QUANTITATIVE ANALYTICS FOR BEYOND VISUAL LINE OF SIGHT OPERATIONAL RISK ASSESSMENTS

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Beyond Visual Line of Sight (BVLOS) flights take planning, coordination, and assessments prior to take off. Approvals for BVLOS flights can be complicated and involve Operational Risk Assessments (ORA) based on the flight's Concept of Operations (CONOPS). Analytical tools exist today that can assess impacts to navigation, communication, and other metrics of interest to an operator. By combining these analytical tools and the ORA process, we can begin to see how we can automate ORAs for BVLOS approval. This paper covers the ASTM BVLOS approval process and how specific analytics can be used to aid in creating the required ORA. Additionally, we look at how we can convert analytical results into operational risk likelihood assessments and propose several ways to visualize risk. We end with some recommendations for future thought and action, on items that should be addressed before any automated BVLOS approval process can be employed.

INTRODUCTION

Performing an operational risk assessment (ORA) for a beyond visual line of site (BVLOS) flight requires several complex steps. In ASTM F3196-18, the BVLOS approval process is laid out, and as part of that approval, in section 7, an ORA is required to be performed. The ORA process is defined in ASTM F3178-16 and includes assessments of risk for a variety of criteria. Examples of practices for performing this ORA are given in Table X2.1 in F3178-16. These examples include recommendations for the pilot to assess communications and to assess GPS performance prior to the flight. In this paper, we show how to quantitatively assess navigation performance, communications performance and a variety of metrics using well-defined analytics that can be used as a risk-based approval mechanism for flights.

Specifically, we discuss position assurance with Global Navigation Satellite System (GNSS) and communications assurance for the communication system between the vehicle and the ground control station. Inherent in these assessments are questions about the algorithms and data used, the Concept of Operations for the ORA request and the ease with which the assessment can be made. In this paper, we recommend strategies for each of these topics, and provide example assessments.

Looking beyond the initial ORA assessment, we also provide guidance on how to make use of additional analytical results for situational awareness in real time, and ways to visualize hazardous situations during planning or operations. For example, understanding your navigation accuracy along a route for a given time period can help define the width of the flight corridor. For flight

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planning, this can help reserve the correct volume in an Unmanned Aerial Vehicle (UAV) Traffic Management (UTM) system, that others can then plan their flights around.

To move forward with BVLOS, ORAs must be made easily and reliably. Using automated ORA assessments is a necessary step towards automating BVLOS approvals and moving toward a more autonomous future. In this paper, we will describe one method for performing these assessments which, we expect, will lead to a broader discussion of quantitative, automated ORA assessments in general.

ASTM APPROVAL PROCESS

The first consideration is that the civil aviation authority (CAA) ultimately determines what operations will be approved, and how they will be approved. ASTM developed and published F3196, F3178, and other standards as recommendations for CAA's and applicants alike to ensure BVLOS operations are executed safely. A CAA may require additional procedures beyond the scope of the ASTM standards, which are beyond the scope of this paper.

Safe operations depend not only on airworthiness of an aircraft and robustness of its infrastructure, but also the environment in which the technology is deployed. The CONOPS documents the BVLOS mission to provide a high-level overview of the operations purpose, environment, staffing, and constraints. The CONOPS must be detailed enough to sufficiently identify hazards relevant to the CAA, BVLOS applicant, and other key stakeholders that may be affected by the operation. These hazards, and respective mitigations, must be analyzed in accordance with the operational risk assessment standard. While mitigations reduce the risk of hazards, the remaining residual risks must be quantified and accumulated to determine if the overall risk is acceptable.

The final ORA is one that makes clear that the residual risks of the BVLOS operation are acceptable to the approval authority. Thus, the ORA is a key document for operational approval from the CAA.

CONOPS-ORA Discussion

CONOPS provide a thorough description of the mission and operating environment, including the purpose of the mission, the vehicle(s) used, staffing, training, geographic boundaries, equipment location, weather, and limitations defined by stakeholders.

Stakeholders include representatives for parties impacted (or potentially impacted) by the operations. Not only does this include the applicant, customers, business partners and regulators, but also the local community due to potential impact of noise, safety, and other costs/benefits defined in the CONOPS.

The CONOPS does not specify the requirements but is a product of them. Moreover, although a CONOPS documents how an operation will comply with mission requirements, further analysis ensures the risks encountered are acceptable to stakeholders. This analysis is provided in the Operational Risk Assessment report.

