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Handling of external risks, including launch and re-entry events, in the aviation and maritime sector

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ABSTRACT

An important part of a flight safety analysis for launch and re-entry events is to ensure safety to air and sea traffic, and maritime infrastructure. Thus, hazard areas are defined based on a risk assessment and risk criteria. Traffic impact depends on size and duration of those areas. Current risk criteria for air and sea traffic as well as maritime infrastructure are reviewed in this paper. Furthermore, this paper will take a closer look on other external risk factors in the aviation or maritime sector. The paper analyses their influence on aviation and maritime operations together with its associated safety measures and compares them with the risk posed by space vehicles. Understanding these relationships can support the conduct of safe space operations and efficient integration of space activities.

1. Introduction

Launch and re-entry events disrupt air and sea traffic and pose a hazard to people on board. Considering the expected increase of operations, it is important to implement more effective procedures to minimize traffic impact. At the same time safety has to be ensured. Both are especially important for launches in areas with high amount of air and/or sea traffic, like Europe or East Asia.

At first current safety procedures for launch and re-entry events are briefly described, including an overview of necessary safety measures according to the East Asian countries with orbital launch capability. The focus is hereby on launches and controlled re-entries. Due to the challenge of predicting the time and location of an uncontrolled re-entry with sufficient precision, standard procedures for uncontrolled re-entries do not yet exist. Exemplary is the airspace closure in parts of Europe as reaction to the re-entry of the Long March 5B first stage in 2022 [1]. The real impact location was located in the Pacific near the Mexican Coast [2].

In a next step, handling and information exchange of other external risks to air and maritime traffic are reviewed. External risk hereby describes a risk over which air and maritime stakeholders have no direct control over, like extreme weather. It means the hazard itself cannot be changed only be avoided or consequences being reduced. Relevant aspects are the hazard type, observation and communication of the hazard, and safety and mitigation measures. Maritime infrastructure is included and discussed, as it might be at risk as well, depending on the launch site.

Procedures for launch and re-entry hazards and other external risks are then compared and discussed. Measures in place for external risks are analyzed regarding transferability to launch and re-entry risks to work out potential areas for improvement regarding handling and communication.

2. Integration of launch and re-entry activities into air and sea traffic

Protection of the general public during launch and re-entry events is achieved by spatial separation through the establishment of danger, restricted or prohibited areas, in general called Hazard Areas (HAs). These areas are based on a thorough risk assessment, generally resulting in high risk areas in launch pad / landing area vicinity and regions of planned debris impact (e.g. jettisoned stages, fairing) necessitating the installment of HAs. Risk mitigation in these HAs can be achieved by restricting or prohibiting access, when on national territory or national airspace. In international waters or airspace, only danger areas can be designated, informing potential users about the hazard, without being able to regulate access to these areas. An example of HAs is illustrated in Fig. 1.

Prior to launch/re-entry the operator needs to ensure that the pre-determined HAs are empty. Regarding safety of people on the ground, launch/re-entry sites are generally located close to open

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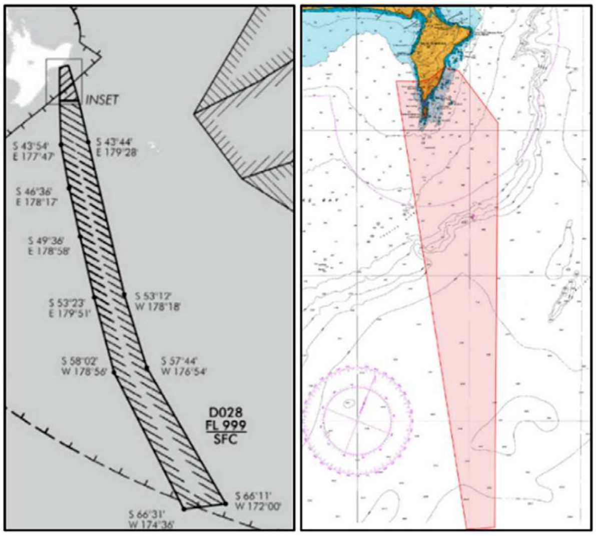

Fig. 1. HAs for air (left) and maritime (right) traffic for a Rocket Lab test launch from the Mahia Peninsula, New Zealand in 2018 [3].

water and/or in remote areas. Evacuation of nearby settlements can thereby be avoided, increasing safety and simplifying mitigation measures. For the same reason flight time over inhabited areas is reduced as much as possible.

