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The Journal of Space Safety Engineering (JSSE) provides an authoritative source of information in the field of space safety design, research and development. It serves applied scientists, engineers, policy makers and safety advocates with a platform to develop, promote and coordinate the science, technology and practice of space safety. JSSE seeks to establish channels of communication between industry, academy and government in the field of space safety and sustainability.

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IMPROVED RANGE SAFETY METHODOLOGIES FOR LONG-DURATION HEAVY-LIFT BALLOON MISSIONS OVER POPULATED REGIONS

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ABSTRACT

This paper reviews the development of a new probabilistic risk methodology that has been developed to address concerns raised by long-duration fatality level exposures to aircraft and ground-level receptors from long/ultra-long duration balloon (U/LDB) flights. The methodology addresses risks during the launch and ascent to float phase, and for any float manoeuvres and planned descent and recovery operations. It is computationally feasible in that it allows for T-1 day or even day-of-launch risk assessments to be generated within a few hours so as to accommodate the most favourable launch conditions. This capability minimizes risks to people and infrastructure while simultaneously expediting the launch go/no-go decision process because deterministic limit exclusion areas are replaced with risk-informed information. The methodology has been successfully applied to NASA’s LDSD 2015 Campaign, notional elements of which are used as a demonstration.

1. INTRODUCTION

Range safety methodologies for scientific and military testing are typically designed for rocket-borne missions that complete within minutes, if not sooner. One result of high velocity flight on a linear trajectory is that incidental exposure to planned debris can be readily identified and mitigated. Moreover, the potential exposure of aircraft and ground receptors to unplanned debris can be quantified by accounting for debris aerodynamic properties and atmospheric uncertainties and propagating ensembles of representative break-up fragments to receptors such as aircraft, ships, and people. For both planned and unplanned debris, the dispersions arising from vehicle path and falling fragment uncertainties can be simulated using well developed aerodynamic modelling techniques. The process is often very computationally expensive, but the calculations can be done well in advance while still accounting for much of the launch-day uncertainties. A category of lift vehicles with a long history that is gaining popularity for deployment of large payloads to the stratosphere and lower mesosphere is the long/ultra-long duration balloon (U/LDB), an example being NASA’s zero pressure difference helium balloons. This class of balloons has several advantages for both scientific and military testing as well as commercial applications [2, 13, 14–16, 19].

For example, balloons are typically less expensive than rockets and enjoy the flexibility of being deployed from mobile launch facilities. Because control and FTS systems are simpler, flight readiness is simpler to verify, and because helium is inert and the balloon lift assembly does not contain propellants, balloons permit quick turnaround schedules. The absence of propellants also limits ground and near-ground catastrophic hazards that are possible from explosive motor failures. Balloons can be designed to lift sensitive payloads of over 3500 kg. Because balloons can ascend and loiter into the lower mesosphere, they can serve as stable platforms for long-duration high-altitude missions lasting several hours or days. LDB balloon flights customarily last up to 3 weeks. With sufficient gas reserve and ballast (typically 6–8% of system mass) so that this neutrally-stable vehicle can respond to diurnal changes, projected loitering times are expected to become hundreds of days in the case of ULDBs [5, 8].

Although launches are routinely conducted without incident, the un-powered nature of U/LDB’s and their large hazard area for planned debris coupled with the ascent dispersion and their large payload capacity means that large populations can be placed at risk. Moreover, unplanned incidents have a high probability of being catastrophic and resulting in fatalities. Stated in other words, the risks from balloons derive from a small inventory of large, high ballistic coefficient fragments. In contrast to balloons, for rockets much of traditional flight safety methodology as drawn from RCC 321-10 and other standards revolves around quantifying the descent hazards from low ballistic coefficient wind-dispersed fragments which intrude into aircraft corridors and onto ground receptors.