The ORA provides the risks associated with the CONOPS, along with the risk mitigation strategies and quantification of the risks, to determine if the risk profile for the CONOPs is acceptable to the applicant, CAA, and other stakeholders. The ORA is coterminous with the CONOPs, and if the ORA determines that risks are unacceptable, the CONOPS is adjusted, and ORA reanalyzed until risks are acceptable to stakeholders.

F-3178-16 §7.1 declares that the ORA is specific to the CONOPS. Further, the Operational Approval from a CAA only applies to operations that comply with the CONOPS. Therefore, if the operating environment changes during a mission, such that the CONOPS is no longer valid for that mission, the ORA no longer applies, and the operation must immediately be adjusted or safely cancelled.

For example, let us presuppose a CONOPS does not include checking for space weather effects such as ionospheric storms, and that the ORA neglects this hazard in its analysis. During the operation, if a high intensity ionospheric scintillation causes loss of GNSS signals during an operation, the CONOPS and ORA, and therefore the CAA approval, no longer apply to that operation. In this scenario, the risk levels due to navigation errors have increased to unknown levels, maybe to the point that the risk of continuing the mission is unacceptable to stakeholders. Depending on the mission, additional analysis may be required to reapprove the CONOPS and ORA. The ASTM ORA standard assumes no malicious interference with UAS operations[4]. However, unintentional interference does occur from both natural and artificial sources. GPS repeaters are meant to assist navigation (and testing) in areas of weak reception but can unintentionally cause navigation problems for nearby users.

The details of the CONOPS and ORA are proportional to the complexity of the mission[5]. ORA's for an operation located in an urban canyon of a densely populated city are expected to be more rigorous than operations in remote, unpopulated areas.

Hazard Identification

Hazards are identified through direct experience, engineering judgement, panels of experts, stakeholder surveys, and other methods. One approach is top down, which first considers the most generic hazardous event, and breaking this down into a variety of hazards that lead to it. This approach is depicted in the notional hazard tree in Figure 1, where "Controlled flight into object" is a high-level hazard. Even better would be "Unintended collision with object" that could break down into "controlled" and "uncontrolled" subcategories.

The completed ORA will identify the hazards that can be encountered, a mitigation for those hazards, along with the residual risk of each hazard. Likelihood scores are then provided for each hazard, preferably achieved through quantitative analysis. Quantitative analysis can be executed by developing fault trees and assessing the likelihood of various conditions that contribute to a hazard.

For example, Figure 1 shows a fault tree for conditions that contribute to the risk of a collision. Typically, catastrophic aircraft accidents are not caused by a single point failure, but rather by a multitude of coincidental conditions that lead to a failure.

New hazards may be identified and reported after the ORA is developed, and its likelihood/impact should be reviewed with the CAA to determine if existing conditions still satisfy the CONOPS.

The following list enumerates some example hazards to evaluate in an ORA:

- Position assurance
- Radio frequency coverage
- Noise generation
- Population density

