a hapless volunteer encaged within it. The device is often still used in magic acts and static electricity demonstrations. In the aircraft, the aluminium skin subs for the lattice, carrying the charge along the outside of the airframe to an exit point.

However, ensuring the aircraft's occupants, systems, avionics and fuel are protected, means there must be no gaps in the conductive path, thus keeping the electrical charge on the outside of the aircraft. So, part of what is known as the "hardening" process against lightning damage involves, among other things, metal strapping across any gaps in the skin to maintain that uninterrupted conductive path.

While aluminium is an excellent conductor, composite media, (graphite-epoxy or "carbon fibre"), are less so. That's why a mesh of copper wire or other conductive material is included in the lay-ups of composite aircraft to provide conductivity. Because a radar antenna cannot be contained in a conductive enclosure, radomes are fabricated of composite media, so to protect them, lightning diverter strips consisting of solid metal bars or closely spaced conductive disks are bonded on the outer surface of the dome to carry the charge into the airframe.

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[32] APU: Auxiliary Power Unit is a device on a vehicle that provides energy for functions other than propulsion. They are commonly found on large aircraft and naval ships as well as some large land vehicles.

Lightning strike hazards include the potential to affect the variety of computers on-board modern aircraft, such as the flight management system (FMS), navigation systems; electronic engine controls and even fly-by-wire systems, due to power surges.

Newton [4] cites an airline incident where a lightning strike "caused the autothrottle to go to idle, the autopilot and yaw damper to disengage, over half the fault lights to illuminate, the captain's flight director and navigation display to fail, and an erroneous indication of an engine failure to occur." These anomalies can happen because, as the lightning charge passes over the exterior of the airframe, induction from the electricity can cause "transients" in wiring inside the aircraft termed "lightning indirect effects." To address this threat, airframe and avionics designers apply a number of hardening techniques and devices to their equipment including simple grounding, various types of shielding and surge-suppression devices to meet aircraft certification requirements imposed by the FAA and other international civil aviation authorities. As everything essential for flight safety must be protected to the maximum extent possible, the risk of lightning being the direct cause of a crash has been greatly reduced during last 50 years.

In designing aircraft today, particular attention is devoted to protection of the fuel system and tanks to ensure that lightning charges cannot produce sparks that could ignite fuel or vapours. Accordingly, the aircraft wings, carry-through structures and other elements involving the fuel system must be sufficiently thick to prevent burn-through, and all brackets, fasteners, structural joints, filler ports, vents, electrical pumps and fuel lines must be designed and insulated to prevent ignition.

The same design philosophy also applies to the engines and their mechanical or electronic controllers. Even further, over the years, petro-chemical refiners have formulated jet fuels with less-explosive vapours.

8. Lightening Events Detection and Avoidance

Knowing the whereabouts of lightning actions is key to avoiding it, and flight crews now have more resources available than ever to do so. These include a network of ground-based detection tools, as well as airborne systems to complement weather radar, to assist in flight planning and, once airborne, chart paths safely around or through active areas.

During the last four decades, considerable research throughout the world has been devoted to understanding the nature of lightning, predicting and detecting it over large areas, and delivering these data to pilots, ATC[33] facilities and airport operators in near real time. Today, in the United States, much of this research has been conducted under the auspices of the National Oceanic and Atmospheric Administration's (NOAA) National Severe Storms Laboratory (NSSL).

Ground-based lightning detection networks (LDNs) have been established in many countries to monitor thunderstorm development, intensity and movement over wide areas. Some are owned and operated by governments, while others function in the private sector, often under contract to users. Data from these arrays are monitored by a variety of agencies for issuing warnings, forecasting and, in severe cases, deployment of rescue/response

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[33] ATC: Air traffic Control

teams. Lightning strike data from these networks are also archived for research purposes, post-accident investigations and even insurance risk calculations.

The U.S. component in this array is the National Lightning Detection Network (NLDN) developed by the New Mexico Institute of Mining and Technology and operated by Vaisala Inc.[34], out of Tucson, Arizona. It has been in existence in one form or another for 30 years. Its origins derive from research conducted under contract for the Electric Power Research Institute by the State University of New York at Albany, principally to determine how to get lightning detection to users in near real time. Eventually, this research was commercialised by Global Atmospherics.

With more than 100 lightning strike sensors installed throughout North America, the NDLN is considered a precision detection network able to see and record both cloud-to-cloud and cloud-to-ground lightning. The sensors are all ground-based, with more being added every year. They detect electrical discharges in the atmosphere, and their raw data are then transmitted via a satellite communications link to Vaisala's Network Control Center at Tucson for processing.

Literally within seconds, Vaisala's software calculates location, time, polarity and amplitude of each strike, which subsequently appears on a digital map or is sent to customers as text data. [4]

In addition to the NLDN, Vaisala operates a global lightning detection network based on a proprietary set of long-range sensors installed in other countries and sells a lightning data package, the GLD360, for it, too. [3] The company also markets its own display software called Thunderstorm Manager that enables users to set up rings around an airport, or any other entity sensitive to lightning, like a powerplant, on a video display at various distances and observe where strikes are occurring. Among Vaisala's U.S. customers for near-real-time lightning data are the FAA and National Weather Service (NWS). All data collected, a trove currently representing more than 160 million "flashes," have been archived since 1989 for research purposes. [4]

Among users of archived data are the NSSL, which manipulates the information to loft 3-D lightning maps to study lightning development and propagation. While it is possible today for meteorologists to forecast the likelihood of lightning activity, being able to predict individual strikes is still beyond reach. So, one of the goals of this work is to construct experimental forecasting models that can accurately forecast the maximum lightning threat every hour. As a related development, the next generation of U.S. weather satellites will contain the Geostationary Lightning Mapper, an instrument that will continuously map both in-cloud and cloud-to-cloud lightning activity over the Americas and adjacent oceanic regions to provide early indication of storm intensification and severe weather events. [4]

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[34] It is a Finish company with headquartered in Helsinki, established more than 80 years ago. It markets meteorological data packages and a broad product line of weather gauging and instrumentation equipment such as wind direction indicators, barometric and temperature measuring devices, and automated weather advisory station (AWAS) equipment. It got into the lightning detection business when it acquired the former Global Atmospherics Inc., in 2002.

9. Conclusions

The objective of this paper was introducing a lightning strike as an imposing functionability action that causes a motion of working systems type through MIRCE Space.

The paper provides an overview of the current scientific understandings of physical mechanism that generate the occurrences of lightening events and assesses their impacts on the functionability performance of working systems types, with a several examples specifically related to the aviation industry.

Finally, the paper provides a brief overview of methods available for dealing with lightening strikes in respect to the provision of safety by detection, protection and design.

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Remote Sensing of Natural and Man-made Disasters

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Abstract

The main objective of this paper is to draw attention on the importance of remote sensing of the small natural and man-made disasters by analysing and recording them, as they posed a risk to human well-being and the environment. Examples presented include oil spills, dam failure, ship disaster, wildfires, hailstorm and flooding. They took place between 2016 and 2022 and present the various examples of intensive and extensive risk. All of them were previously made in poster format for an easier use in practical applications, making it similar to International Disaster Charter activation products. This paper is intended to unite them in one place, and to serve as a reminder of the importance of necessity for properly analysing and recording each of them. Small disaster events are of special interest to be addressed, because if their consequences are forgotten and over passed the greater damage to people and the environment could be experienced when the next disaster happens. Many of the small disaster events impoverish the people and households through space and time making them more vulnerable to the upcoming future hazards.

Key words: remote sensing, natural disaster, man-made disaster, hazard, oil spill, flood, dam failure, hailstorm

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1. Introduction

Remote sensing plays a significant role in disaster risk reduction and provides considerable potential to reduce vulnerability of people to natural and man-made hazards. Its main advantages are summarised below:

- Provide a continuous, repetitive, large-scale synoptic view relative to traditional point-based field measurements
- Practical way to obtain data from dangerous or inaccessible areas
- Relatively cheap and rapid method of acquiring up-to-date information over a large geographical area
- Easy to manipulate with the computer, and combine with other geographic coverage in the GIS [2]

Disasters are often viewed as exogenous shocks that destroy and erode development gains. Disaster risk, however, is far from exogenous to development. It is configured over time through a complex interaction between development processes that generate conditions of exposure, vulnerability and hazard. Intensive and extensive risk, refer to the relative concentration or spread of disaster risk in space and time, at whatever scale risk is observed.

Intensive risk is related to areas where high geographic concentrations of vulnerable people and economic assets are exposed to a very severe small number of hazard events. *Extensive* risk presents the geographically dispersed exposure of vulnerable people and economic assets to mainly low or moderate intensity hazards. Wide regions are exposed to more frequently occurring low-intensity losses. [3]

Man-made hazards are defined as those “induced entirely or predominantly by human activities and choices”. This term does not include the occurrence or risk of armed conflicts and other situations of social instability or tension which are subject to international humanitarian law and national legislation. Technological hazards are normally considered a subset of man-made hazards. Chemical, nuclear and radiological hazards, as well as transport hazards are defined as those originate from technological or industrial conditions, dangerous procedures, infrastructure failures or specific human activities. Examples include industrial pollution, ionizing radiation, toxic wastes, dam failures, transport accidents, factory explosions, fires and chemical spills. Technological hazards also may arise directly as a result of the impacts of a natural hazard event. A technological accident caused by a natural hazard is known as a “Natech”. [4]

The list of disasters addressed in this paper is as follows:

1. Wildfire in Trebinje Region. July 7, 2016. Republika Srpska, Bosnia and Herzegovina
2. Wildfires in Trebinje Region. September, 2016. Republika Srpska, Bosnia and Herzegovina
3. Brumadinho dam disaster. January 25, 2019. Brazil
4. Hailstorm disaster. July 7, 2019. Backa Palanka, Serbia
5. Oil spill disaster near the coast of Rennel Islands. February 5, 2019. Solomon Islands
6. Flooding of South Morava river. January 12, 2021. Serbia
7. Cargo ship disaster near Sri Lanka west coast. May 20, 2021. Sri Lanka
8. Oil spill disaster near the coast of Callao. January 15, 2022. Peru

2. Example cases

2.1 Wildfire in Trebinje Region. July 7, 2016. Republika Srpska, Bosnia and Herzegovina

Example of Initial Assessment for wildfire burn severity mapping using the NBR (Normalized Burn Ratio) index and dNBR (dNBR = NBRprefire – NBRpostfire) with thematic map which represent burn severity. [1] Wildfire started 07.07.2016. according to NASA Fire and Thermal Anomalies layer from NASA Worldview.

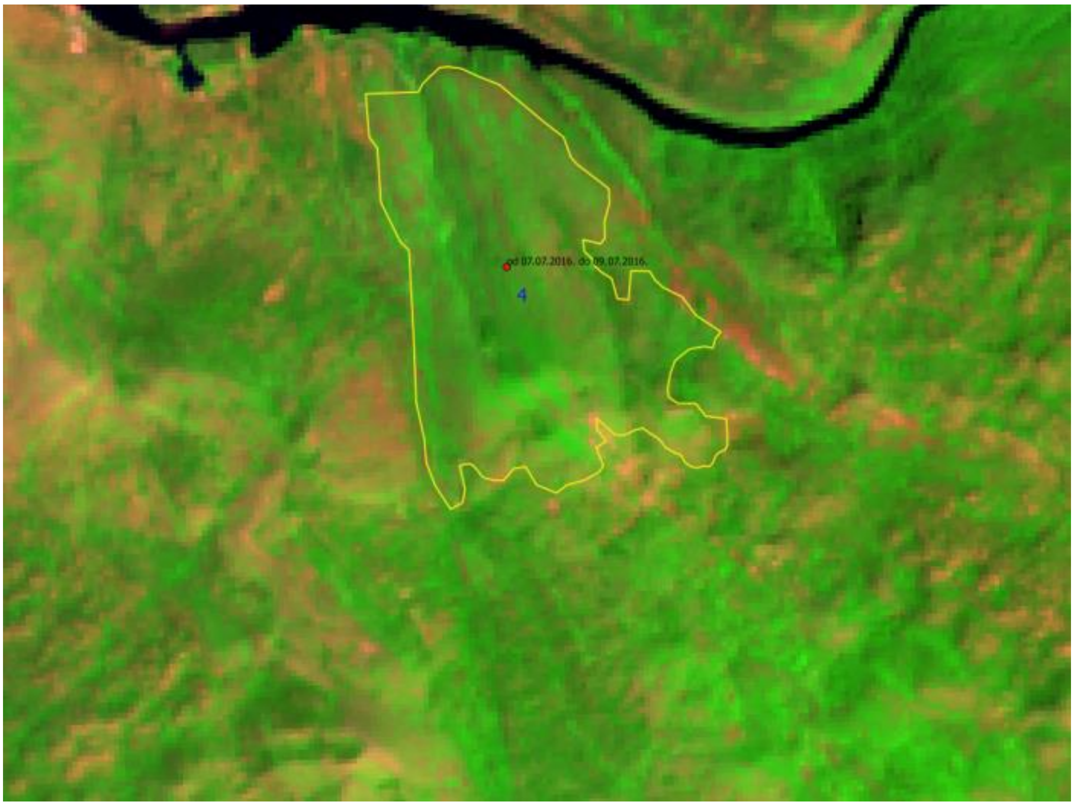

Figure 1. Landsat 8 (band combination 7,5,3) image before wildfire event 21.07.2015. [5]