For balloon launches the converse is true. Much of the uncertainty is dictated by wind-driven dispersion during ascent, while the footprints from planned and unplanned debris (such as large recovery parachutes and gondolas)
during descent are moderated by the simpler vehicle and the lack of significant forward velocity and ∆V’s [11]. Because much of the wind uncertainty for the ascent phase cannot be resolved until day-of-launch for U/LDB’s, there is a much greater need for real-time risk assessment methodologies for both planned and unplanned debris in order to minimize any catastrophic risks to people and infrastructure. With these distinctions between the two risk management problems in mind, this paper illustrates the development of a new probabilistic risk methodology that has been developed to address the differences by quantifying the long-duration fatality-likely exposures to aircraft and ground-level receptors to U/LDB flights.

The methodology addresses risks during to launch operations during the ascent to float phase, and for any float manoeuvres and planned descent and recovery. It is computationally feasible, allowing for day-of-launch risk assessments to be generated within a few hours so as to accommodate the most favourable launch conditions. Since break-up state vectors and associated debris are physically propagated to ground receptors, the methodology avoids the undesirable smoothing which can occur with kernel density estimator methods [7] and expedites launch decisions by avoiding the need for “hard” exclusion corridors for ground risk. The methodology has been successfully applied to NASA’s LDSD 2015 Campaign, notional elements of which will be used as a demonstration.

2. DESCRIPTION OF PROBLEM

References [1] and [2] provide background on historical and recent developments in U/LDB’s. These balloons have continued to increase in size and lift capacity such that payloads on the order of 3000 (kg) can be lofted to 40–45 (km), and above 50 (km) with smaller payloads.

These altitudes can be viewed in the context of the physical atmosphere depicted in Figure 1. The ability to inexpensively lift tons of payload above 99.7% to 99.9% of the atmosphere and permitting its safe recovery while minimizing launch debris is significant.

Figure 2 shows a typical altitude flight profile for these missions — in this case from the NASA-sponsored “Big 60” mission launched on August 25, 2002, Lynn Lake, Manitoba, Canada. Not atypically, the actual launch occurred after several weeks of weather delays. The balloon — designed to have an ultimate lift capacity of 750 kg — carried instrumentation weighing 690 (kg) for the study of cosmic rays. As Figure 2 shows, the balloon climbed to a peak altitude of 49.4 (km). The mission was terminated normally after approximately 23 hours of flight time.

A more interesting payload was provided by the LDSD mission, which is the focus of this paper. This is a NASA effort to develop inflatable pressure vessels called Supersonic Inflatable Aerodynamic Decelerators (SIADs) for delivering future payload and manned missions to the Martian surface. These drag devices are attached to the outer rim of an atmospheric re-entry vehicle and inflate at Mach 3.5 or greater, in order to decelerate the vehicle to Mach 2 where it becomes safe to deploy a supersonic parachute. An overview of the scientific program developed by NASA to test this concept in the earth’s upper atmosphere, where conditions mirror those on Mars, is given in Refs. [2–3, 6].
Stratospheric tests of the LDSD were conducted in 2014 and 2015 at the Pacific Missile Range Facility operated by the U.S. Navy on Kauai, Hawaii, as shown in Figure 3 [3, 4]. The mission revolves around a U/LDB provided by NASA Wallops Flight Facility and the Columbia Scientific Balloon Facility. This zero-pressure balloon is used to lift a solid-rocket powered test vehicle (TV) to an altitude of about 120,000 (ft) [37 (km)]. Once within earth’s stratosphere and having transited over a suitable location and with the TV correctly oriented, the LDSD payload is dropped and then boosted by the solid rocket to supersonic speeds as discussed above.

Once boosted to “Martian” re-entry velocities, the tests of the deployment and functioning of the SIAD’s commences, followed by recovery of the balloon and test vehicle in the Pacific Ocean. The mission sequence is shown in Figure 4. This paper is only concerned with the risk assessment from balloon launch to stratospheric float, conditioned on malfunctions during this phase.

Risk assessment considerations differ from standard rocket launches, as briefly discussed in the introduction [9]. Risk assessment for rockets generally proceeds from the standpoint of a nominal trajectory and planned debris, with guidance and performance uncertainties well characterized and constrained over the entire flight through an ensemble of trajectories. Malfunction trajectories and debris are incorporated on top of this basic methodology.