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[4] ASTM F3178-16, §1.3

[5] ASTM F3178-16 §7.1.2

- Weather
- ADSB traffic
- VLOS coverage
- Vehicle / Obstacle detection ability

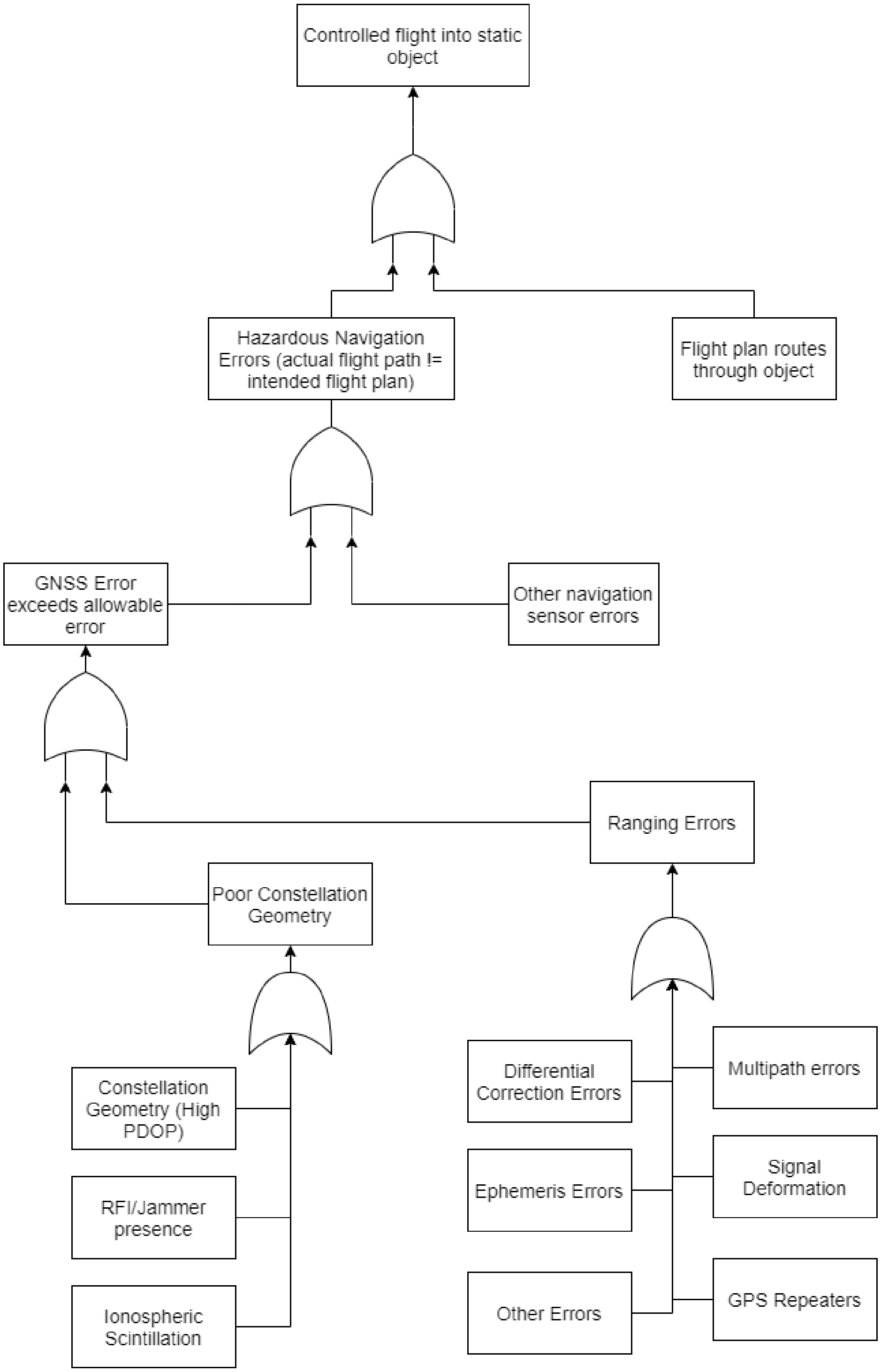

Figure 1. Example GNSS Navigation Fault Tree

Hazards Versus Expectations

The GNSS navigation hazard example in Figure 1 presents the outcome of colliding with an object due to GNSS navigations errors. Although high navigation errors imply an increased likelihood of collision, the expected navigation performance is also important to consider since high navigation errors may be acceptable to your mission.

If your mission depends on GNSS being accurate within 1 kilometer, and flights are designed to ensure ground-based objects are beyond 1 kilometer, then there is only a small risk that GNSS navigation will cause a collision with a building or terrain. This is because all the expected GNSS errors will remain well within this predefined, over-engineered, boundary.

On the other hand, if you design a flight path in such a way that GNSS errors must be less than 10 centimeters, every type of GNSS error phenomenon must be carefully accounted for because typical GNSS errors are on the order of meters.

Differential correction systems for commercial aircraft such as the Ground-Based Augmentation System (GBAS) and Space-Based Augmentation System (SBAS), consider expected navigation performance, the required performance, and residual risks of exceeding these limits through the use of Protection Levels, Alarm Limits, and Hazardous-Misleading Information (HMI). Protection Levels define the best estimation of the position to a strong degree of confidence[6]. See Appendix A for more on Protection levels and alarms.

Summary of Hazards

To determine the risk of the top-tier hazard in the fault tree, the risks of each of the lower-level hazards must be quantified. Using the example from the fault tree, let us calculate P_{DOP}, the probability of encountering a DOP > T_{DOP} during a half-hour period, where T_{DOP} is the maximum allowable DOP threshold. High DOP can occur when conditions in Table 1 are encountered.

Table 1. Methods to Quantify Probability of Errors

Term:	Probability Of:
P_{RFI}	Radio Frequency Interference
P_{Iono}	Ionospheric scintillation
P_{LOS}	Object(s) or terrain blocking the line-of-sight vector
P_{GNSS}	Poor GNSS constellation orientation

Using Boolean analysis, the probability of the higher-level term is a summation of the lower levels[7]:

$$P_{DOP} = P_{RFI} + P_{Iono} + P_{LOS} + P_{GNSS} \qquad \text{Eq. 1}$$

Do be aware that this is a simplification which presumes that only one of these situations could occur at the same time. However, in this case, the simplification will provide a conservative result. Another assumption is that these low-level hazards are independent of each other.