Figure 2. Geographic location of disaster marked with red polygon. Image: NASA Blue Marble 2004 [5]

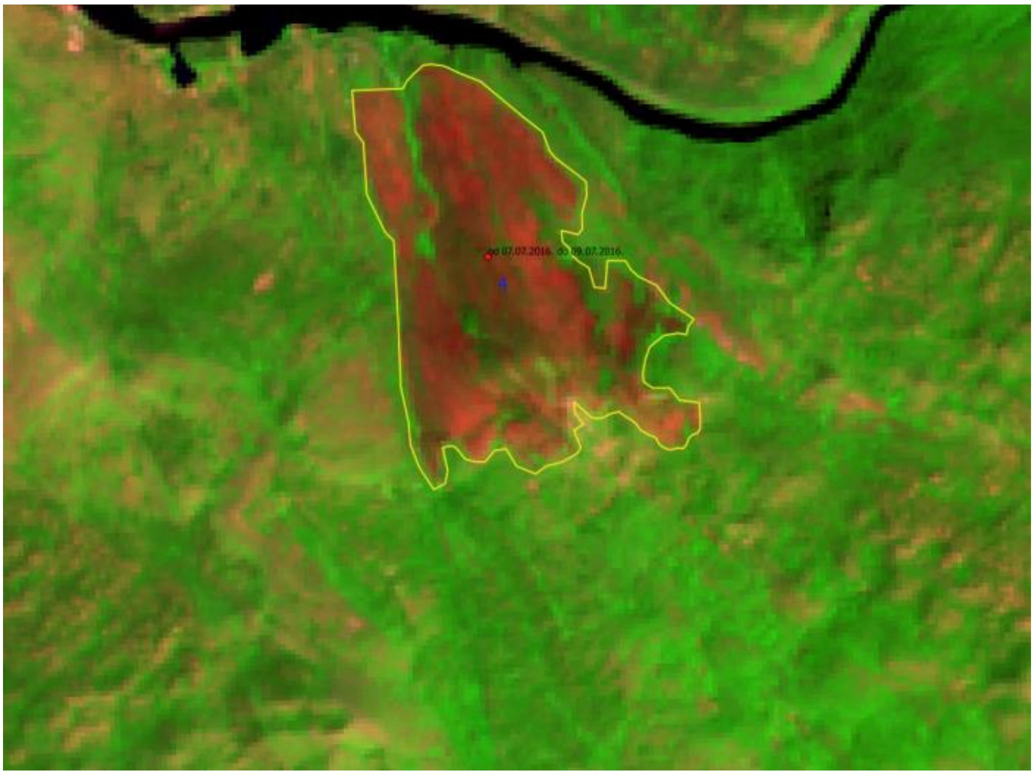

Figure 3. Landsat 8 (band combination 7,5,3) image after the wildfire event 23.07.2016. [5]

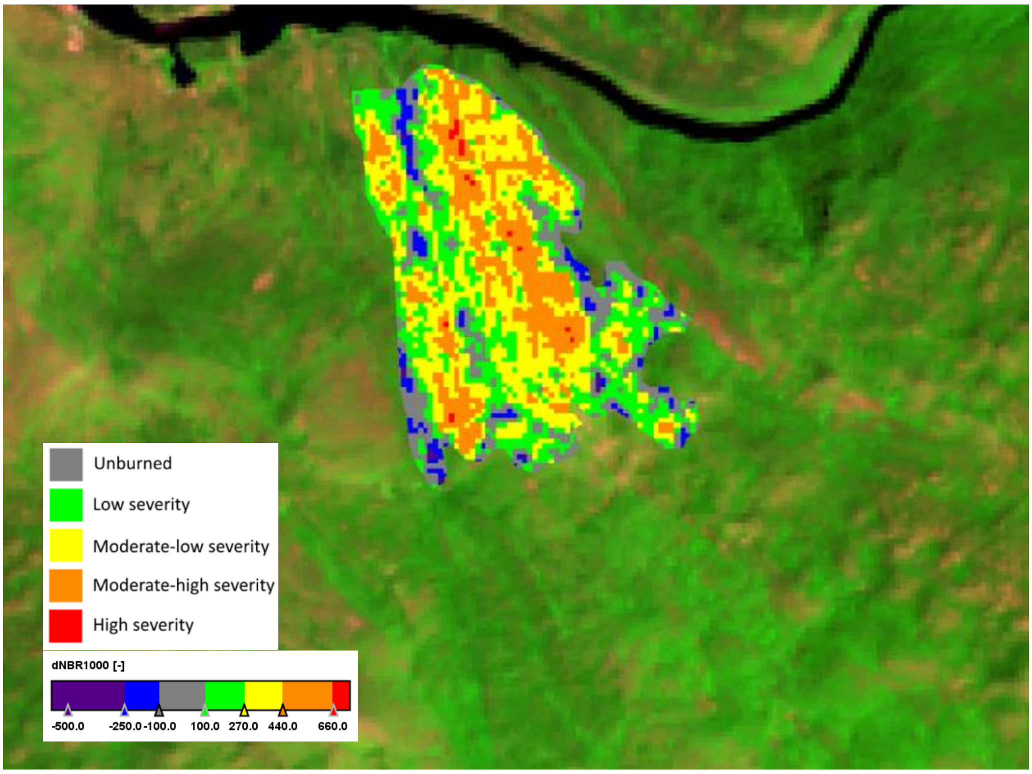

Figure 4. Burn severity map. [1]

2.2 Wildfires in Trebinje Region. September, 2016. Republika Srpska, Bosnia and Herzegovina

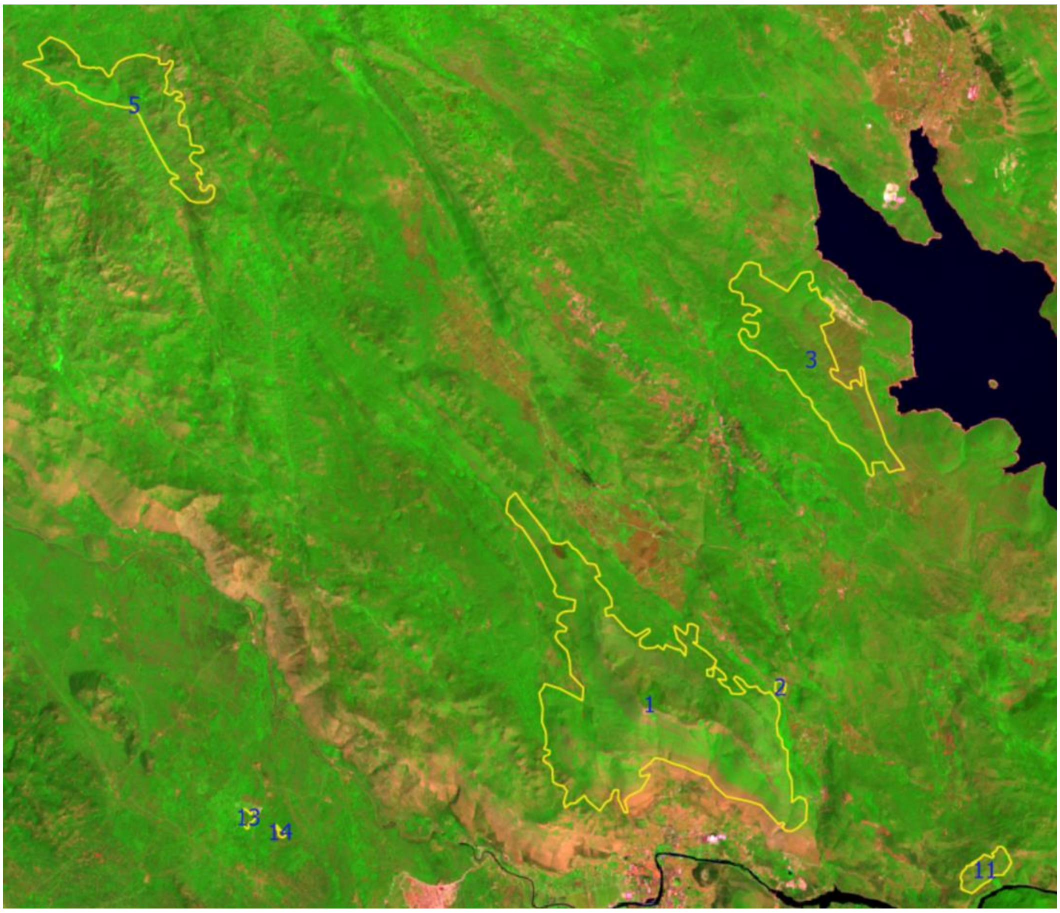

Figure 5. Satellite image before the wildfire event. Landsat 8 satellite image 23.07.2016. in 7,5,3 band combination. [5] Yellow polygons represent burned surfaces.

Burned surface area: surface 1 = 1987 ha, surface 2 = 6 ha, surface 3 = 648 ha, surface 5 = 464 ha, surface 11 = 64 ha, surface 13 = 10 ha, surface 14 = 3 ha.

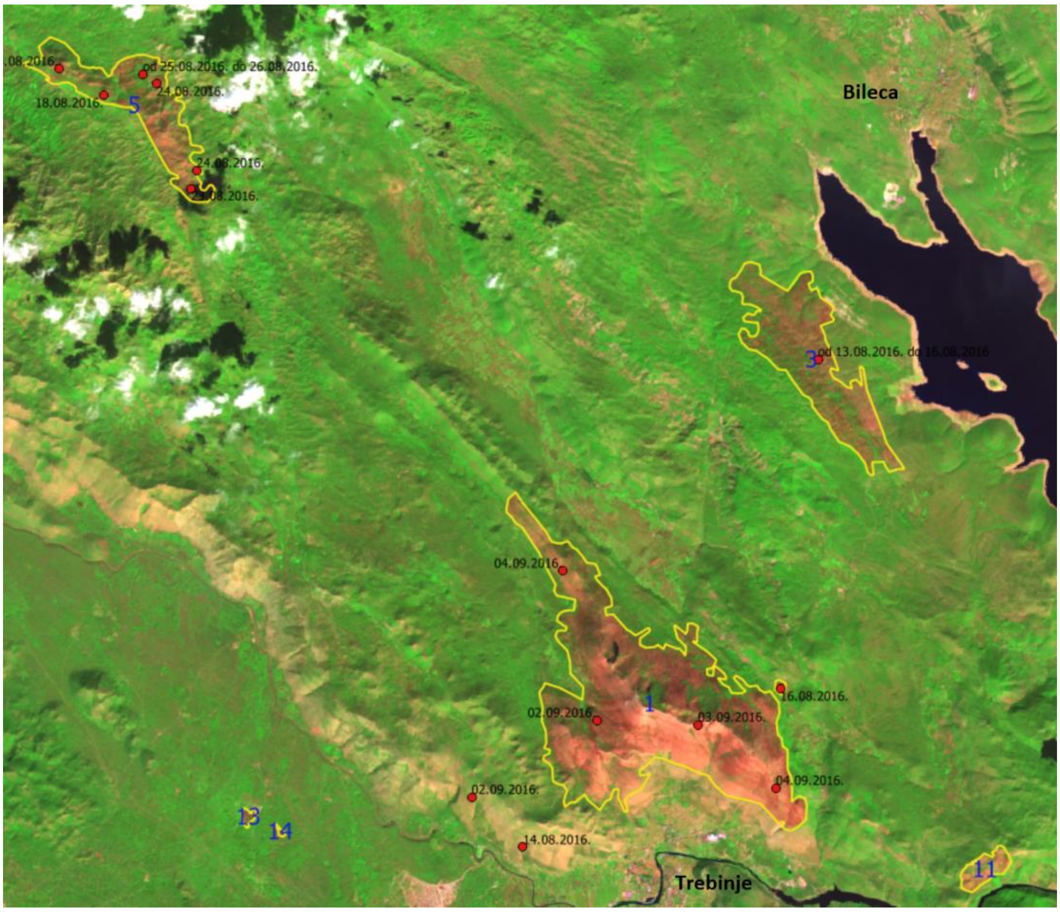

Figure 6. Satellite image after the wildfire event. Landsat 8 satellite image 25.09.2016. in 7,5,3 band combination. Yellow polygons represent burned surfaces. Red dots represent the date of fire occurrences from NASA Worldview. [5]

Figure 7. Geographic location of disaster marked with red polygon. Image: NASA Blue Marble 2004 [5]

2.3 Brumadinho dam disaster. January 25, 2019. Brazil

The Brumadinho dam disaster occurred on January 25, 2019 when a tailing dam at the Córrego do Feijão iron ore mine suffered a catastrophic failure. The dam, located 9 km east of Brumadinho in Minas Gerais, Brazil, is owned by the mining company Vale, which was also involved in the Mariana dam disaster of 2015. The collapse of the dam released a mudflow that engulfed the mine's headquarters, including a cafeteria during lunchtime, along with houses, farms, inns, and roads downstream. 270 people died as a result of the collapse, of whom 259 were officially confirmed dead, in January 2019, and 11 others were reported as missing. As of January 2022, 6 persons were still missing. [6]