Air and sea traffic are negatively influenced by launch and re-entry activities and related safety measures as they need to reroute to avoid HAs. Nevertheless, a more proactive reaction is possible than regarding fixed settlements. The integration of launch and re-entry operations into air and sea traffic are further discussed in this chapter, with emphasis on the risk criteria used to define the necessary HAs, communication of the determined areas and the integration into traffic management procedures.

2.1. Risk criteria

To determine HAs based on a risk assessment, it is necessary to define which risk is acceptable and where additional risk mitigation measures, like HAs, are necessary. At the same time the area dimensions depend on the risk criteria. An overview of different risk thresholds is presented in previous work of the author [4]. Missing, and therefore object of this chapter, are risk criteria of East Asian nations that are capable of orbital rocket launches.

2.1.1. Japan

A launch plan including a plan to ensure public safety is necessary to get a launch permit in Japan [5]. The launch plan must include a disaster prevention plan, areas of restricted access and communication plans to inform air and sea traffic about the launch activity [6]. In the *Guidelines on Permission related to launching of Spacecraft etc.* [7] contents of the launch plan are further defined. Regarding vessels all areas with an individual probability of debris impact larger or equal to 1×10^{-5} require access restrictions. The hazard areas for aircraft must at least cover the ground and ship hazard areas. Planned impact areas have to be communicated to air and sea traffic. Additionally, the Expected Casualties (E_C) should be determined. E_C is a collective risk measure, describing the expected number of casualties from a single mission. The method to determine the E_C is further described in the *Conditions and Methods for Calculating Expected Casualties* [8]. Supplementary to a described method to calculate Ec, based on the Federal Aviation Administration (FAA) Flight Safety Analysis Handbook, an overview of international criteria for the Ec is given.

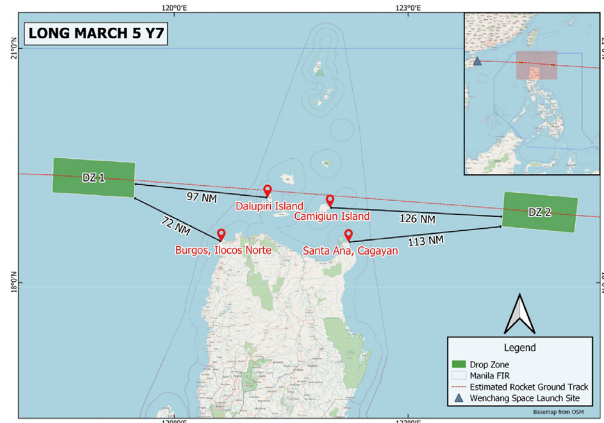

Fig. 2. Drop Zones for a Long March 5 launch from Wengchan, Hainan. The Drop Zones are located near the Philippines. The Philippian space agency contacted affected government agencies and authorities to inform them about the hazards in these areas. [12].

Regarding controlled re-entries, an impact area needs to be defined and air and sea traffic must be informed about it. Coastal areas, exclusive economic zones (EEZ), traffic and offshore plants should be avoided. [9]

2.1.2. People's Republic of China

The application for a launch license in China must include a Safety Design Report, describing the hazards to the public and relevant measurements to reduce them [10]. Further refinement of the contents of a Safety Design Report is not included. Nevertheless, information of HAs for aircraft and sea traffic is communicated prior to launch. An example of such HAs is illustrated in Fig. 2. The Civil Aviation Authority of China recommends that safety measures are taken to protect air traffic passing through these areas [11].

2.1.3. Republic of Korea

According to the *Space Development Promotion Act [13]* launching from the territory of the Republic of Korea or a launch of a vehicle owned by the Government or a citizen of Korea requires a permission by the ministry of science and ICT. The application must include a launch plan and a safety analysis report. Latter includes a description of measures to ensure safety of the launch vehicle and the launch pad [14]. No explicit risk criteria are mentioned either in the act itself or in the associated enforcement decree.

The flight safety analysis [15] for the first test flight of the KSLV-I in 2009, was based on the flight safety analysis methods of the FAA. For the maritime area near the launch pad an individual risk criterion for a debris impact on a vessel is set to 1×10^{-5} and a safety margin of 9 km is added. Regarding the risk to air traffic a 10 km buffer is added in all directions to the maritime hazard area. The aircraft velocity is the reason for the increased aircraft HA [16]. Additionally, for the third test flight areas around the planned impact side of the first stage and fairing were published as HAs and inhabitated islands near the launch trajectory were evacuated [16]. The Launch Safety Control Plan for the first KLSV-II launch [17] seems to be based on similar risk criteria.