In the LDSD mission, the only analogue to planned debris occurs during the ascent phase, with carefully timed ballast releases which are intended to “boost” ascent wherever local temperature and pressure act to retard upward acceleration. Apart from the ballast releases, which are engineered to produce no risk to people or aircraft, the only other source of risk arises from unplanned debris, should a balloon malfunction occur, an inadvertent release of the TV occur, or the need to remedy other abnormal conditions with a flight termination action. These scenarios are characterized by the production of at most a handful of extremely heavy and/or large debris. Because of the large ballistic coefficients associated with the debris, the descent footprint is associated with much less uncertainty than that present during ascent.

More severely, the balloon equivalent of a nominal trajectory does not exist. Balloon ascent trajectories depend critically on the current weather and atmospheric profiles, solar conditions, and shading from clouds. During a typical launch window period the ensemble of possible ascent trajectories can meander and “sprawl” to essentially carpet a vast ground area. In contrast to constrained ensembles of nominal and off-nominal trajectories for rockets, the character of an ensemble of ascent trajectories appears much more like a random walk, with the variance growing the longer the mission, and the longer the mission window. In order to respond to mission-terminate needs, whether due to balloon or equipment malfunctions, ballast exhaustion or weather anomalies, flight termination systems must be active constantly to protect civilian airspace and limit ground exposure and exhibit high reliability.

In the case of the LDSD, under ideal launch conditions the expected ascent track will carry it directly off-shore, or off-shore immediately after in-shore surface winds.
are breached [4]. Figure 5 provides examples of ground tracks when such ideal conditions are present. Under these “ideal” ascent conditions it is evident that the ascent ground track is over land for a limited period of time. With the general north-easterly ascent paths shown in Figure 5 the only exposure to population and population centers occurs in the beach areas.

The ground tracks shown in Figure 5 can be considered “ideal.” The movement of weather fronts and anomalies in seasonal wind patterns, among many other factors, combine to produce ascent trajectories which are likely to over-fly population centers. Because over-flight of this character can affect many population centers, and the over-flight tracks can be disparate over a launch window, the strict use of hazard containment boundaries can lead to mission delays even when actual risks are tolerable.

Experience at this location has indicated that under normal weather conditions the uncertainty associated with ascent trajectories is not significantly increased once weather forecasts are within a T-1 day window. As a general rule, therefore, launch go/no-go decisions are made on the basis of T-1 day forecasts. One the other hand, this interval constrains the amount of time available for risk assessment calculations.

3. PROBABILISTIC RISK ANALYSIS USING META-RRAT

The time “parameterization” requirement identified in the previous section was implemented using a tool called Meta-RRAT, a risk analysis program for complex mission scenarios developed by ACTA Inc. Meta-RRAT is designed to allow the organization and execution of one or more sets of risk analyses which have been parameterized by a number of possible mission parameters, such as failure and break-up modes.

Meta-RRAT essentially functions as a high-level scripting language in which an arbitrary number of single risk analyses can be performed, and the risks combined in various ways such as weighting by individual analysis or union-combining to ascertain the maximum risk.

Meta-RRAT analyses include the following three types of mission scenarios. First, it may be used when there exist very limited data to describe the vehicle performance and malfunction behaviours. The “simplification” is that the vehicle malfunction probabilities and associated response are not realistically modelled. The input break-up state vectors represent only very general trajectory misbehaviour and the probabilities of each type of malfunction are significantly over-estimated (perhaps 100% for each). In this type of situation it is often desirable to consider the maximum risk from any type of malfunction. This can be particularly useful early in mission planning to provide indications of potential risk issues.

The second situation is when a wide range of trajectories is possible during mission planning. An example is the launch of an interceptor toward a target. During planning there is typically a large engagement volume where the intercept can occur. When the mission actually occurs, between the times of target and interceptor launch, the intercept location is determined with uncertainty much smaller than the whole intercept region. During mission planning it is therefore appropriate to study the range of trajectories that reach the volume. By performing a Meta-RRAT analysis to examine the risks of all these trajectories a range safety office can approve launch for any engagements within the planned intercept box.