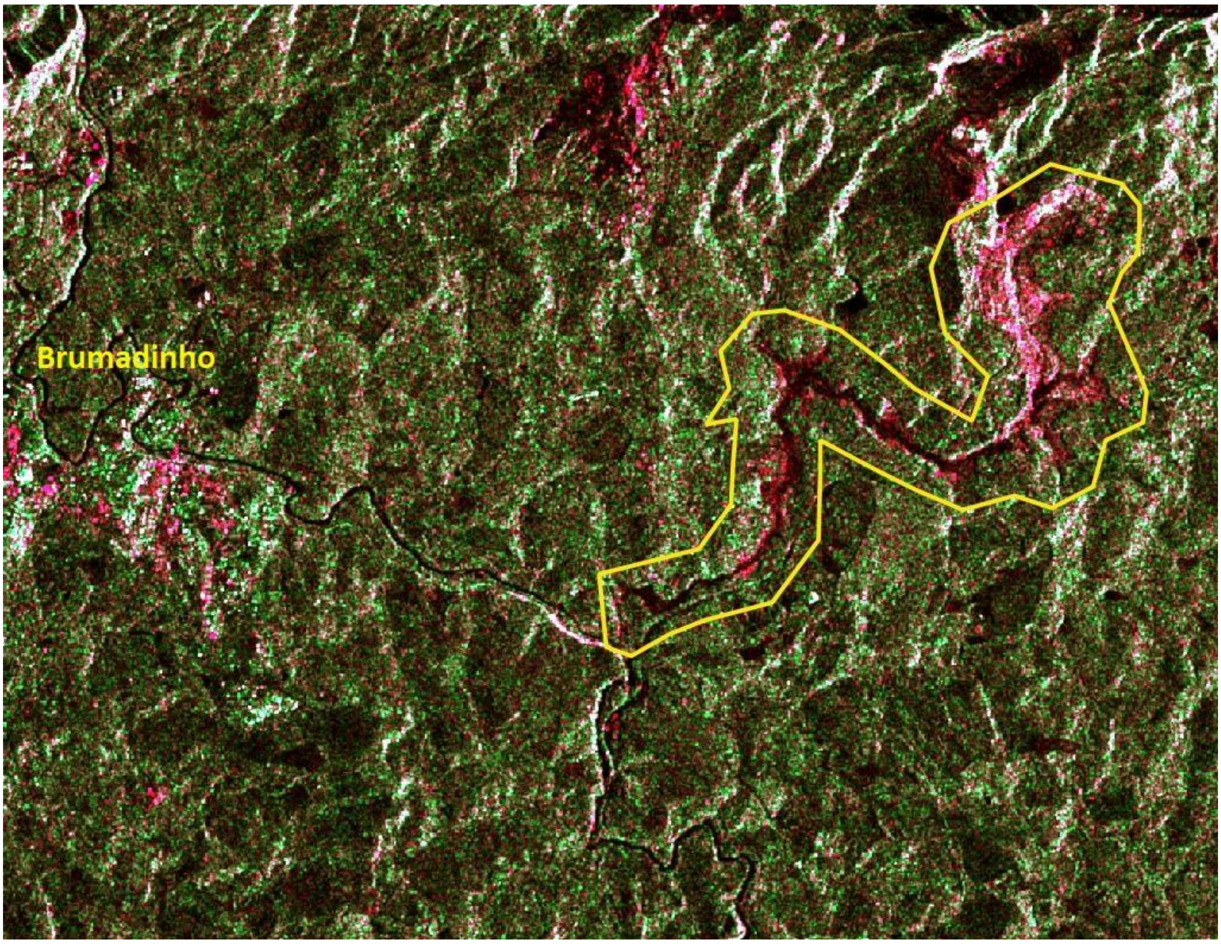

Figure 8. Sentinel-1B satellite image in Dual Pol Multiple RGB visualisation from 03.02.2019. after the Brumadinho dam disaster which occurred on January 25, 2019. Yellow polygon represents an affected surface. Mudflow extent can be seen in shades of red color inside the yellow polygon. [7]

Figure 9. Geographic location of disaster marked with red polygon. Image: NASA Blue Marble 2004 [5]

2.4 Hailstorm disaster. July 7, 2019. Backa Palanka, Serbia

Light-blue polygon represents damaged surface by extreme weather event with high winds, heavy rain and hail, which occurred 07.07.2019. The color-infrared image of 29.06.2019. shows agricultural fields and forest area before the hailstorm (Figure 10.). From color-infrared satellite image of 19.07.2019. it could be seen the damaged agricultural fields and forest area near the Danube river (Figure 11.). Figure 12. presents the image from the field 28.07.2019. of damaged soybean agricultural field number 2.

Figure 10. Sentinel-2 color-infrared satellite image of agricultural fields and forest area near Backa Palanka town on 29.06.2019. before the hailstorm event. [7]

Figure 11. Sentinel-2 color-infrared satellite image of damaged agricultural fields and forest area of river Danube near Backa Palanka town on 19.07.2019. twelve days after the hailstorm event. [7]

Figure 12. Complete damage of soybean agricultural field number 2. by hailstorm event 07.07.2019. Image taken 28.07.2019.

Figure 13. Image of the upcoming hailstorm taken on 07.07.2019.

Figure 14. Geographic location of disaster marked with red polygon. Image: NASA Blue Marble 2004 [5]

2.5 Oil spill disaster near the coast of Rennel Islands. February 5, 2019. Solomon Islands

On February 5, 2019. an oil spill occurred near East Rennell, the only natural World Heritage site in the Pacific that is on the Danger List. The bulk carrier MV Solomon Trader carrying an estimated 700 tonnes of heavy fuel oil ran aground in Kangava Bay, Rennell Island, while loading bauxite ore. [8] Later impact of cyclone Oma amplified the disaster and spread of oil.

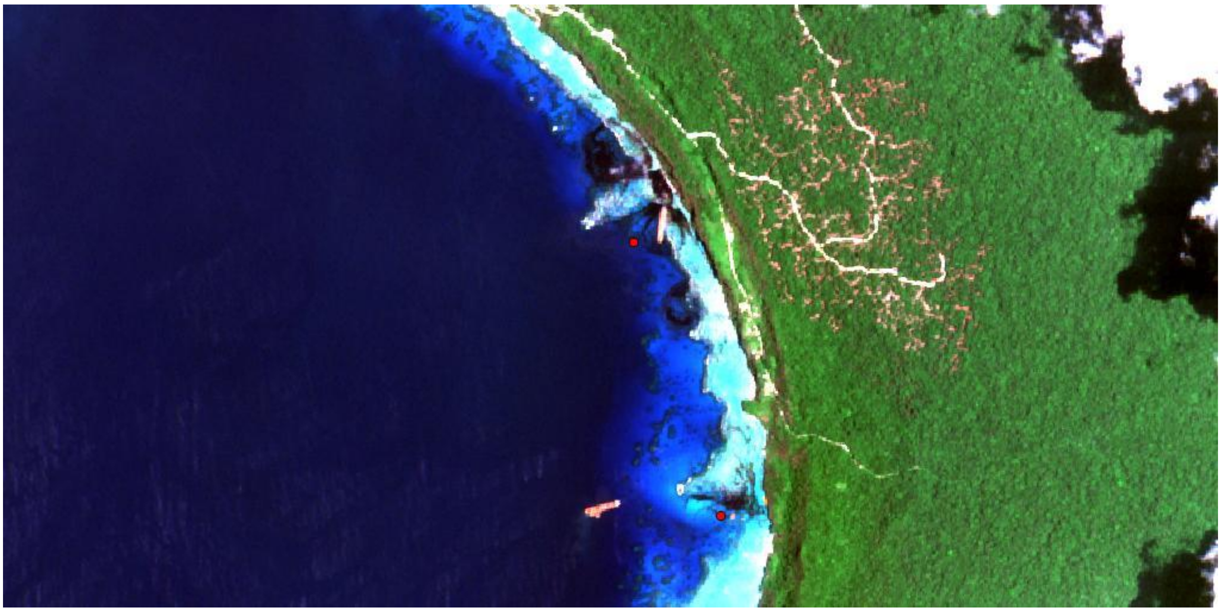

Figure 15. Sentinel-2 RGB satellite image from 22.02.2019. after the oil spill disaster event in February 5. Red dots represent locations of spotted oil spills. [7]

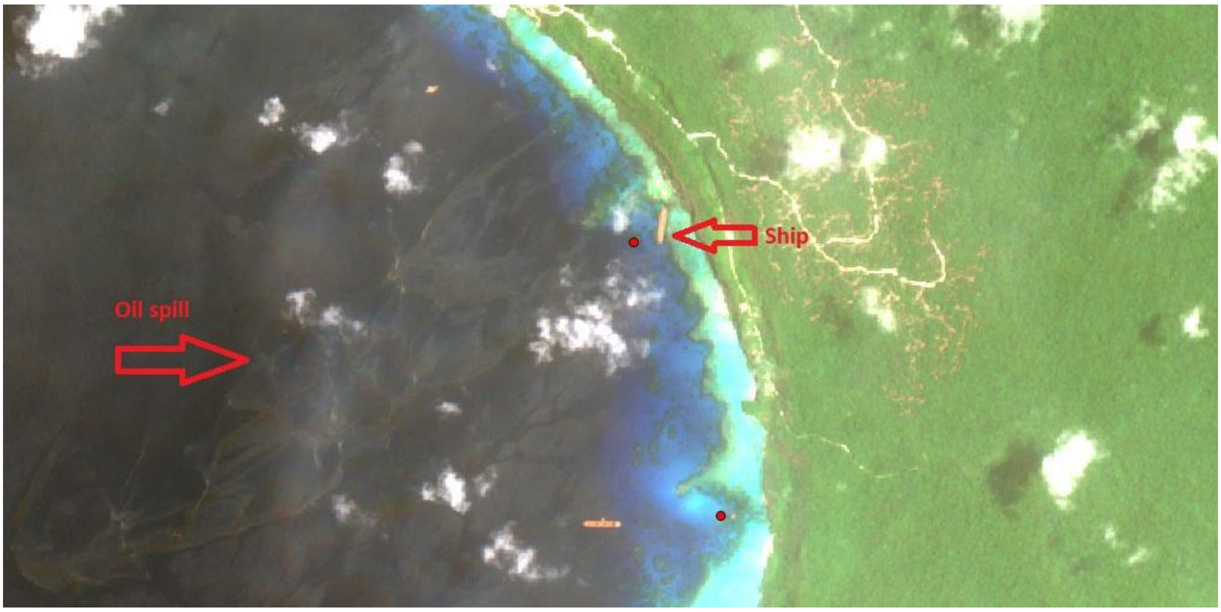

Figure 16. Sentinel-2 RGB satellite image from 04.03.2019. after the oil spill disaster event in February 5. Red dots represent locations of previously spotted oil spills. [7]

Figure 17. Geographic location of disaster marked with red polygon. Image: NASA Blue Marble 2004 [5]

2.6 Flooding of South Morava river. January 12, 2021. Serbia

The flooding caused the damage to more than hundreds of households and agricultural buildings, leaving many of them without electricity.

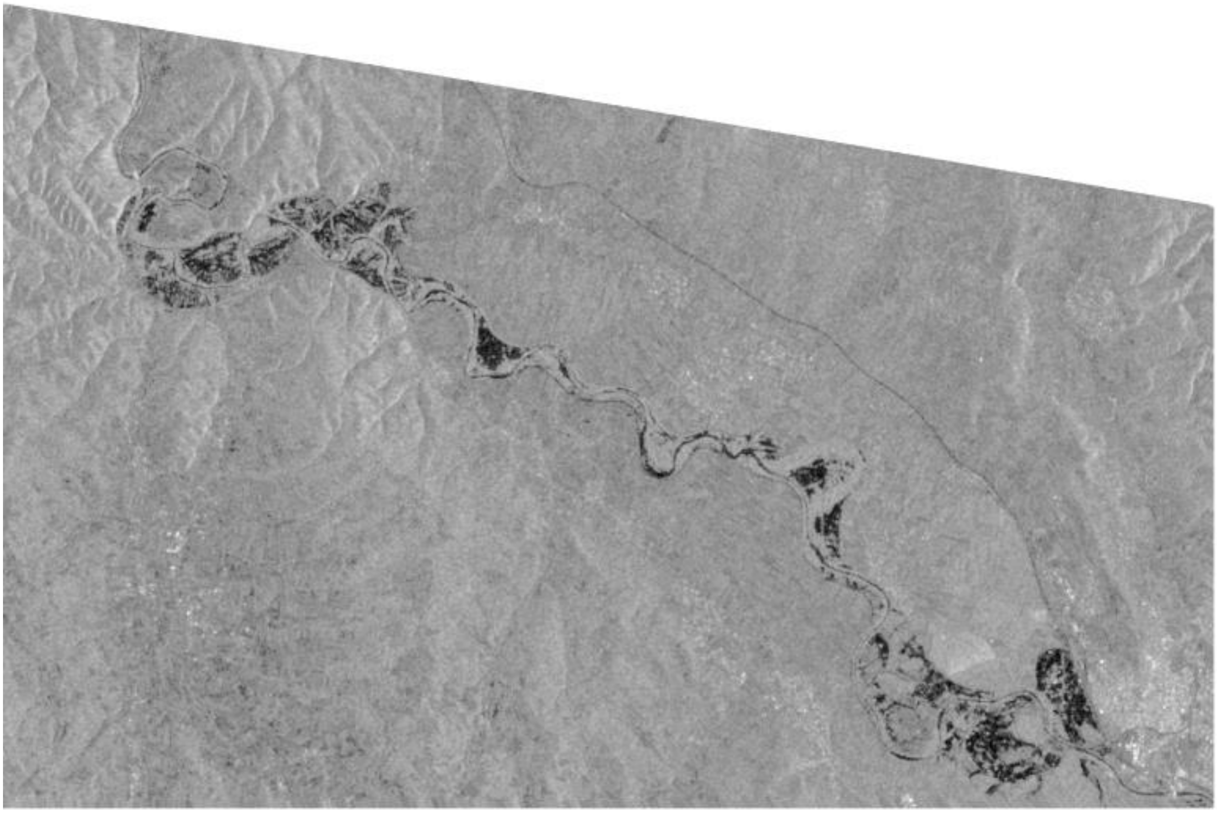

Figure 18. Sentinel-1 radar image in VV polarization during the flooding of South Morava river near Aleksinac. The image was acquired 13.01.2021. Dark tones represents the flooded surfaces. [9]