2.2. Communication and integration of launch and re-entry activities

In case air and sea traffic is informed in time about upcoming launch and re-entry activities they react via re-routing the traffic around the designated hazard areas. In case of a non-nominal event during launch and re-entry, air traffic is able to faster leave a potential hazardous debris area than maritime traffic, due to its higher velocity. On the other hand, the aircraft speed increases its vulnerability to debris and the operation altitude shortens the response time. Maritime traffic may take longer to abandon hazardous areas resulting of non-nominal events, but the risk itself is potentially smaller than the one to aircraft.

2.2.1. Air traffic

According to *ICAO Annex 15* [18] Notice to Air Missions (NOTAM) shall be used to communicate hazards to aircraft like rocket launches or rocket debris. NOTAM should be issued at least seven days in advance [19] and are therefore only feasible for communicating pre-determined HAs. In practice, NOTAM may be published with less lead time, e.g. only two days in advance [11]. Hazard areas can be [20]:

- Prohibited Areas: All flights are prohibited of these areas. Must be located above land or territorial waters.
- Restricted Areas: When complying with specific conditions flights in this area may be authorized. As with prohibited areas only above land or territorial waters.
- Danger Areas: Information about potential hazards to aviation. Operators and pilots decide if they risk entering the area.

To correspond with prohibited and restricted areas, air traffic is re-routed. Regarding danger areas related to launch and re-entry activities re-routing is also best practice. In case one of the designated aircraft hazard areas are not clear of air traffic the space operations are set to hold to stick to the safety management plan. Following non-nominal events current best practice is to inform responsible air navigation service providers about endangered areas via hotline connection [21].

2.2.2. Maritime traffic

Hazard areas for maritime traffic may be communicated via Notice to Mariners (NOTMAR) and navigational warnings. NOTMAR are used to ensure safety of life at sea, updating nautical charts. They contain information about objects or events that pose a direct hazard to maritime traffic and people on board [22]. Navigational warnings contain information of more immediate hazards. After six weeks, when there was enough time to issue NOTMAR, navigational warnings are not necessary anymore. In general, navigational warnings inform maritime users about navigational hazards, to ensure safe navigation. This includes information that may threaten vessel safety like a space mission [23].

As in aviation, restricting access is only possible within territorial waters [24]. Similar is also the best practice to re-route traffic to avoid the areas issued via NOTMAR and navigational warnings. Nevertheless, there are several examples (see [25,26]) of delayed rocket launches due to vessels being present in active hazard areas. For real time communication of potential hazardous events and affected areas, a hotline is used [27].

Maritime infrastructure may be passed by trajectories and are therefore at risk. If possible, it should be ensured, that there is no maritime infrastructure present in the designated HAs. If this is not possible, risk mitigation measures should be installed to protect workers. Additionally, environmental risks should be carefully addressed before the launch and re-entry operation takes place. As example, NASA expressed its concern about potential new drilling areas in the Atlantic in 2015 [28]. They worried about meeting safety criteria for launches from the Wallops Flight Facility. Back in 2002 the impact location of a Titan IV B booster was estimated to be near Canadian oil rigs, resulting in a plan to evacuate them. Evacuation was called off, when risk assessments showed very low impact probability [29]. Both examples show that safety of maritime infrastructure should be considered for launch and re-entry activities.

3. External risks for aviation

There are multiple hazardous effects that pose a risk to aviation, other than launch and re-entry operations. Emphasis in this chapter is on external risks, meaning risks which aviation stakeholders (e.g. pilots or air traffic controllers) do not have an influence on. While risk mitigation and avoidance are possible, the risk itself stays unaffected.

3.1. Extreme weather

Around 70% of delayed air operations are due to weather [30]. Weather delays are influencing the efficiency of flight operations, but extreme weather may also pose an in-flight risk [31]. While aircraft are designed to withstand extreme weather conditions [32], people on board can be hurt and the aircraft itself can be damaged [33]. Therefore, extreme weather is avoided by commercial airliners. For example, a rule of thumb is to keep a minimum distance of 20 NM to a storm cell [34].