A third situation is to perform basic sensitivity analyses in order to compute uncertainty on $E_c$ and for risk profiles. Here, several of the internal computations and results of each baseline analysis are randomly adjusted to account for uncertainty in the risk models. With a standard input set for a given vehicle, the risk engine will produce a single mission casualty expectation, $E_\iota$, or risk profile. This value is a point estimate of $E_\iota$ or a risk profile. In order to obtain the uncertainty about this best estimate value requires a set of results where each corresponds to a randomly perturbed input data set.

The LDSD mission constitutes a fourth application, one which seems undocumented in the literature. One can think of the balloon state vectors at failure as defining a rising and expanding “tube” which envelopes the ascent space. The state vectors are based on the balloon ascent dynamics and the T-1 day wind forecasts. Break-up times are randomly sampled over the duration of the ascent phase. The resulting “termination points” are mapped to debris which is then propagated to the ground, using
the same forecasted wind field, and used for hazard assessment. Both the break-up list parameters and the wind field incorporate uncertainties.

This new methodology yields time-dependent estimates of the individual and collective risks, and the “evolution” of the debris footprints on the ground. This information has proven itself invaluable in order to unambiguously establish the periods during the mission which contribute the most to the risk, and whether, for example, the relative risks during those times in comparison to the total mission risk is excessively concentrated. The next section will illustrate this fourth methodology.

4. EXAMPLE ANALYSIS

The first step in the risk assessment commingles the forecasted wind profile obtained from the Global Forecast System (GFS) with the JPL wind uncertainty model in a form usable by Meta-RRAT [4, 11]. GFS is a weather forecast model produced by the National Centers for Environmental Prediction (NCEP). It is run four times per day, with forecasts up to sixteen days ahead. As already indicated, JPL has empirically found that (in the absence of weather systems or local anomalies) that ascent uncertainty is not greatly improved once inside a twenty four hour window to launch. An example of a standard GFS forecast obtained for T-1 day is shown in Figure 6.

As can be inferred from Figure 6, GFS only provides a mean forecast. An algorithm was developed to incorporate the JPL 3-σ uncertainty model for the PMRF location in order to generate the appropriate covariance matrices to model local wind ensembles, with typical results for each step of this process shown in Figure 7 and Figure 8.

The analogue to the standard ensemble of nominal trajectories — namely an ensemble of ascent trajectories — was simulated by JPL, using models for the balloon, environment, wind forecasts, along with uncertainty models for each aspect of the physics. The simulations were performed with SIBNAD (Scientific Balloon Analysis Model), as discussed in Refs. [3, 4, 18].

The resulting model was used to simulate ascent trajectories to failure, resulting in a file consisting of several thousand randomly spaced (in time) points called...
termination points, defined by the time since launch and the predicted altitude at failure. Each termination point represents a balloon state vector at conditional balloon failure, defined by the geodetic position, altitude, and the three components of the mean “free stream” velocity.

The reliability of the balloon was considered constant over the ascent (launch-to-float phase), with a value of about 6%, a value recommended by CSBF and consistent with historical data for these types of balloons [10, 12]. Failure rates are of course conditional, since launch go/no-go decisions incorporate gates which preclude launching into adverse atmospheric conditions that would elevate risk. Communications failures (“FTS”) were assessed as part of the launch-to-float analysis. For the most part, flight systems are performing passive functions during this phase. There is no restriction, of course, in applying non-constant failure rate models as part of the overall methodology when justified.

The resulting ensemble of termination points was segregated into a set of contiguous windows, five minute each in length. Depending on final termination time, these parameters resulted in between 30 and 40 separate risk analyses, using the parameters summarized in Figure 9. A program was developed to aggregate, process, and partition these data into the appropriate input format.

Figure 10 shows probability of impact contours when all the termination states are considered for the entire ascent, in this case thirty five minutes. One can infer from this depiction that the launch initially proceeds off-shore and then drifts south and, at some time, turns eastward along the southern coast. While individual population centers can be interrogated for total mission risk, neither such point information nor the aggregate summary in Figure 10 gives any indication regarding how much time the balloon spends over any location nor when in time the risk is concentrated. Situations can and do occur when the balloon loiters as it ascends, “building up over-flight risk”, or conversely when it sweeps rapidly over large populations and/or critical infrastructure.