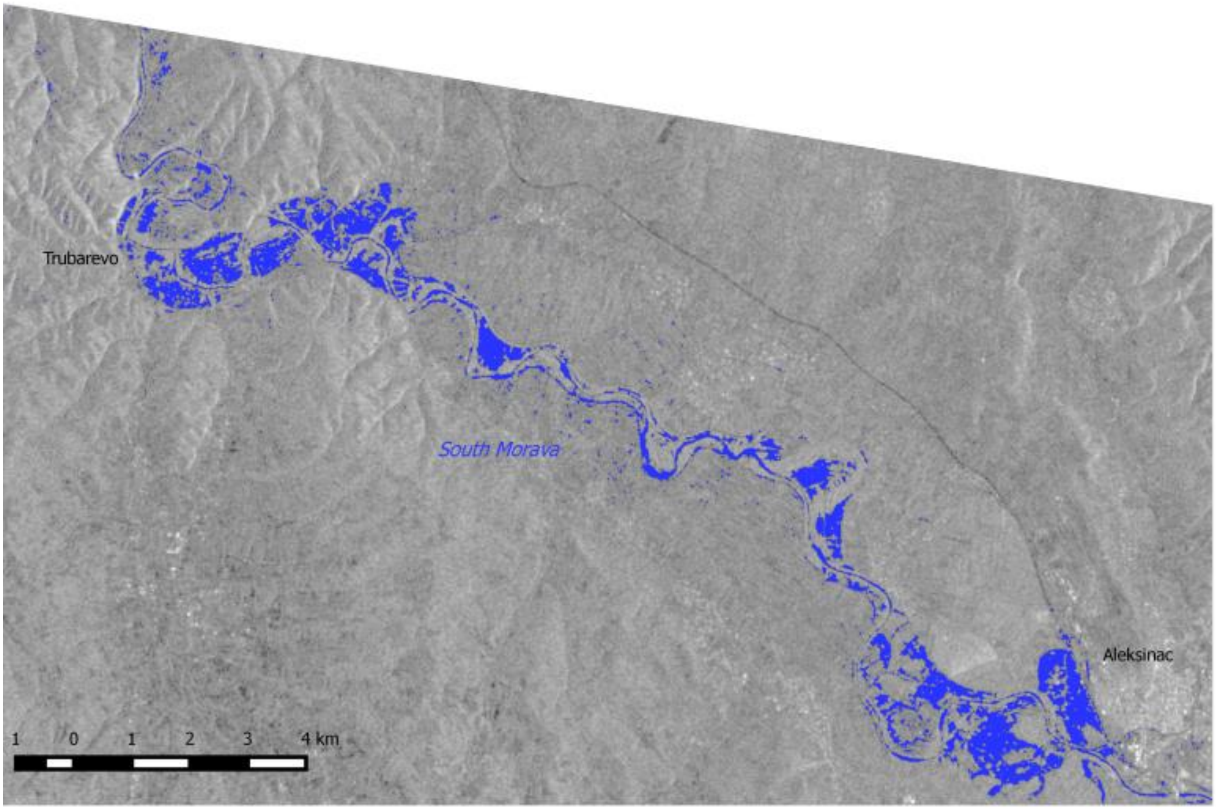

Figure 19. Flood mask derived from Sentinel-1 radar image in VV polarization. [9]

Figure 20. Geographic location of disaster marked with red polygon. Image: NASA Blue Marble 2004 [5]

2.7 Cargo ship disaster near Sri Lanka west coast. May 20, 2021. Sri Lanka

On May 20, 2021, cargo ship X-PRESS PEARL, with 1,486 containers on board carrying 25 tons of nitric acid, caustic soda, solid sodium methoxide solution, cosmetics, methanol and vinyl acetate, including micro plastics, plastic pellets together with other cargo, caught fire approximately nine nautical miles (16 km) off the coast of Colombo’s commercial shipping harbour. The fire continued to burn until end-May 2021 and a number of small explosions were heard from the container ship during the fire. [11]

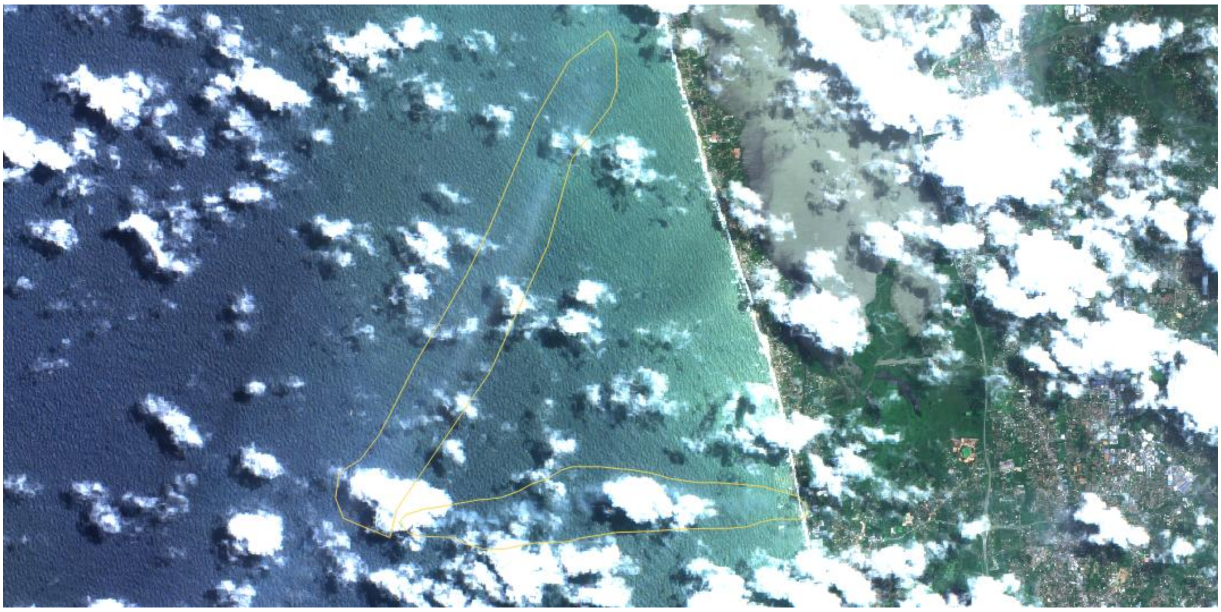

Figure 21. Sentinel-2 RGB satellite image from 30.05.2021. during the cargo ship disaster event. Yellow polygons represent the smoke plume from the burning cargo ship carrying tonnes of chemicals near the Pamunugama coast, in Sri Lanka. [9]

Figure 22. NOAA-20 satellite image VIIRS Fire and Thermal Anomalies product from 28.05.2021. Red dot represent the location of the spotted burning cargo ship. [5]

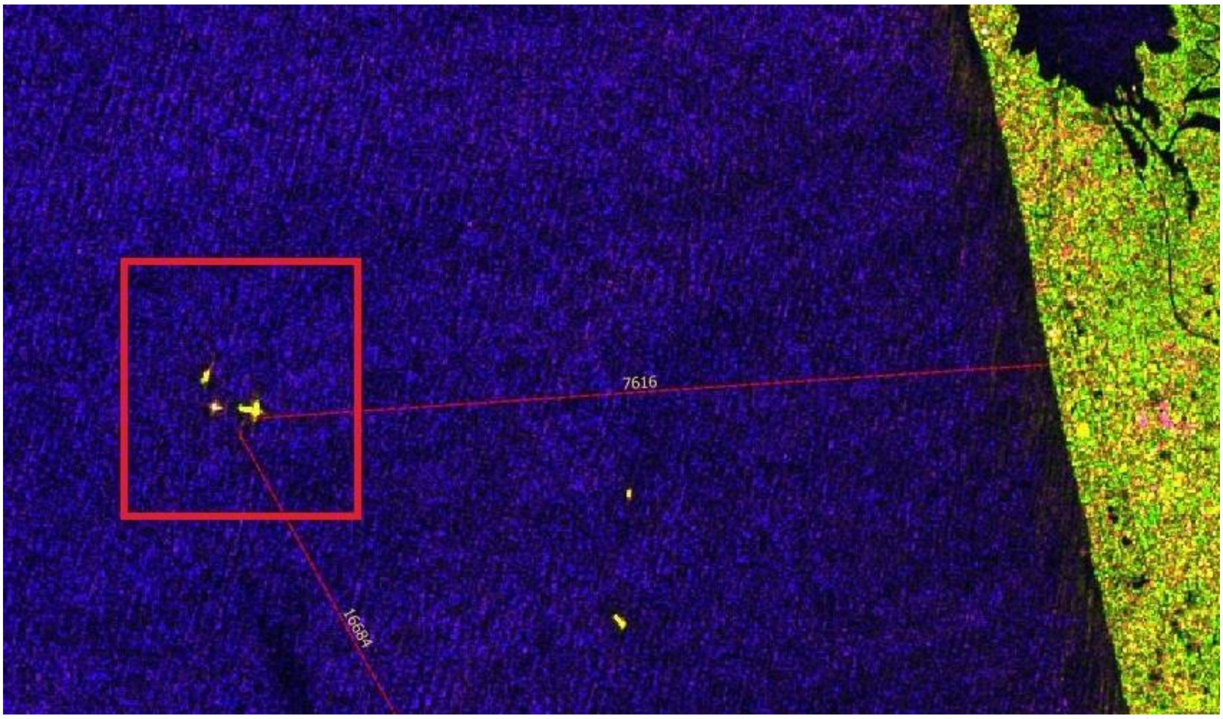

Figure 23. Sentinel-1 RGB (VV,VH,VV/VH) radar satellite image from 27.05.2021. during the cargo ship disaster event. Red polygon represents the location of the burning cargo ship and two other vessels are fire fighting vessels. [9]

Figure 24. Landsat 8 RGB satellite image from 01.06.2021. during the cargo ship disaster event. Red lines represent the distance in meters from the burning cargo ship carrying tonnes of chemicals to the Pamunugama coast and Colombo. [5]

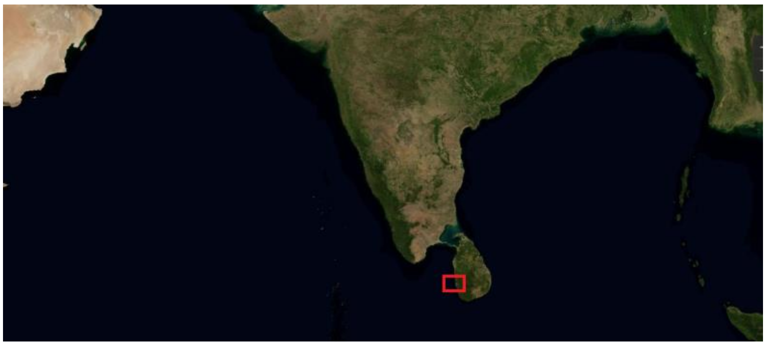

Figure 25. Geographic location of disaster marked with red polygon. Image: NASA Blue Marble 2004 [5]

2.8 Oil spill disaster near the coast of Callao. January 15, 2022. Peru

This disaster happened when the tanker which was unloading crude oil at its refinery was hit by strong waves caused by the volcanic eruption near Tonga. Some 6,000 barrels of crude oil had spilled into a bio-diverse swath of Peru’s Pacific. On the right side of the image it is shown the Ancón District. Oil spill can be seen clearly between the coast and the sun glint pattern area due to the wind waves on the left side of the image. Thin-film interference phenomenon of the oil surface can be seen on the bottom of the image near and south of the Playa La Puntilla. The oil spill has left hundreds of fishermen without work, in already poor coastal districts and threatened two protected marine reserves. [12] Example of Natech disaster. [4]