Regarding en-route weather, there are two types of messages to communicate relevant information to pilots, operators and air traffic controllers. One describes predicted weather, while the other informs about weather observations.

3.1.1. Weather predictions

In accordance with *ICAO Annex 3* [35] there are World Area Forecast Centres that prepare weather predictions, which includes predictions of significant weather (SIGWX). These SIGWX messages are valid for 24 hours and are issued for moderate or severe icing, moderate or severe turbulences or cumulonimbus clouds.

3.1.2. Weather observations

Responsible for the observation of current weather and issuance of significant meteorological phenomena (SIGMET) is the Meteorological Watch Office (MWO). SIGMET are used to communicate en-route weather and potentially dangerous weather phenomena. They are valid for a maximum of six hours and should be published not more than four hours in advance. Included in a SIGMET is information about the area of thunderstorms (e.g. frequent) or turbulences etc. Responsibilities and contents of SIGMET are described in [35]. Air reports of pilots about encountered weather inflight are an important source of information for creating a SIGMET [36].

Both types of weather information messages should be shared with pilots, operators and air traffic services [35]. Close cooperation between air traffic services and MWOs should be established, enabling fast transmission to the aircraft [36]. Based on weather predictions air traffic control can start to re-route flights to avoid encountering potential hazardous weather, while the pilot may use the predictions to prepare for potential encounters [31]. Observation enables the aviation stakeholders to evaluate the current situation and take a well-informed decision, in case of extreme weather phenomena. If possible, the weather is avoided or in case of an encounter measures to mitigate the risk can be taken.

3.2. Discussion of risk of extreme weather for aviation

Weather is difficult to predict and may change very quickly. Hence, weather predictions, like the ones in SIGWX, are only viable for a rather short period of time. Risk of launch and re-entry operations on the other side can be assessed in advance, including uncertainties. Therefore, hazard areas can be issued via NOTAM days in advance. Hence the concept of communicating HAs, described in Section 2.2, cannot be compared to the concept of communicating extreme weather.

Weather effects on air traffic are more comparable to the risk of non-nominal events of space activities, rather than to the pre-mission safety aspects.

In case of a non-nominal event during a launch or re-entry current best practice is to inform air traffic control via hotline. Air traffic control then communicates with the pilots to redirect endangered aircraft to safe areas. In the case of extreme weather, it is up to the pilot to decide whether or not to avoid the weather. To support decision making, the pilots are provided with prediction and observation information of the weather and are supported by air traffic control. The pilots' experience and familiarity with extreme weather contributes to their assessment of the hazard. Further, aircraft are designed to withstand even extreme weather.

Pre-calculated and real-time HAs are based on a quantitative risk assessment and risk thresholds. In addition, the pilots lack familiarity with the hazards of launch and re-entry activities. Therefore, relieving the pilot of the responsibility for evaluating the associated risk may be the preferred option. Unlike with extreme weather, there should be no evaluation of the pilot or air traffic control on which areas to avoid. Nevertheless, close cooperation between both is required to vacate affected areas as quickly as possible.

To maximize safety in non-nominal situations, air traffic control and pilots, should be informed in real-time about the hazard and its development. Similar like SIGWX and SIGMET provide the latest weather information. This enables pilot and air traffic controller to assess the situation and take the right action to reduce the risk. At the same time thorough information about the hazard, can help the air traffic controller to manage other aircraft nearby, but not within the hazard area. This can reduce the consequential risk from sudden re-routes and trajectories to exit the hazard area.

Short term information on launch day, additionally to the HAs issued by NOTAM, like the predictions in SIGWX, can help to increase situational awareness of the air traffic controller and pilot. For example, the aircraft might carry more fuel. This does not affect the direct risk by the launch and re-entry operation, but the potential follow-up risk of fuel shortage due to re-routing can be reduced.

More real-time information, like included in SIGMET for weather, can help aviation stakeholders to react more quickly to potential changes in the flight plan or even flight cancellations reducing the negative impact rocket launches may have on air traffic.

In general, the provision of more detailed information immediately before and during launch and re-entry could enable a more dynamic reaction of air traffic, in particular to non-nominal situations. A more dynamic response may also reduce the impact short-term cancellations or delays of launch activities have on air traffic. A system to regularly provide the latest information is already used in the aviation sector to communicate extreme weather conditions.