A reason why such information may be of great value for go/no-go decisions can be ascertained by examining the total mission risks for this particular case, as shown below.

\[
\begin{align*}
\text{MISSION } & E_c = 1.73 \times 10^{-4} = (173 \div 1 \text{ million}) \\
\text{MISSION } & E_f = 1.57 \times 10^{-4} = (157 \div 1 \text{ million})
\end{align*}
\]

These aggregated risks are typically the chief concern for rocket missions, given a rocket’s short flight time. Note that as mentioned earlier there is little distinction between the fatality risk and casualty risk for balloons, since most of the debris is very massive or, in the case of the balloon carcass, has great hazard area (see also Figure 9).
the populated southeast intuitively contribute to the accumulated risk. However Figure 10 provides no information at all regarding when during the ascent the risk is concentrated.

This type of crucial information is provided by the new methodology based on time-parameterization of the mission using Meta-RRAT. The actual time-dependent risks from which the mission $E_i$ and $E_c$ were obtained are shown in Figure 11. Figure 11 indicates that risk does not begin accumulating until well after five minutes into the launch.

![Figure 11. Time-dependent casualty and fatality risks obtained using a five minute window.](image)

The methodology also enables quantitative comparisons between ascent situations under different weather patterns to be made, by examining temporal trends, as shown in Figure 12. Here, two different days (green and magenta) exhibit maximum risk during the initial launch phase, while the third (in blue) has a similar maximum risk but a much slower decay rate.

Fatality information at this level of time/spatial fidelity is particularly important in identifying potential situations which could “fly under the radar” on a total-mission basis but which could pose a catastrophic hazard, if only for a relatively short amount of time. Such situations could and have been observed to occur when the time-dependent footprints sweep across large crowds, such as invited observers and popular beach areas, or critical government and public infrastructure.

![Figure 12. Comparison of risk evolution across ascent time for three different mission scenarios.](image)

It is also important to realise the potential for balloon failures (leaks, for example) to occur at any time, necessitating flight termination decisions to be instigated immediately. Knowledge of the time-evolution of the risk footprint provides additional information for screening the best time or times for bringing down the balloon.

5. COMMENTS AND CONCLUSIONS

Risk analysis for long duration balloon missions is seen to be characterized by mission times that can exceed several hours or days, a feature that is coupled with ascent uncertainties which manifest themselves as trajectories which exhibit features of a “random walk”, namely spatial variance increasing as some function of time. These two features stand in marked contrast to more typical rocket-based missions, whose durations are limited to hundreds of seconds (and usually much less), and which have impact distributions dominated by descent uncertainty, especially for the smaller unplanned debris. And, unlike the same for rockets, balloon risk analysis must be conducted within a T-1 day window, in order to effectively use accurate wind and environmental forecasts, since these dominate ascent uncertainty.

The methodology described in the paper builds on traditional and accepted practices refined for shorter missions. What it accomplishes is a time-parameterization of the risk over a lengthy mission, so that launch phase and subsequent FTS decisions can be based on detailed population and critical infrastructure exposures throughout the mission. This methodology moves the framework from a hazard containment approach to a risk-informed one, and has helped avoid excessive conservatism associated with the former.
The methodology uses an ensemble of termination points which are binned into discrete time windows. The failure modes associated with the termination points are mapped to break-up state vectors, and these are propagated to the ground through the correlated wind field in order to produce probability of impact and casualty/fatality probability distributions.

Apart from the generic risk modeling questions which arise in any mission, the primary question which the new analysis raises is the choice of window width. For an LDSD-type mission, with a maximum mission time expected not to exceed four hours, a window width of five minutes was found to yield excellent characterization of time-risk profiles consistent with distribution of population centers. This recommendation is based on analysis of several different day-of-launch weather profiles. It should be noted that this recommendation is conditioned on the ensemble wind and overall weather conditions for this mission locale, namely Kauai, and for well-behaved weather patterns. Application to other locales will need to verify the best choice of window time.

The methodology was implemented in Meta-RRAT and optimized to enable throughput of day-of-launch winds into time and location dependent go/no-go decision criteria within an hour.

6. ACKNOWLEDGEMENTS

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7. REFERENCES


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