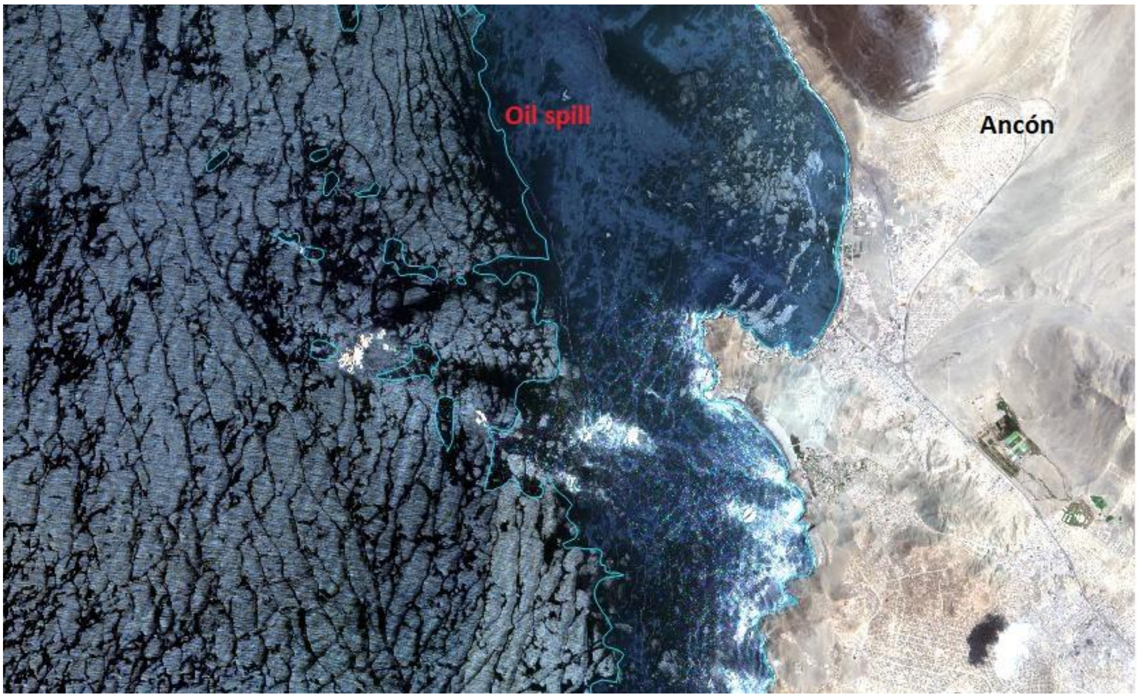

Figure 26. Sentinel-2 RGB satellite image from 18.01.2022. during the oil spill disaster event. Light-blue polygons represent the surfaces where are the oil spills spotted near the coast of Peru. Thin-film interference phenomenon of the oil surface can be seen on the bottom of the image near the Playa La Puntilla. [10]

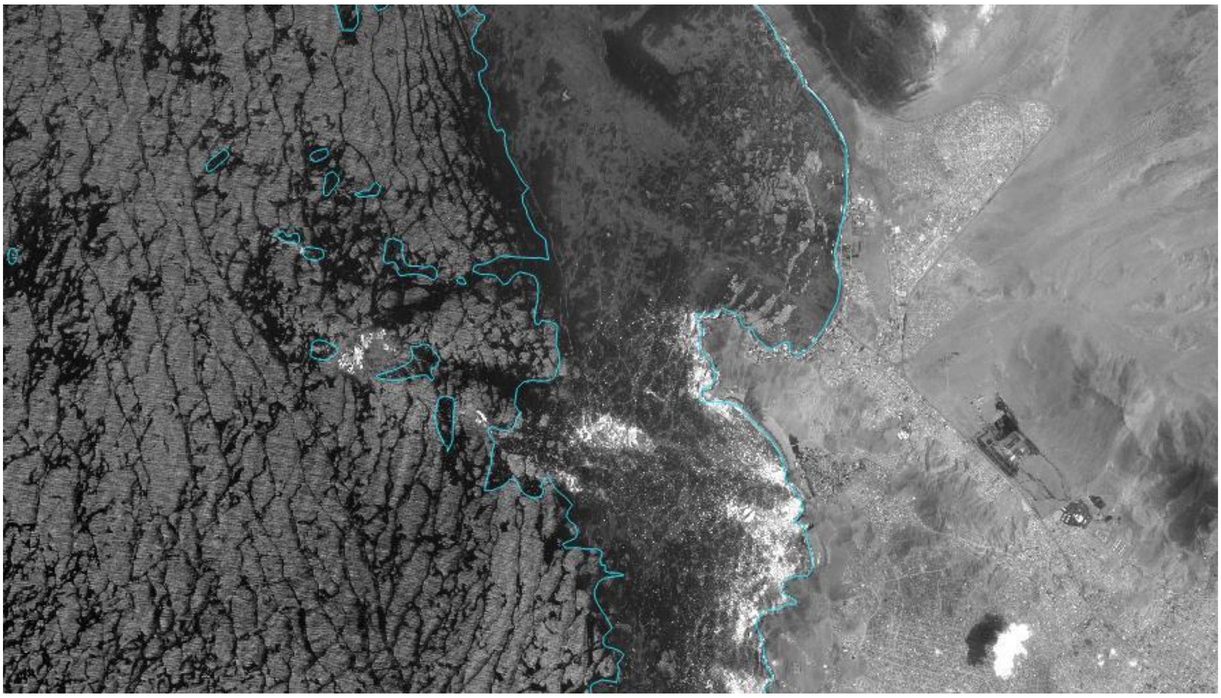

Figure 27. Sentinel-2 RGB satellite image band-2 (blue) from 18.01.2022. during the oil spill disaster event. Light-blue polygons represent the surfaces where are the oil spills spotted near the coast of Peru. [10]

Figure 28. Geographic location of disaster marked with red polygon. Image: NASA Blue Marble 2004 [5]

3. Conclusion

Remote sensing plays a significant role in disaster risk reduction and provides considerable potential to reduce vulnerability of people to natural and man-made hazards. Many of the disasters could be prevented if better information were available on the exposed populations and property, environmental conditions, patterns and behavior of particular hazards. This paper presents the diverse use of some of the open access satellite images. The one of the importance of remote sensing of natural and man-made disasters is also in visually informing the international community and decision makers to deal with every kind of disaster (small or large) in every country on the same way, by improving the response, recovery on the current disaster event and preparedness, mitigation on the future potential disaster event.

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MIRCE Science: Functionability Management of Autonomously Working Systems on Earth Affected by Impacts of Severe Space Weather on Orbiting Satellites

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Abstract

Harmful impacts of severe space weather on a large number of modern technological systems like: power networks, aviation, satellite services, radio communication and pipelines; have been observed and documented in the literature. Hence, the author concluded that space weather must have a similar impact on the digital technologies that will be used to provide the autonomy to the autonomously working systems in the future, like cars, trains, ships, drones and so forth. Thus, this paper briefly examined the space weather phenomena that could affect functionability of autonomously working systems by impacting provision of data provided by sensors contained in Earth orbiting satellites. Thus, MIRCE Science based philosophy made the author to conclude that functionability management of autonomously working systems in the future should focus on the protection of the sensors located in orbiting satellites from the exposure to continuously generating space weather in the Sun, by accurately monitoring their trajectories. Hence, when the damaging impact of severe space weather is predicted, the targeting satellite(s) should be temporarily moved to different orbital positions. This new type of functionability management is the only feasible solution for the provision of continuous operation of autonomously working systems of the Earth, as the physical execution of any maintenance tasks on sensors damaged by the impact of the space weather, within satellites, is impossible.

Key words: MIRCE Science**,** functionability of autonomous systems on Earth, impact of space weather on satellites, preventive maintenance by orbital repositioning

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MIRCE Science unique identifier: MSA2024-10-19

0. Dedication

This paper is dedicated to the memories of my father, Milija Knezevic, who died a year ago, in his 99th year. He wholeheartedly supported my love for science and assisted my professional career on a few crucial junctions!

1. Introduction

The philosophy of MIRCE Science is based on the premise that the purpose of the existence of any working system is to do expected work through time. The work is considered to be done when a measurable function(s) is performed. It is a theory for the prediction of the motion of working systems through MIRCE Space, resulting from any functionability actions whatsoever and the actions required to produce any functionability motions. To that end a scientific understanding of mechanisms that generate positive and negative functionability events is an imperative. Without full understanding of these mechanisms the prediction of occurrences of functionability events is not possible, and without the ability to predict the future, the use of the word science becomes inappropriate.

To scientifically understand the functionability actions generated mechanisms of the in-service behaviour of several thousands of components, modules and assemblies of working systems in defence, aerospace, nuclear, transportation, motorsport and communication industries have been conducted at the MIRCE Akademy, by staff, students and Fellows. Results obtained had shown to the author that any serious studies of the functionability mechanisms have to be based between the following two boundaries [1]:

- the “bottom end” of the physical world, which is at the level of the atoms and molecules that exists in the region of 10^{-10} of a metre.
- the “top end” of the physical world, which is at the level of the solar system that exists in the physical scale around 10^{+10} of a metre.

This range is the minimum sufficient “physical scale” which enables scientific understanding of relationships between physical phenomena that take place in the natural environment and the physical mechanisms that govern functionability events during the life of working systems.

On 27th February 2023 a powerful solar storm, containing a large amount of charged solar particles, reached Earth and temporarily disrupted operations of several Canadian oilrigs, which was the very first time in living memory that the drilling operations were suspended. The cause of the interruption was the exposure of the digital sensors located in the Earth orbiting satellites to the space weather. Resulting impact was the in-accuracy of GPS data that were driving the electronics in the part of the equipment which determines the direction and inclination the drill bit is going. [2]

However, the response to the same storm of 27th February 2023 by the American Company SpaceX was to promptly delay the planned launch of the Starlink rocket. That was the direct result of the costly lesson learned from 3rd February of 2022 when 38 out of 49 satellites launched by SpaceX’s Falcon 9 rocket just perished! They were launched in Low Earth Orbit (LEO) during a moderately strong geomagnetic storm.

Its magnetic cloud was traced back to the Sun as a halo that erupted on 29th January 2022 at 22:45 UT and travelled at a moderate speed of 690 km/s. The impact of the loss of the Starlink satellite systems had cost the company millions of dollars. Consequently, SpaceX has started paying greater attention to space weather forecasts and even became a regular supplier of the data from Starlink's onboard sensors to the U.S. National Oceanic and Atmospheric Administration (NOAA) to help them to improve the space weather forecasting models. [2]

An autonomously working system can be defined as a collection of mutually interactive entities put together to deliver at least one measurable function independently of human interaction by receiving its inputs from a set of electronic senses that are processed in accordance to established algorithms. Autonomous ships, trains, cars and similar systems are expected to operate independently of human interactions, by receiving inputs information from the range of physical sensors. Recent development of digital technologies enabled immense amounts of information to be compressed on small storage devices that can be easily preserved and transported. They have made fundamental changes to many aspects of human lives, including the creation of autonomously working systems. However, most of these digital sensors are managed by satellites that are orbiting the Earth, which get exposed and impacted by space weather. Thus, the ability to accurately maintain the continuously changing flow of information between the physical reality of autonomously working systems and the performance of their expected functions via Earth orbiting satellites are essential for reliable, safe and profitable day-to-day operation.

In summary, the main objective of this paper is to draw the attention of the operational managers to the MIRCE Science approach to the maintenance of the autonomously working systems of the future. It is totally different from all other known maintenance types as it is based on the accurate predictions of the occurrences of severe space weather generated by nuclear reactions taking place on the Sun and the execution of the preventing avoidance manoeuvres to protect the digital technology sensors located in the Earth orbiting satellites that are the providers of autonomy to autonomously working systems on the Earth.

2. The Concept of Space Weather

Terrestrial weather, manifested through physical phenomena like: wind, snow, rain, hail, thunder and lightening, has significant impacts on the operation of terrestrial systems. Physical impacts of these metrological phenomena are reasonably well understood and included in reliability analysis of the majority of systems deployed. [3]

Similarly, space weather is manifested through physical phenomena like: evolving ambient plasma, magnetic fields, radiation, flows of charged particle in space and similar. The effects of space weather, although unfelt by human senses, are observed in the interruption or degradation of functionality and performance of space located systems during their lifetimes. In addition, increased radiation due to space weather may lead to increased health risks for astronauts participating in manned space missions. The aviation sector may also experience damage to aircraft electronics and slightly increased radiation doses at aircraft altitude during large space weather events. In addition to the Sun, non-solar sources such as galactic cosmic rays can be considered as space weather since they alter space environment conditions near the Earth. [4]

2.1 Impact of space weather on Earth's environment

The Sun is not a steady-state star. Its surface boils at over 6,000° C, with complex electric and magnetic fields twisting, winding and plunging in and out of the depths. It continuously undergoes changes, which sometimes could be extremely violent. These changes are transferred by the solar wind to the Earth and disturb its magnetic field. The regular changes in the level of solar activity over long-periods are known as the solar cycle. The duration of the solar cycle varies between 9.5 and 11 years. Usually, solar activity is measured by the number of sunspots on the solar surface. The solar cycle is also seen in the number and strength of the solar flares, which are resulting from tremendous explosions in a localised region on the Sun. In a matter of just a few minutes they heat material to many millions of degrees. [5]

The solar wind consists of ionized particles, mostly protons and electrons with a small admixture of helium ions. The density of solar wind is low, about 10 particles per cc. Solar wind also carries the Sun's magnetic field, which at the Earth's orbit has strength of only a few nT. The wind speed at the Earth's orbit is about 450 km/s or more. On its trajectory the solar wind encounters the Earth's magnetic field, which deflects the particles and shields the Earth from the direct effects of the solar wind.

Solar Storms happen when a Sun emits large bursts of energy in the form of solar flares and coronal mass ejections. These phenomena send a stream of electrical charges and magnetic fields towards the Earth at high speed, in the form of x-rays, ultraviolet and radio emissions, which can cause disruptions to the Earth's ionosphere leading to radio and communications interference.