3.3. Volcanic ash

Encounters of volcanic ash can result in engine malfunctioning or failure, increased erosion, or blockade of static sensors [37]. Volcanic ash is a considerable threat for safe aviation operation and can cause large disruptions to air traffic. Before the eruption of Eyjafjallajökull in 2010, volcanic ash areas were completely avoided by aviation. Due to the wide spread and large impact on air traffic of the eruption, procedures were developed to enable flight through volcanic ash under certain requirements [38].

Volcanic ash advisory centers (VAACs) are providing information about the volcanic ash and its distribution [39]. They also model the ash development to include predicted ash concentrations and ash movements [40]. Air traffic control functions as the critical link between VAACs and aircraft [37].

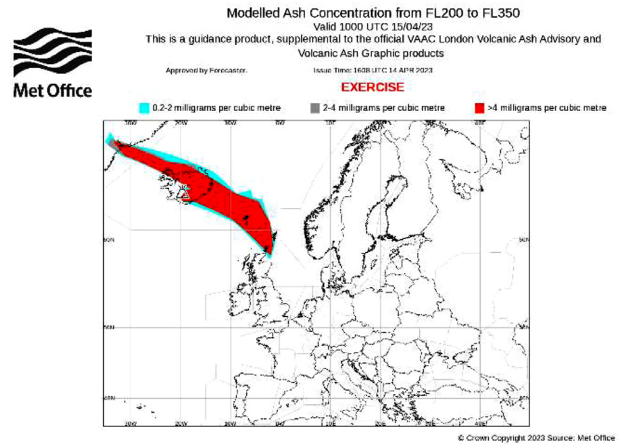

Fig. 3. Exemplary ash concentration chart by the UK Met-Office for an eruption of an Icelandic volcano [41].

The type of message and distributed information regarding volcanic ash are described in the *ICAO Volcanic Ash Contingency Plan EUR and NAT regions* [37]. Information about volcanic ash is regularly issued by the VAACs in volcanic ash advisories (VAA) or volcanic ash graphics (VAG). MWOs use this information to prepare SIGMET. For significant changes in the ash concentration and/or distribution also NOTAM, referencing to VAG or SIGMET, may be published by responsible NOTAM offices. The European VAACs (London and Toulouse) additionally issue volcanic ash concentration charts, see Fig. 3, containing multiple polygons marking areas with different level of ash contamination. These are valid for six hours and can be published for different flight levels. The ash concentration levels are:

- Low contamination: ash concentration greater or equal to 0.2 mg/m³ and smaller or equal to 2 mg/m³ (cyan in Fig. 3)
- Medium Contamination: ash concentration greater 2 mg/m³ and smaller 4 mg/m³ (gray in Fig. 3)
- High Contamination: ash concentration greater or equal to 4 mg/m³ (red in Fig. 3)

The concentration threshold levels were determined in a joined effort between Rolls Royce, the UK Met-Office and international and European regulators [38]. Analysis of a gas turbine engine showed ash concentrations up to 2 mg/m³ to be safe and everything above approximately 80 mg/m³ as unsafe [42]. Further research, see [43], proposes to account for the time spent in volcanic ash by setting a limit for an acceptable ash dose an engine withstands, but currently only for ash concentrations not surpassing 4 mg/m³. Further, flight in concentrations lower than 0.2 mg/m³ pose no hazard regardless of time of exposure.

The German air traffic control permits flights in high contamination areas, although exceptions are possible. For flights in medium contaminated areas, mandatory inspections and maintenance measures have to be performed. Flight in low contamination areas is possible without any further measures [44]. In case of an encounter of hazardous ash concentrations, emergency procedures like reducing thrust should be initialised [37].

3.4. Discussion of risk of volcanic ash for aviation

There are some similarities in handling volcanic ash and launch and re-entry operation. For both hazards NOTAM might be issued and in both cases another way of transmitting more time critical information is necessary. While for volcanic ash there are multiple ways e.g. ash concentration charts, real-time information of hazards resulting of a non-nominal launch or re-entry event are currently communicated using a hotline.

The areas communicated are either based on pre-determined deterministic threshold values of ash or on a probabilistic casualty risk assessment. However, regarding ash concentration charts, three different areas are communicated divided by the hazard level. The main purpose of communicating the low contamination area is to increase situational awareness, as there are no flight restrictions. On the other hand, entering high contamination areas is prohibited, at least in Germany.