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[6] http://www.egnos-pro.esa.int/Publications/GNSS%202001/SBAS_integrity.pdf

[7] SAE ARP4761 §D.10.1

When hazards become dependent on each other, or contribute to multiple high-level failures, or involve time dependency, these probability calculations become complex. SAE ARP4761 describes how to apply such Boolean analysis in additional detail.

To quantify the probabilities, various methods can be used, but must be agreed upon with the CAA. Table 2 outlines some methods that may be used for these cases.

Table 2. Methods to Quantify Probability of Errors

Term	**How to define**
P_{RFI}	On-site analysis can provide an empirical estimate of how often a receiver encounters RFI in each area.
P_{Iono}	SBAS systems such as WAAS provide real-time status of ionospheric activity, though in the CONUS, ionospheric scintillation is generally negligible. Empirical analysis on-site or using public data of nearby receivers can determine the likelihood of encountering future scintillation.
P_{LOS}	LOS vectors can be pre-calculated using a simulated mission and accurate 3D surface and building models.
P_{GNSS}	DOP based on nominal satellite constellations can be pre-calculated, as demonstrated in the following sections.

QUANTIFYING RISK LIKELIHOOD FROM ANALYTICS

Operational Risk Assessment Automation – What can be done?

In the ASTM standard F3178-16, Operational Risk is assessed. Risk is defined in a specific way, in Tables 1, 2 and 3, of that standard. For reference, those tables a reproduced in Appendix C.

Risk is separated into two categories – *severity* and *likelihood*. Risk severity is necessarily defined by the CONOPS. Severity can only be understood and quantified by looking at the flight plan and the conditions under which that flight will take place. Under consideration are the areas over which that flight will take place, the population, infrastructure, and other factors that may raise the severity score should something unforeseen happen. Given this, severity is something that may be able to be automated but is beyond the scope of this paper.

Risk likelihood represents the general probability that given outcome may occur. This category is better suited to automation because analytics exist to assess various metrics of concern for operators. So, how can one convert an analytical result to a likelihood result quantitatively? First, we will need some analytics of interest, and then, something to assess those analytics against. The next section describes our approach to this method.

A View into the Analytics

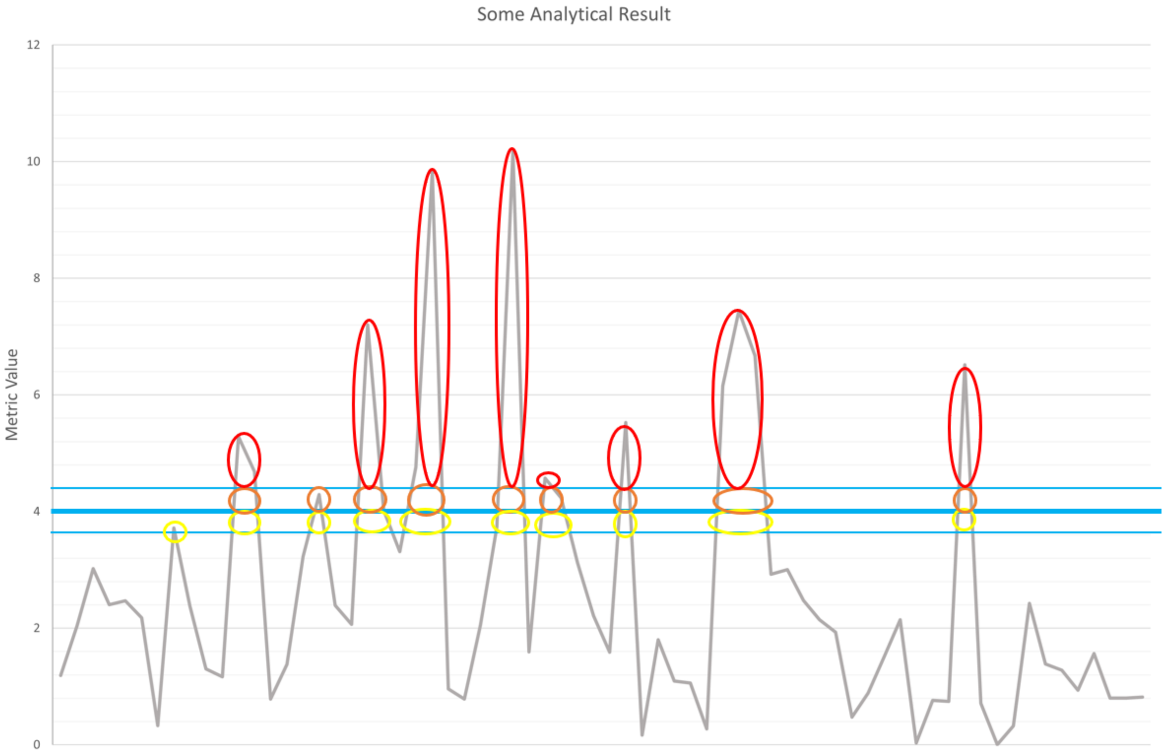


Figure 2. Typical Analytical Result

Figure 2 shows a typical analytical result for a metric value of interest. The gray line represents the value of the metric over time, which may or may not occur at the same location. In general, analytics are generated as