One of the effects of space weather striking Earth is the creation of the "northern lights" which are seen in the regions around the Arctic Circle. An adverse effect of solar storms is the disruption of satellites and other electronic means of communications. [6]

2.2 Types of solar storms

Solar Storms come in the form of the following types [7]:

- Solar Flares, which are manifested as a sudden flash of increased brightness on the Sun, usually observed near its surface and in proximity to a sunspot group. Powerful flares are often, but not always, accompanied by a coronal mass ejection. Even the most powerful flares are barely detectable in the total solar irradiance
- Coronal Mass Ejections (CME), which are a result of the twisting and realignment of the sun's magnetic field. As magnetic field lines "tangle" they produce strong localised magnetic fields that can break through the surface of the Sun at active regions. It is manifested through a significant release of plasma and accompanying magnetic field from the solar corona. They often follow solar flares and are normally present during a solar prominence eruption
- Geomagnetic Storm, which is a temporary disturbance of the Earth's magnetosphere caused by a solar wind shock wave and/or cloud of magnetic field that interacts with the Earth's magnetic field, caused by changes in the solar wind and interplanetary magnetic field (IMF) structure

- Solar Particle Events, or solar proton event (SPE), occurs when particles (mostly protons) emitted by the Sun become accelerated either close to it during a flare or in interplanetary space by coronal mass ejection shocks.

3. Impact of Space Weather on the Satellites Operations

Satellites are critically important for the successful operation of the autonomously working systems. Thus, it is essential to understand the consequences of their exposures to space weather, solar storms and consequential geomagnetic storms. When the Earth atmosphere absorbs energy from these space phenomena it heats up and expands upward. This expansion significantly increases the density of the thermosphere, the layer of the atmosphere that extends from about 80 km to roughly 1000 km above the surface of Earth. Higher density means more drag, which could cause a problem for them to maintain the altitude. [2]

Drag is just one hazard that space weather poses to space-based technological systems. Strong geomagnetic storms generate the significant increase in high-energy electrons within the magnetosphere, which penetrate the shielding on a satellite and accumulate within its electronics. The build-up of electrons can discharge in small lightning strikes and damage electronics, generating failures.

Penetrating radiation or charged particles in the magnetosphere, even during mild geomagnetic storms, can also alter the output signal from electronic devices. This phenomenon can cause errors in any part of a satellite's electronics and if the error occurs in critical parts, the entire satellite can fail.

Finally, space weather can disrupt the ability of satellites to communicate with Earth using radio waves. Many communications technologies, like GPS, for example, rely on radio waves. As the atmosphere continuously distorts radio waves by some amount, design engineers correct for this distortion when building communication systems. However, during geomagnetic storms, changes in the ionosphere, the charged equivalent of the thermosphere that spans roughly the same altitude range, will change how radio waves travel through it.

3.1 Impacts of space weather on digital technology driven sensors

Recent developments of digital technologies have made fundamental changes to the way humans live their lives. Among others, digital technology is a driving force behind all autonomously working systems, from passenger cars to spacecraft. In general, autonomously working systems can be defined as a set of entities that can operate independently of human interactions. They are performing expected functions by receiving inputs from a set of electronic senses that are processed in accordance to established algorithms. Thus, the ability to continuously exchange information relevant to the safe operation of autonomously working systems is of vital importance for their reliability. [2]

Autonomously working systems contain, among many other entities, communication and control parts that provide their autonomy. According to [8] the following elements are driven by digital technologies which are used in a range of physical sensors that control autonomous functions, such as:

- RAdio Detecting And Ranging (RADAR) is electromagnetic sensor used for detecting, locating, tracking and recognasing objects of various types at considerable distances
- LIght Detection And Ranging (LIDAR) is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth.
- Global Positioning System (GPS) is a network of satellites and receiving devices used to determine the location of something on Earth.
- Infra-Red (IR) camera is a measuring instrument used for non-contact measurements of the surface temperature of objects
- Inertial Navigation System (INS) is a self-contained navigational technique using motion sensors to calculate position, orientation, and velocity.

Consequently, the reliable and safe operation of autonomously working systems depends also on the reliability and accuracy of the controlling sensors listed above, which in turn, depend on reliability of Earth orbiting satellites in which they are imbedded and technology used. [9]

3.2 Impact of space weather on functionability of autonomously working systems

After a brief analysis of the space weather it became obvious that its continuous generating phenomena could have severe consequences on the in-service reliability and safety of autonomously working systems. Primarily, it was attributed to its impacts on the reliability and quality of controlling information provided by digital technology driven sensors contained in Earth orbiting satellites. Thus, the author has faced a question, “How to maintain operation of autonomously working systems on Earth in the cases of the failure of digital technology driven sensors located in Earth orbiting satellites, caused by space weather.”

Clearly, it is physically impossible to perform any corrective maintenance task on the failed sensors in orbiting satellites, on one hand, and no satellites are designed to be brought back to the Earth for maintenance, on the other. Hence, the maintenance activities applied to the Earth operating systems are out of considerations.

Some of the impacts of solar weather can be reduced by shielding electronics from radiation or developing materials that are more resistant to radiation. The most frequently used materials for electromagnetic shielding include: sheet metal, metal screen, and metal foam. Any holes in the shield or mesh must be significantly smaller than the wavelength of the radiation that is being kept out, or the enclosure will not effectively approximate an unbroken conducting surface. However, there is only so much shielding that can be done in the face of a powerful geomagnetic storm, on one hand, and the adding weight to a spacecraft that is demanding more fuel, on the other.

The research performed in the context of MIRCE Science has shown that the maintenance of autonomously working systems against potential failures of the sensors located in Earth orbiting satellites from the impact of continuously generating space weather in the Sun, could be served the best if the satellites are temporarily moved from the trajectory of incoming harmful space weather generating particles. This is an equivalent of the well known preventive maintenance policy commonly applied to safety critical systems on the Earth. However, for this solution to work it is necessary to provide real time observations and predictions of space weather, equivalent to the 24/7 produced forecasts for the Earth weather. However, this could be the biggest obstacle for the practical implementation of the proposed maintenance policy for autonomously working systems.

4. Placing Space Weather in MIRCE Science

MIRCE Science is a theory of the motion of working systems through MIRCE Space caused any action whatsoever. It is used to predict expected work and risk of a given working system. It is achieved my making us of MIRCE Functionability Equation, defined by the author, in [10], thus:

$$y(t) = 1 - \sum_{i=1}^{\infty} F_S^i(t) + \sum_{i=1}^{\infty} O_S^i(t) \tag{1}$$

In the above equation $F_S^i(t)$ is a cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the i^th^ consecutive negative functionability event, $TNE_S^i(t)$ of a system considered. In MIRCE Science it is defined by a following convolution integral:

$$F_S^i(t) = \int_0^t O_S^{i-1}(x) dF_{S,i}(t-x), \qquad i = 1, \infty \tag{2}$$

where: $F_{S,i}(t)$ is a cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the i_{th} negative functionability event, $TNE_{S,i}(t)$ of a system considered. In the case that this random variable is governed by the impact of a space weather on the autonomously working system, it is denoted as $TNE_{S,i,SW}$, and it is defined by the following expression:

$$F_{S,i,SW}(t) = P(TNE_{S,i,SW} \le t) = \int_0^t f_{S,i,SW}(t) dt \tag{3}$$

where: $f_{S,i,SW}(t)$ is a probability density function of the random variable that defines the time to the occurrence of i_{th} negative functionability event, which in this specific example is solar weather. The above equation is in the most generic form and as such covers all possible variations and behaviours of solar weather, which means that its users have to determine the applicable mathematical expressions for their specific application.

In the equation (1) $O_S^i(t)$ is a convoluted form of cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the i^{th} consecutive positive functionability event, $TPE_S^i(t)$ of a system or component considered. In MIRCE Science it is defined by the following convolution integral

$$O_S^i(t) = \int_0^t F_S^i(x) dO_{S,i}(t-x), \qquad i = 1, \infty \tag{4}$$

where: $O_{S,i}(t)$ is a cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the i_{th} positive functionability event, $TPE_{S,i}(t)$ of a system considered. In this case the random variable considered is governed by the impact of a recovery action from occurred space weather on the autonomously working system. It is denoted as $TPE_{S,i,SW}$, and it is defined by the following expression:

$$O_{S,i,SW}(t) = P(TPE_{S,i,SW} \le t) = \int_0^t o_{S,i,SW}(t)dt \qquad (5)$$

where; $o_{S,i,SW}(t)$ is a probability density function of the random variable that defines the time to the occurrence of i_{th} positive functionability event, which in this specific example is space weather recovery action. The above equation is in the most generic form and as such covers all possible positive functionability actions that could be taken to return a system to PFS, after solar storms.

In summary, it is essential to stress the following two points:

- The above presented equations are a generic mathematical interpretation of the physical reality of the functionability of working systems. However, the accuracy of their predictions are in the hands of their users, whose knowledge and understanding of the physical reality guide them to the selection of the most appropriate mathematical functions to represent the impacting natural and human actions.
- The impact of space weather could be experienced at the component level, that might or might not affect the functionability of a working system considered or at the system level, that will affect the functionability of a system without a failure of any individual consisting component, as it was the case with 38 out of 49 Starlink satellites launched in February 2022.

The Equation (1) is the fundamental, and the only one known to the author, for normalising all feasible options of design, operation and maintenance options for the future autonomously working systems, at the time when their life cycle has been considered in respect of the expected deliverables, namely expected work and associated risk, for comparative reasons.

5. Predicting Space Weather

The successful management of functionability of satellites accurate prediction of space weather is essential, which is a very challenging task. The research performed by the author has shown that scientists are currently trying to find ways to increase the amount of lead time before a solar storm reaches Earth orbiting satellites. It could be achieved by closely monitoring the short energetic bursts of solar eruptions from the Sun's surface. Changes in the position, size and number of sunspots can also be used as indicators of solar activity, as there is a direct proportionality between the quantity of sunspots and the Sun activities. With enhanced observation and prediction techniques supported by rapidly developing applications of artificial intelligence (AI) the space weather predictions could be dramatically improved.

The globally recognised authority for forecasting and monitoring space weather is the Space Weather Prediction Centre, which is part of the US National Oceanic and Atmospheric Administration (NOAA). It estimates the impacts of geomagnetic storms, solar radiation storms and radio blackouts, as indicators of the severity of the coming solar events.

Each of the three event types is ranked on a five-point scale from minor (1) to extreme (5) to provide descriptions of how events at the different levels might affect power systems, satellite operations, spaceflight operations, navigation systems and biological organisms.

It is interesting to point out that the NOAA had warned that, following a coronal mass ejection, a geomagnetic storm was "likely" to occur the day before or the day of the February 2022 Starlink launch. Totally unaware of the consequences the SpaceX went ahead with the mission, as scheduled.

Another well know institution is the National Centre for Atmospheric Research Mauna Loa Observatory located on the Big Island of Hawaii, at an elevation of 3397 m above sea, whose a round-based instrument called the K-Coronagraph is able to predict when harmful solar energetic particles are heading toward astronauts in the International Space Station. By measuring white light from the lower corona, the K-Coronagraph is able to detect the beginnings of solar activity that creates space weather, providing an extra 20 minutes of warning time. With this extra time astronauts can take safety measures, such as moving behind protective metal shields within the space station.

6. First Solar Storm That Simultaneously Impacts Earth, Moon and Mars

A coronal mass ejection that took place in August 2021 sent simultaneously energetic particles to Mars, the Earth and the Moon, emphasising the need to prepare human space missions for the dangers of space weather. [11] This CME caused an influx of highly energetic, and thus fast-moving, charged particles across the surface of these solar system bodies.

The detection of the same coronal mass ejection on these three different worlds for the first time highlighted the necessity for a better understanding of a mechanism that drives interaction between a planet's magnetic field and atmosphere. This is instrumental for the determination of methods for shielding autonomously working systems from such radiation.

The 2021 CME detection was the very first-of-its-kind. Interestingly, at the moment of the eruption, Earth and Mars were on opposite sides of the Sun with a distance between them of around 250 million km. This outburst was detected by the:

- Euglena and Combined Regenerative Organic-Food Production in Space (Eu:CROPIS) orbiter around Earth.
- ExoMars Trace Gas Orbiter (TGO) on Mars,
- Chang'e-4 Moon lander and NASA's Lunar Reconnaissance Orbiter (LRO) on the lunar surface

In October of the same year a coronal mass ejection was observed by the ESA/NASA Solar and Hemispheric Observatory (SOHO) experienced by a rare event called a "ground level enhancement" during which charged particles from the Sun travel fast enough to penetrate the magnetosphere and reach the ground. This particular occurrence is just the 73rd example of such an event since records began in the 1940s, and it remains the last to be recorded. [12]
As Mars and the Moon do not have a magnetic field, charged solar particles can strike their surfaces more often than on Earth generating a secondary radiation from their surfaces. However, the atmosphere on Mars, while much thinner than Earth's, can still stop low-energy particles and slow high-energy particles.

7. Conclusion

Autonomously working systems are rapidly expanding. For example, maritime systems have been exposed to autonomy from surface to underwater vehicles being deployed for patrol, oceanographic and maintenance among other purposes. Furthermore, cargo ships projects involving coastal and ocean-going routes with different degrees of autonomy are being tested. In October 2021, the International Maritime Organization (IMO) approved an output to develop regulation for Maritime Autonomous Surface Ships (MASS). [13]

Space weather is natural phenomena that will continue to follow its own course of actions. As it has evidential impacts on the operation of autonomously working systems through digital technologies located in the Earth orbiting satellites, it is essential to understand it better. This paper has shown that space weather has impacted reliability and safety of a large number of modern technological systems, through real life examples. This fact led the author to conclude that space weather could have similar impacts on the reliability and safety of future autonomously working systems.