In space operations, as discussed in Section 2.1, there is only a distinction between safe and hazardous areas. Applying the concept of various ash concentration levels to space operations, would result in the classical HAs, which should be avoided, surrounded by lower risk areas. Aviation users would be informed about a risk present in these areas and could then, considering other factors, decide if they want to take the risk or not.

Such information can be communicated prior to a mission. Thereby, it can be included in flight planning. Communicating different levels of risk can also be beneficial for the reaction to non-nominal events. By not only distinguishing between safe and unsafe, the risk can be compared with other potential risk resulting out of the avoidance of areas at risk, such as mid-air collisions or fuel shortages, to determine the safest route.

Mandatory inspections, when flying through a debris fall area, could prove useful. Similar to those prescribed following exposure to medium volcanic ash concentrations. Additionally, exposure time could be factored in when assessing flight risk, comparable to the ideas regarding ash dose. There is already some research (e.g. [45,46]) looking into similar concepts for launch and re-entry HAs to reduce air traffic impact.

Regarding other products to inform about volcanic ash, differentiating between flight levels is something not yet performed for HAs of space operations. Nevertheless, this could further reduce air traffic impact as debris dispersion increases with decreasing altitude. The affected areas from debris fall are therefore smaller at higher altitudes.

Increasing the complexity of HAs, for example by including different risk levels and considering the change with altitude, would benefit from communicating the information on a map, such as the one in Fig. 3. Hazard area predictions like for example in VAGs is less practicable for launch and re-entry activities.

4. Maritime external risks

Similar to aviation, weather is the main external risk regarding maritime traffic and infrastructure. Entailed to extreme weather are often extreme wave conditions. Other external risk factors can be ice or icebergs and for fixed offshore installations earthquakes.

4.1. External risks to shipping

The *Guide to Marine Meteorological Services* [47] by the World Meteorological Organization (WMO) describes the hazard meteorological phenomena can have on shipping. According to them, information about wind and wave conditions are the two most critical for maritime traffic. Both can cause significant structural damage and especially waves can negatively influence ship handling. Whether current conditions are critical for safety strongly depends on the size and type of the vessel. Other risks are bad visibility (collision danger), thunderstorms and tropical cyclones. Additional hazards in polar regions are associated with sea ice, which may result in damage and reduced handling, and icebergs. Latter are a major thread for all kinds of vessels.

Information about the weather, weather forecasts, and wave and ice information should be made available on a daily basis to protect life at sea [48]. At the same time ships have to report hazardous conditions. Weather information service is provided by the Worldwide Met-Ocean Information and Warning Service (WWMIWS) [47] and is issued using weather bulletins. These are divided into three parts [49]:

- Warnings: necessary for hazardous winds (larger than seven on the Beaufort scale), tropical cyclones and other potentially hazardous conditions
- Synopses: most important weather conditions including their movement
- Forecasts: forecast of relevant weather conditions and long-term weather prediction (exceeding 24 h)

Due to the hazards of weather to ship traffic, it is advised to include available information into route planning, called weather routeing [50]. This increases safety and may increase efficiency (reduced crossing time, less fuel consumption) as well [47]. A ship routing agency, a service offered by many countries, provides route recommendation using forecasts and historical weather data. Real-time route adaptions and information about approaching hazardous weather are part of the service, too [51].

Although taking precautionary measures, encountering bad weather cannot always be avoided. Hence, withstanding regularly appearing weather conditions, eventually for multiple days, is included in the ship design [47]. Another mitigation measure is providing guidance, as in [52], on how to avoid dangerous conditions when experiencing extreme weather. Examples would be speed reduction or change of course. Forecasts can help the crew to initiate such precautionary measures, as cargo securing etc. can take multiple hours [47].

Information about other temporary hazards are issued by navigational warnings. As already mentioned, this includes space debris but also drifting hazards, acts of piracy, presence of dangerous wrecks or establishment of offshore structures [23]. Other dangers, like icebergs, tsunamis or abnormal changes to sea, are communicated using navigational warnings as well, and are supported by the WMO [49]. The warning should contain all information necessary to enable the receiver to assess the situation. At minimum hazard and position have to be described [23].

Planning ship routes includes the afore mentioned weather routeing and consideration of the navigational warnings and NOTMAR, supplementary to up-to date charts [50].

4.2. Discussion of external risks to shipping

Naturally, the characteristics of hazardous weather for shipping are the same as for aviation. The main difference is the time factor. Ships are considerably longer en-route and therefore planning further ahead is much more important. This can be also seen by the time span of weather forecasts, and the fact historical weather is also used for ship route planning. Concerning launch and re-entry operations this means the procedure by publishing NOTMAR or navigational warnings for predefined HAs in time, should be sufficient for route planning. However, this means for maritime traffic it is important, that the NOTMARs and navigational warnings are published with sufficient lead time to be effective.

At the same time, ships are much more prone to suddenly appearing hazards, as they are much slower. This transfers to the risk non-nominal events pose. While aircraft can leave the resulting hazard area rather quickly, ships may encounter the risk for a much longer duration. Therefore, it is important that the crew is well informed about the risks and can initiate preparational procedures accordingly. One possibility would be to create guidance documents, similar to ones on avoiding dangerous situation in adverse weather.

The risk from falling debris can be quantified, whereas the risk from weather events is difficult to quantify. While in international waters ships cannot be prohibited from entering areas where the risk exceeds the risk thresholds, ships should be aware of the risk and potential consequences. Only by avoiding these areas a certain level of safety can be achieved.

Informational sessions to increase the familiarity with the risk space operations pose could be one possibility to do so. While bad weather is more or less daily business for seamen, launch and re-entry events and resulting debris are rather new and unknown hazards. Changing that may increase safety and awareness in the shipping industry. To mitigate the risk further an advisory service, like for weather routing, for affected vessels may prove useful as well.

The risk of external hazards to a vessel strongly depends on the size and vessel type. Therefore, a considerable dangerous situation for one ship may be of no concern for another one. This could be used to reduce maritime traffic disruptions by considering different HAs depending on ship category and communicating them appropriately. Multiple HAs could be provided depending on certain ship types and their characteristics. This is already partially done for example by the FAA [53], but mainly to calculate the expected casualties. The concept would be similar to providing several HAs at different altitudes for air traffic.

4.3. External risks to maritime infrastructure

Maritime infrastructure differs from shipping as they are either stationary or mobility is greatly limited. Therefore, avoiding external risks should be considered when choosing the location, as far as possible. Alternatively, the structure has to be designed to withstand the hazards. Main hazards are extreme weather, earthquakes, ship collisions and helicopter accidents [54]. The focus is on maritime oil and gas infrastructures as they are generally manned and can pose a significant environmental threat.

With regard to extreme weather conditions, the design must be able to tolerate weather conditions that frequently occur. One threshold is the design for weather conditions with a frequency of appearance above 1×10^{-4} times per year [54]. In case of forecasted weather events exceeding the design limits, some preparational measures can reduce the risk of damage. The resilience of oil rigs, for example, can be considerably increased by facing the storm [55]. Another measure is to evacuate the personal and shutting down fixed platforms, while rigs are moved to safer waters [56].

Regarding risk due to earthquakes, the design criteria are similar. The structure must be able to withstand two different earthquake intensities. The first one is the probable maximum intensity during a period of 200 to 500 years. The second one is the highest realistic intensity the structure could face depending on the location. While the first one should be elastically absorbed, when encountering the second one collapse should be avoided [57]. Another threshold would be, as with hazardous weather conditions, the ability to withstand all ground movements occurring 1×10^{-4} times a year [54].

Other hazards are the collision of a ship or helicopter with the structure. Helicopters are often used to transport workers [54]. The risk of a helicopter collision is rather low [58]. At the same time the heliport area is designed to survive helicopter impacts and evacuation afterwards is normally not necessary [54]. Regarding ship collisions, impacts of smaller supply vessels are considered in the design process [59]. This is done by setting impact energy thresholds or exemplary impact conditions of ship mass and velocity to be designed against [60]. As security measures against bypassing vessels, safety zones can be declared within an exclusive economic zone of up to 500 m around the installation [24]. Ship collisions are, as helicopter accidents, rather rare [58].

4.4. Discussion of external risks to maritime infrastructure

Issuing HAs and expecting them to be cleared is often not possible and can be associated to rather significant costs for the operator of the infrastructure. Therefore, trajectories surpassing maritime oil and gas infrastructure should be avoided if possible. This holds especially for potential infrastructure in HAs.

In case avoidance is not feasible, as with other external risks for maritime infrastructure, the hazard should be thoroughly assessed and compared to other design criteria. These are often referring to the probability of a certain event occurring and hence comparable to individual risk criteria for launch and re-entry events.