The research presented in this paper has shown that the maintenance of autonomously working systems against potential failures of the sensors located in Earth orbiting satellites from the impact of continuously generating space weather in the Sun, could be served the best if the satellites are temporarily moved from the trajectory of incoming harmful space weather generating particles. This is an equivalent of the well known preventive maintenance policy commonly applied to safety critical systems on Earth. However, for this solution to work it is necessary to provide real time observations and predictions of space weather, equivalent to the 24/7 produced forecasts for the Earth weather. However, this could be the biggest obstacle for the practical implementation of the proposed maintenance policy for autonomously working systems.

The future research that should enable safer and more reliable operation of autonomously working systems could go in two directions. The first, further improvement of the space weather prediction services towards provisioning of the early warnings in time sufficient for the maintenance action described in the paper to be taken by potentially endangered working systems. The second direction for the future research should be focused on innovative technologies and methods for designing equipment that is able to operate safely or protect autonomously working systems in the events of harmful impacts of solar storms in the future.

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MIRCE Science: Clear Air Turbulence as a Mechanism of the Motion of Aircraft through MIRCE Space

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Abstract

MIRCE Science is a theory of the motion of a working system through working process, resulting from any imposing natural and human action whatsoever. Clear air turbulence is a unique natural action that occurs when turbulent masses of air moving at different speeds collide without visual clues, often blindsiding pilots as result. This form of turbulence could be dangerous for passengers and crew who are moving around the cabin when it occurs or sitting without their seatbelts fastened. Hence, the main objective of this paper is to understand the physical mechanisms that generate the occurrences of clear air turbulence and assesses their impacts the motion of an aircraft through MIRCE Space. The available methods for dealing with this imposing functionability action in respect to the provision of safety and protection are also addressed in the paper.

Key words: MIRCE Science, working process, clear air turbulence, functionability performance

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1. Introduction

Aviation is an important mode of transportation process that enables people and cargo to be moved quickly and efficiently across long distances. However, the imposing meteorological actions, like: thunderstorms, icing, turbulence, fog and so forth make significant impacts on the aviation working process and performance.

On 22nd May 2024 Singapore Airlines B777, was flying from London Heathrow to Singapore Changi Airport, with 211 passengers and 18 crew members on board. When it reached Thai airspace an unexpected severe turbulence developed causing severe injuries to 7 passengers, 32 passengers and crew had moderate injuries (16 of which were transported to the hospital) and 14 were treated at the airport. Regretfully one elderly passenger died[35]. The damage to the interior of the aircraft was substantial according to the passengers that confirmed that “overhead bins were dented and ceiling panels where oxygen masks drop from were broken as people's heads went straight through”. Although the full investigation of this accident will be performed by relevant aviation authorities, the aviation specialist accepted that the cause was Clear Air Turbulence (CAT).

The last accident caused by CAT with fatalities took place in March 1966. The BOAC B606 was on a scheduled flight service from Tokyo to Hong Kong. While the flight 911 “treated” their 113 passengers to a close-up view of Mount Fuji, the disaster struck violently and without warning. Extreme air turbulence in the wake of the volcano ripped the Boeing 707 apart in midair, sending it spiralling downward toward the world’s most iconic mountain in full view of hundreds of witnesses. None of the 124 people on board survived the catastrophic plunge from 16,000 feet.

Turbulence, resulting from atmospheric disturbances and variations in wind speed and direction, could be highly dangerous for aviation. It can occur in various forms, such as: thermal turbulence, orographic turbulence and CAT. [1]

The National Transportation Safety Board in the USA (NTSB) analysis of CAT concluded that between 2009 and 2022 over 163 passengers sustained severe injuries from turbulence onboard commercial flights. The majority of those injured were flight attendants who were working in the cabin when the events occurred. A brief description of several CAT related events are given in appendix A.

According to Delta Air Lines and NASA, up to two-thirds of flights deviate from the most fuel-efficient altitude due to turbulence. Each of these deviations adds 41 minutes, on average, to the duration of the flight. Consequently, fuel is wasted, up to $600\text{x}10^6$ litres annually, which contributes $1.5\text{x}10^6$ tonnes of unnecessary CO_2 emissions to climate change (equivalent to the annual emissions of 324,000 cars). Thus, airlines should start thinking about how to manage the increased turbulence, as it costs the aviation industry $150–500 million annually in the USA alone[36].

The main objective of this paper is to investigate the clear air turbulences, as a mechanism of the motion of an aircraft through MIRCE Space, which compels additional flying hours for delivering the transportation function required.

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[35] https://simpleflying.com/severe-turbulence-singapore-airlines-london-flight-causes-fatality-injuries/

[36] https://www.nationalgeographic.com/travel/article/what-is-turbulence-explained

The available methods for dealing with this imposing natural action in respect to the provision of safety and protection of aircraft are also addressed in the paper, as every additional minute spent travelling through turbulence increases structural damage to the aircraft and increases the probability of injuries to passengers and crew members.

2. Brief Overview of MIRCE Science

MIRCE Science is a theory of the motion of working system[37] through a working process compelled by any imposing functionability action whatsoever. The kernel of MIRCE Science is the scientific understanding of the phenomena that generate functionability actions in order for accurate predictions of the expected trajectory to be made by making use of Mirce Functionability Axioms and Equations. [2]

In accordance to MIRCE Science philosophy at any instant of time a working system could be could be in one of the following two states, from functionability point of view:

- Positive Functionability State (PFS), a generic name for a state in which a system is able to deliver measurable function(s)
- Negative Functionability State (NFS), a generic name for a state in which a system in not able to deliver a measurable function(s), from any reason whatsoever.

Being in one of these two functionability states is a physical manifestation of the motion of system functionability through working process. This motion is compelled by any imposing functionability actions, which in MIRCE Science are classified as following:

- Positive Functionability Action (PFA), a generic name for any natural process or human activity that compels a system to move to a PFS,
- Negative Functionability Action (NFA), a generic name for any natural process or human activity that compels a system to move to a NFS.

The mechanisms, nature, frequency and complexity of functionability actions, positive and negative, are specific to each system, but the sequential transitions to a corresponding functionability state is common for working processes.

The motion of working system through the functionability states is physically manifested through the occurrences of functionability events which, according to MIRCE Science philosophy, are classified as following:

- Positive Functionability Event (PFE), a generic name for any physically observable occurrence during a working process that signifies the transition of a system from a NFS to a PFS,
- Negative Functionability Event (NFE), a generic name for any physically observable occurrence during a working process that signifies the transition of a system from a PFS to a NFS.

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[37] Working system is a collection of mutually related resources that is able to deliver a measurable function(s) under given constrains.

Consequently, a working process could be considered as the motion of working system through functionability states through time. The pattern generated forms the functionability trajectory that uniquely determines the functionability performance of the functionability system engaged in a given working process. [2]

Research studies conducted at MIRCE Akademy by staff and students had shown that any serious studies of the mechanisms of the imposing functionability actions have to be based between the following two boundaries [2]:

- the “bottom end” of the physical world that is at the level of interactions between the atoms and molecules of working system engaged, which is in the region of 10^{-10} of a metre.
- the “top end” of the physical world that is within boundaries of the actions within the solar system, which is within a region of around 10^{+10} of a metre.

This range is the minimum sufficient “physical scale” which enables scientific understanding of relationships between physical phenomena that take place in the natural environment and the functionability mechanisms that govern occurrences of functionability events of the given working process.

3. The Earth Atmosphere

The atmosphere of the Earth is a thin spherical shroud containing a mixture of gases that are retained by gravitational attraction. Its highest layer extends up to 10×10^3 km (exosphere), containing extremely low densities of hydrogen, helium and several heavier molecules. The atoms and molecules are so far apart that they can travel hundreds of kilometres without colliding with one another, no longer behaving like a gas, and finally escaping into space.

The lowest layer of the atmosphere, the one in which humans live, is called the troposphere[38], and it hosts what is commonly known as weather. It extends to about 11 km. The troposphere undergoes vertical air movement, for example, convection, an upward motion of air due to heating. This effect may alter the lapse rate and cause instability. The rising air gets colder. Once the moisture in the air reaches saturation at the dew-point temperature, it condenses on the huge number of aerosols, dust particles, salts, ions, and so forth, which are contained in the air. The resulting movements of clouds, thunderstorms, and precipitation are part of the origin of local weather, making the meteorological prediction of local weather difficult. [3]

Global circulation, however, concerns a more constant meteorological pattern, driven by the overall effects of sun’s radiation. Local weather, in a larger geographical area, results from a perturbation – or disturbances – superposed on the basic global pattern. Because of the higher position of the sun in the sky, more energy is delivered by radiation to the equatorial regions. In complicated interactions of pressure and radiation differences occurring at all latitudes, air rises near the equator and flows at high altitudes toward the poles.

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[38] The Greek word *tropos* means turning; turbulent air motion results in continual mixing.

Due to the Earth rotation, however, all motions are affected accordingly in respect to the latitude. The force caused by the rotation of the Earth, known as Coriolis[39] force, pushes moving objects out of their straight path. Flows moving away from the equator turn to the east (to the right) in the Northern Hemisphere and westward in the Southern Hemisphere. The law applied to ocean currents as well, and the Gulf Stream is the prime example found north of the equator.

3.1 Aviation portion of the atmosphere

The composition of the air in the aviation portion of the atmosphere, which is approximately up to 11 km above sea level, are gases that include nitrogen, oxygen, argon, carbon dioxide and water vapour, together with solid particles such as dust, sand and carbon (smoke), with traces of other gases such as helium, hydrogen and neon.

The density of gases and solid particles is the greatest near the surface of the Earth due to the weight of the air above. This value decreases with increase of the height. This reduction in density affects the amount of water vapour present in the air and it decreases with the increase of height, so that the lower stratosphere is almost dry.

The most important single property of the atmosphere is its variability, both horizontally and vertically in pressure, regarding the following physical properties:

- Atmospheric pressure, which is defined as the weight of air in the column above unit area of the Earth’s surface. It is expressed in millibars, which are equal to 100 N/m^2.
- Temperature, which is the most controlling factor in meteorology. Change in temperature leads to density changes which cause vertical air movement and changes in pressure leading to horizontal air movements and winds.
- Humidity, which represents the amount of water in the air. As the water vapour is completely transparent it has to be measured. The amount of water vapour in a unit of air is called the absolute humidity. Water vapour can change to water droplets, liquid water and to ice. When and how this occurs, and the processes involved is germane to the formation of cloud and fog and to precipitation.
- Wind, which is the sustained movements of air from one place to another. The wind velocity reflects its speed and direction. Wind speed is given in knots.

Visibility is defined as the furthest horizontal distance that a dark object can be seen by an observer with normal eyesight. It is measured in meters at eye level above the ground. Thus, visibility reflects the clarity of air, or how obscured it is. Reasons for obscurity are in two categories; water and ice crystals in the air and solid particles such as dust, sand and smoke.

3.2 The impact of weather on aviation

Weather phenomena have a significant impact on aviation operation, from a safety point of view. Hazards generated by weather embrace a wide range of atmospheric conditions that can affect functionability of the air transportation process.

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[39] Gaspard de Coriolis (1792-1843), a French mathematician, mechanical engineer and scientist, who experimentally calculated the effects and mechanics of the Earth’s turning, in 1935 (Paris).

The most common weather hazards are briefly presented below:

- Thunderstorms; a natural phenomenon that are able to generate severe turbulence, strong winds, heavy rain, hail, and lightning strikes. These hazards pose risks to aircraft during takeoff, landing, and en route.
- Wind Shear; a natural phenomenon that is manifested as a sudden change in wind speed and/or direction, which can lead to unstable air conditions. It poses a significant risk during takeoff and landing, as it can cause sudden changes in airspeed and affect aircraft control.
- Fog and Low Visibility; a natural phenomena that reduce visibility and can lead to delays or diversions. In these situations pilots rely heavily on instrument landing systems and other navigation aids for safe operations.
- Snowstorms and Ice; a phenomena which if deposited on aircraft surfaces can affect aerodynamics and increase drag. De-icing procedures are crucial before takeoff and during the flight are applied to prevent affected aircraft performance.
- Turbulence; a natural phenomenon that results from strong air currents and is a common hazard during certain weather conditions. It can cause discomfort to passengers and crew and potentially lead to injuries if not managed properly.

4. Air Turbulence

Turbulence is caused by the relative movement of disturbed air through which an aircraft is flying. Its origin may be thermal or mechanical and it may occur either within or clear of cloud. The absolute severity of turbulence depends directly upon the rate at which the speed or the direction of airflow, or both, is changing[40].

Significant mechanical turbulence occurs from the passage of strong winds over irregular terrain or obstacles. Less severe low level turbulence can also be the result of convection occasioned by surface heating.

Turbulence may also arise from air movements associated with convective activity, especially in or near a thunderstorm or due to the presence of strong temperature gradients near to a Jet Stream.

Very localised, but sometimes severe, Wake Vortex Turbulence may be encountered when following or crossing behind another aircraft. This turbulence is due to wing tip trailing vortices generated by the preceding aircraft; however, this phenomenon is distinctively transient.