While for a certain location the probability of extreme weather or an earthquake cannot be changed, the probability that it results in a certain consequence can. Oil and gas platforms are therefore designed to withstand the majority of such events. Similarly, the probability of a debris impact on static maritime infrastructure cannot be changed without changing the launch or re-entry characteristics. Therefore, the design criteria should be compared to the potential debris impacts.

Maritime oil and gas infrastructure are designed to withstand heavy loads like those of helicopter impacts or ship collisions. Structures and subsea arrangements are additionally designed for falling and impacting loads [54]. Most of the non-nominal event debris is light and small and should not be a considerable hazard to the structure itself. Nevertheless, workers should be informed to enable them to seek shelter. Hazards posed by potential larger debris and explosives should be assessed and carefully considered against the design criteria. In case the design criteria are not sufficient to meet the risk thresholds, the operator should be informed to allow for shutdown and evacuation if necessary. This is sometimes done to ensure crew safety and minimize damage in the event of extreme weather.

5. Conclusion

The current procedures to inform air and maritime traffic about launch and re-entry events are described in Section 2. For launches and/or re-entries, a license or permit is necessary. Part of the application process is to show that measures are taken to protect people on the ground, as well as air and maritime traffic. In Japan and Korea probabilistic risk criteria are used to define hazard areas. These are issued via NOTAM, NOTMAR and navigational warnings and must be clear of traffic during the space operation. Communicating potential endangered areas in case of a non-nominal event is done by hotline.

Procedures and messages in place to communicate other external risks like extreme weather, volcanic ash for aviation or drifting objects for shipping were briefly described and compared to current procedures for launch and re-entry activities in the foregoing chapters. The pre-operational phase of space missions is relatively aligned to communication of other external hazards. However, as the risks of space operation have no natural cause, aviation and maritime stakeholders should be included in the planning phase to minimize impact on traffic and ensure maximum level of safety. The same holds for operators of maritime infrastructure at risk by the launch.

Multiple HAs for different flight levels or communicating multiple areas of different risk levels may improve integration of launch and re-entry events. Issuing several altitude or risk dependent hazard areas is already done for volcanic ash. Regarding shipping, HAs depending on ship type might be issued, as vulnerability can vary greatly. This is comparable to the ability of ships to withstand extreme weather, which is also highly dependent on ship characteristics.

Larger differences exist in communicating real-time hazards. Meteorological offices are in close contact to aviation and maritime stakeholders. Weather observations and forecasts are constantly communicated with aviation and maritime stakeholders using a variety of different messages. Hence, appropriate decisions can be made and pre-cautionary measures can be taken. Hazards due to a non-nominal event during launch or re-entry are less well communicated. Paired with the novelty and unfamiliarity of the risk of space vehicle debris, missing information can lead to bad decisions and considerable follow-up risk. While information overload should be avoided, providing the relevant stakeholders with relevant information at the right time would increase safety and could increase efficiency as well.

For instance, situational awareness of air traffic controllers can be improved by keeping them informed about the current mission status. The controllers could notice deviations from the nominal case and take precautionary measures, preparing for a subsequent non-nominal event.

This example illustrates the benefits of improved information sharing. Improved awareness and anticipation might add valuable time to leave hazardous areas or initiate risk mitigation measures. Latter is especially important for ships and maritime infrastructure as exiting the hazard areas might not be possible. For that case, guidelines to reduce debris impact risks might prove useful.

In comparison to information exchange and handling of other external risks to aviation and shipping, both can be improved for launch and re-entry events. The procedures in place regarding nominal hazards enable route planning and preparation but could be improved to reduce traffic impact. Research for new concepts of air traffic HAs can be found in [45] and [46]. Close communication between aviation and maritime stakeholders and the launch and re-entry side would improve safety regarding non-nominal events. This includes sharing relevant data as quickly as possible, optimally in real-time. Having these kind of information enables aviation and maritime stakeholders to increase situational awareness and consequently taking the right decision to minimize risk and improve safety.

Within this context, the German Aerospace Center (DLR) currently develops a “Launch Coordination Center” [61] to improve information sharing, in pre-mission phase, during the mission and afterwards. Moreover, the FAA is working on a “Space Data Integrator” to enhance information exchange [21]. The ECHO 2 project (European Concept for Higher Airspace Operations), part of the SESAR 3 research and innovation program for the digitalization of European skies, is looking into this topic as well [62].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Tobias Rabus: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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