Air moving over or around high ground may create turbulence in the lee of the terrain feature. This may produce violent and, for smaller aircraft, potentially uncontrollable effects resulting in pitch and/or roll to extreme positions.

Relative air movements which involve rapid rates of change in wind velocity are described as wind shear and, when severe, they may be sufficient to displace an aircraft abruptly from its intended flight path such that substantial control input is required to compensate. The consequences of such encounters can be particularly dangerous at low altitude where any loss of control may occur sufficiently close to terrain to make

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[40] https://skybrary.aero/articles/turbulence

recovery difficult. The extreme down-bursts which occur below the base of cumulonimbus clouds called Microbursts are a classic example of circumstances conducive to Low Level Wind Shear[6].

For the purpose of reporting and forecasting of air turbulence, it is graded on a relative scale, according to its perceived or potential effect on a 'typical' aircraft, as Light, Moderate, Severe and Extreme.

- Light turbulence is the least severe, with slight, erratic changes in attitude and/or altitude.
- Moderate turbulence is similar to light turbulence, but of greater intensity - variations in speed as well as altitude and attitude may occur but the aircraft remains in control all the time.
- Severe turbulence is characterised by large, abrupt changes in attitude and altitude with large variations in airspeed. There may be brief periods where effective control of the aircraft is impossible. Loose objects may move around the cabin and damage to aircraft structures may occur.
- Extreme turbulence is capable of causing structural damage and resulting directly in prolonged, possibly terminal, loss of control of the aircraft.

In-flight turbulence assessment is essentially subjective. Routine encounters involve light or moderate turbulence, although to inexperienced passengers (or pilots), especially in small aircraft, these conditions may seem to be severe.

The perception of turbulence severity experienced by an aircraft depends not only on the strength of the air disturbance but also on the size of the aircraft - moderate turbulence in a large aircraft may appear severe in a small aircraft. Therefore, pilot reports of turbulence should mention the aircraft type to aid assessment of the relevance to other pilots in, or approaching, the same area.

5. Clear Air Turbulence

Clear-air turbulence is a common and hazardous form of turbulence for aircraft to encounter. It is invisible from the cockpit and undetectable by satellites and on-board weather radar. The International Civil Aviation Organisation (ICAO) defines it as turbulence generated in clear air, in regions without clouds, which is invisible to the naked eye.

The U.S. Federal Aviation Administration (FAA) defines CAT as “sudden severe turbulence occurring in cloudless regions that causes violent buffeting of aircraft”. CAT is higher altitude turbulence (normally above 15,000 ft) particularly between the core of a jet stream and the surrounding air. This includes turbulence in cirrus clouds, within and in the vicinity of standing lenticular clouds and, in some cases, in clear air in the vicinity of thunderstorms. The thunderstorms can generate CAT that extends 20 miles or more from the edge of an anvil cloud. This type of turbulence is sometimes referred to as Convectively Induced Turbulence (CIT).

5.1 Common causes and sources of CAT

Clear-air turbulence is generated by Kelvin–Helmholtz shear instabilities, which may be initiated by gravity waves in an otherwise stable shear flow. The spontaneous emission of gravity waves from balanced flow had historically been regarded as an unimportant source of atmospheric gravity waves. However, research led by Williams [3] showed that balanced flow spontaneously generates gravity waves at a much larger rate than previously thought – decaying to zero slowly (linearly) with the Rossby number[41], rather than exponentially. This evidence was obtained by analysing a novel laboratory experiment using a sophisticated flow visualisation technique, which allowed the spontaneous-emission process to be studied in unprecedented detail. These findings suggested that the spontaneous emission of atmospheric gravity waves could be an important, but previously unrecognised, source of clear-air turbulence.

The main four physical phenomena that cause clear air turbulence are briefly described below. Thus:

- **Jet Stream:** A narrow, fast moving current of air, normally close to the Tropopause and generated as a result of the temperature gradient between air masses. Although not all jet streams have CAT associated with them, there can be significant vertical and horizontal Wind Shear on the edges of the jet stream giving rise to sometimes severe clear air turbulence. Any CAT is strongest on the cold side of the jet stream where the wind shear is greatest. In the vicinity of a jet stream, CAT can be encountered anywhere from 7,000 feet below to about 3,000 feet above the tropopause. Because the strong vertical and horizontal wind shear occurs over short distances, this jet stream related CAT tends to be shallow and patchy so a descent or climb of as little as 2,000 feet is often enough to exit the turbulence.

- **Terrain:** High ground disturbs the horizontal flow of air over it, causing turbulence. The severity of the turbulence depends on the strength of the air flow, the roughness of the terrain, the rate of change and curvature of contours, and the elevation of the high ground above surrounding terrain.

- **Cumulonimbus (Cb)**: A heavy and dense cloud of considerable vertical extent in the form of a mountain or huge tower, often associated with heavy precipitation, lightning and thunder. The mature Cumulonimbus cloud has a distinctive flat, anvil shaped top with cells that have strong vertical currents. Aircraft passing within 20 nautical miles horizontally, or less than 5,000 feet above the top, of a Cb may encounter CAT.

- **Cyclogenesis:** The process of cyclone development associated with the development of extra-tropical cyclone and intensification. It is initiated by a disturbance occurring along a stationary or very slow-moving front between cold and warm air. This disturbance distorts the front into the wavelike configuration.

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[41] A dimensionless number relating the ratio of inertial to Coriolis forces for a given flow of a rotating fluid. Explicitly, the Rossby number is $R_o=U/fL$, where U is the velocity scale, f is the Coriolis parameter and L is the horizontal length scale. This number plays a fundamental role in defining the regime of large-scale geophysical fluid dynamics.

5.2 Observation and prediction of CAT

According to figures from the National Transportation Safety Board (NTSB), the flight crew had no warning in about 28% of turbulence-related accidents from 2009 to 2018 (see Appendix A).

Although turbulence can occur almost anywhere and at any height, some areas are known for being more susceptible. After an analysis of around 150,000 different flight routes, the turbulence prediction website Turbli found that the journey between Santiago, Chile and Viru Viru International airport in Bolivia to be the most bumpy, while the route between Almaty, Kazakhstan, and the capital of Kyrgyzstan, Bishkek, came in second on the list, which was released last year. Nashville, Tennessee to Raleigh/Durham in North Carolina was ranked as the North American route with the highest average turbulence.

5.3 Current "nowcasting" of turbulences

Existing weather forecasts models cannot predict turbulence at airplane-sized scales, and pilots frequently misreport turbulent locations by many dozens of miles. Hence, since 2005 the National Centre for Atmospheric Research (NCAR) in USA is currently developing more precise turbulence tools, named "nowcasting[42]". An algorithm currently installed on around 1,000 commercial airliners analyzes information from onboard sensors to characterise each plane's movement at any given moment. Using data on forward velocity, wind speed, air pressure, roll angle, and other factors, the algorithm generates a local atmospheric turbulence level, which is fed back into a national system every minute. Used in conjunction with national weather forecasts and models, the tool annotates forecasts with real-time conditions, which in turn helps to strengthen weather prediction models.

Meteorologists better understand the atmosphere now, and their computing ability has meant it is possible to provide better descriptions of turbulence. As, by its very nature, turbulence is so chaotic it requires a lot of computer power to be used in order to see what is actually happening.

Over 12,000 Delta Airlines pilots currently use tablets loaded with the tool to check conditions along their flight paths. In addition to the domestic planes currently equipped with the algorithm, international carriers including Qantas, Air France and Lufthansa will also join in. Also, Boeing has begun to offer the algorithm as a purchase option for new aircraft.

5.4 Future expectations of CAT

A study by researchers from Reading University, UK, reported that severe turbulence had increased by 55% in the past four decades due to the impact of climate change. [4] The report, published in June 2023, found that at an average point over the North Atlantic, which is one of the world's busiest flight routes, total yearly duration of severe turbulence had risen by 55% between 1979 and 2020.

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[42] The World Meteorological Organisation defines nowcasting as forecasting with local detail, by any method, over a period from the present to six hours ahead, including a detailed description of the present weather.

Williams' analysis [7] predicted that clear-air turbulence would increase significantly across the world in the coming decades. Typically, on a transatlantic flight, currently it is expected around 10 minutes of turbulence, while in a few decades this may increase to 20 minutes or to half an hour. Hence, the seat belt sign will be switched on a lot more, unfortunately for passengers, but for their and crew's safety.

6. CAT Mitigating Risks and Enhancing Safety Actions

As severe turbulence encounters have caused injuries to passengers and cabin crew the best practices, applying recommended techniques and procedures are developed to reduce the probability of risk of injuries. [6]

To ensure the safe motion of aircraft through the working process, the following measures are taken to address weather-related risks, namely:

- Weather Monitoring and Reporting: Air traffic control closely monitors weather conditions and shares critical information with pilots, which helps them to make informed decisions regarding flight routes, altitudes. [6]
- Technology and Tools: Advanced weather radar systems, satellite imagery and predictive models assist in detecting and tracking weather systems. These tools aid in better forecasting and provide real-time information to enhance safety. [5]
- Awareness: SIGMET[43] charts give forecasts of the location and level of clear air turbulence. Information on local terrain induced CAT may be contained in appropriate Aeronautical Information Publications. In addition, Electronic Flight Bag (EFP) applications provide pilots with tools that gather information on reported and forecast turbulence. An example is the Turbulence Aware platform from the International Air Transport Association (IATA). [5]
- Training and Education: Pilots and air traffic controllers undergo comprehensive training on aviation weather. They learn to interpret weather data, understand weather-related risks, and make informed decisions accordingly. [6]
- Pre-flight crew communication: Captains should brief flight attendants on expected timing and duration of forecast turbulence for incoming flights.
- In-flight crew communication: When pilots become aware of impending turbulence, they should let cabin crew know as quickly as possible. This can be done via interphone or through a public address announcement. If time is critical, a warning can be signalled by multiple chimes and/or flashing the seat belt signs.
- Suspension of Cabin Service: Obviously the serving of hot drinks and meals during turbulent conditions puts both cabin crew and passengers at risk. [6]
- External flight crew collaboration: Effective collaboration between pilots, air traffic controllers, and meteorological experts is crucial to address weather-related challenges. Clear and concise communication ensures that the latest weather information reaches all stakeholders. [5]

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[43] SIGMET stands for Significant Meteorological Information, and affect all aircraft related to the more severe weather conditions, which usually valid for 4 hours.

7. Conclusion

Clear air turbulence is one of the meteorological hazards that present significant problems to flight safety. While technology and advanced meteorological information have contributed to improved weather forecasting and risk management, it remains ever present and requires constant attention. Thus, the main objective of this paper was to understand physical mechanisms that generate the occurrences of clear air turbulence and assesses their impacts on the motion of aircraft through MIRCE Space and consequential impact to functionability trajectory generated.

The available methods for dealing with this imposing functionability action in respect to the provision of aviation safety and protection are also addressed in the paper. In essence, the effective collaboration between meteorologists, pilots, air traffic controllers and airport authorities is crucial to ensure the safety of aviation operations. Through ongoing research, advancements in technology and continuous training, aviation can strive to minimize the risks posed by meteorological hazards and maintain the highest levels of safety.

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Appendix A: Observe Clear Air Turbulence generated functionability events

- On 25th February 2015, a Boeing 737-800 encountered severe clear air turbulence as it crossed the Pyrenees en-route, south southwest of Toulouse France. Due to serious injuries sustained by two cabin crew the flight was divert to Bordeaux.
- On 5th December 2021, an Airbus A350-900 in vicinity Cayenne French Guiana encountered a very brief episode of unexpected CAT. Not having had prior warning, the senior cabin crew member fell and was seriously injured.
- On 16th January 2022, an Airbus A320 near Okayama Japan was in cruise when experienced, very briefly, CAT. Despite being secured in a seat, one passenger sustained a serious injury resulting in hospitalisation with a broken rib.
- On 17th January 2021, a Boeing 777-300 which had just begun descent into Beirut encountered unexpected moderate to severe clear air turbulence which resulted in one major and several minor injuries to unsecured occupants including cabin crew.
- On 17th January 2021, a Boeing 777-300, en-route north northwest of Tanegashima Japan, encountered unexpected moderate to severe CAT just as begun descent into Beirut. It resulted in one major and several minor injuries to unsecured occupants including cabin crew.
- On 28th May 2021, a Boeing 767-300, encountered unexpected moderate to severe CAT while climbing over central South Korea. A serious injury occurred to one of the cabin crew who was unable to return to her crew seat and secure herself due to short notice that turbulence risk would increase from moderate to severe.
- On 10th July 2019 an Airbus A380-800, en-route to Bay of Bengal India in the cruise at night encountered severe CAT approximately 13 hours into the 17

hour flight. 27 occupants were injured as a result, one seriously. The detailed Investigation concluded that the turbulence had occurred in clear air in the vicinity of a significant area of convective turbulence and a jet stream

- On 13th February 2019, a Boeing 737-800, en-route over the southern Adriatic Sea unexpectedly encountered severe CAT resulting in injuries of two unsecured cabin crew and some unsecured passengers, which were thrown against the cabin structure and sustained minor injuries.
- On 2nd February 2020, an Airbus A380, en-route to Wyoming, USA, in the cruise encountered unforecast CAT with the seatbelt signs off and one unsecured passenger in a standard toilet compartment sustained a serious injury as a result.
- On 21st August 2019, an Airbus A340-600, en-route, northern Turkey, encountered sudden-onset moderate to severe CAT resulted in a serious passenger injury

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