$$f(\vec{R}, t, \vec{U}) \qquad \text{Eq. 2}$$

where $\vec{R}$ is the position, t is time and $\vec{U}$ represents an optional vector of parameters required for the calculation of the metric.

To begin understanding how this varying metric value can affect a flight, we need a condition to compare against. Operators typically have a threshold below which they consider the metric value good. In the graph, a constant threshold of 4 meters has been drawn in light blue, with thinner lines above and below the threshold representing a small percentage away from the threshold (say, 10%). This represents the case where an operator may have a threshold of 4 meters of positioning error, +- 10% before takeoff approval can be granted, for example.

Intuitively, the areas below the lower threshold bound hold less risk for the flight, just as the areas above the upper threshold bound hold the most risk; with more risk being associated with a higher metric value or a longer time over the threshold. Intermediate areas of concern occur where the metric value is located between threshold bounds. These specific areas are highlighted in Figure 2, with yellow, orange, and red ellipses, representing some concern, moderate concern, and high concern areas under the analytic curve, respectively.

To quantify this intuition, we have created a method whereby we can use any analytic assessment and map the analytic values to risk likelihood states from Table C2. Equation 3 defines the inputs for the algorithm, with the output being the resultant risk likelihood for that analytical metric. The algorithm defined by Eq. 3 takes both the metric value and duration in the threshold regions from Eq. 2 into account, and it is useful for understanding how risky a flight may be based on specific analytics. Eq. 3 takes the analytic function f (Eq. 2) as an input as well as the user-specified Threshold to assess that metric against. The threshold function $T_f(\vec{R},t)$ is specific for that metric and can be different for any position and time. An example of this would be location determination errors before launch having a small threshold and the threshold for that same metric while in flight being much larger.

To produce correct operational results, Eq 3. must be tuned to specific operator and CAA requirements and rules for flight approvals. These tuning parameters are provided in the vector parameter $\vec{\beta}(\vec{R},t)$.

$$L(f(\vec{R},t,\vec{U}),T_f(\vec{R},t),\vec{\beta}(\vec{R},t)) \qquad \text{Eq. 3}$$

Being able to quantitatively determine risk for any type of metric has many benefits. In the next section, we show how to build up a risk likelihood case for a proposed flight, by layering risks from various systems into a single metric.

QUANTIFYING RISK LIKELIHOOD, AN EXAMPLE

For an analytic example, we will use positioning error analytics for GPS, and communication analysis between the ground control station (GCS) and the vehicle. After specifying a planned flight route, we calculate navigation performance for the vehicle along the route. For the same flight, we also use a GCS communications analysis to show two different indicators of communications health; the number of 'bars', representing the signal strength of the received transmission from the GCS to the vehicle, and a Quality of Signal (QOS) metric that represents the amount of intended signal strength at the vehicle, compared to unintended signal strength within the same frequency band. Unintended signal strength comes from interference sources in the same frequency band that is unfiltered by the receiver. See Figure 3. The Instantaneous Risk Likelihood values are calculated from Equation 3 and are represented as those in Table C2. The operator thresholds in these cases are in Table 3.

Table 3. Analytical Metric Thresholds

Analytical Metric	Example Operator Threshold Value
Position Accuracy	6 meters
Communications Signal Strength	Minimum of 2 out of 5 'bars'
Communications Quality of Service	0.75 *(1.00 represents no interference, 0.00 represents complete interference)*

Evaluating these metrics along the route will provide numbers we can analyze. Looking at metric plots does not provide insight into risk however, especially as many metrics begin to stack, as will be the case in an ORA. Evaluating these metrics through a quantitative risk methodology, allows risk to be determined in aggregate for the specified route. These risks can then be combined in aggregate to represent a composite risk score for the entire planned flight.

In the next section, we explore ways to visualize both instantaneous risk likelihood and aggregate risk likelihood, leading to fast interpretation of various risk categories and a framework upon which automated decisions can be made.

Figure 3. Analytical and Instantaneous Risk Results

REPORTING AND VISUALIZING RISK LIKELIHOOD

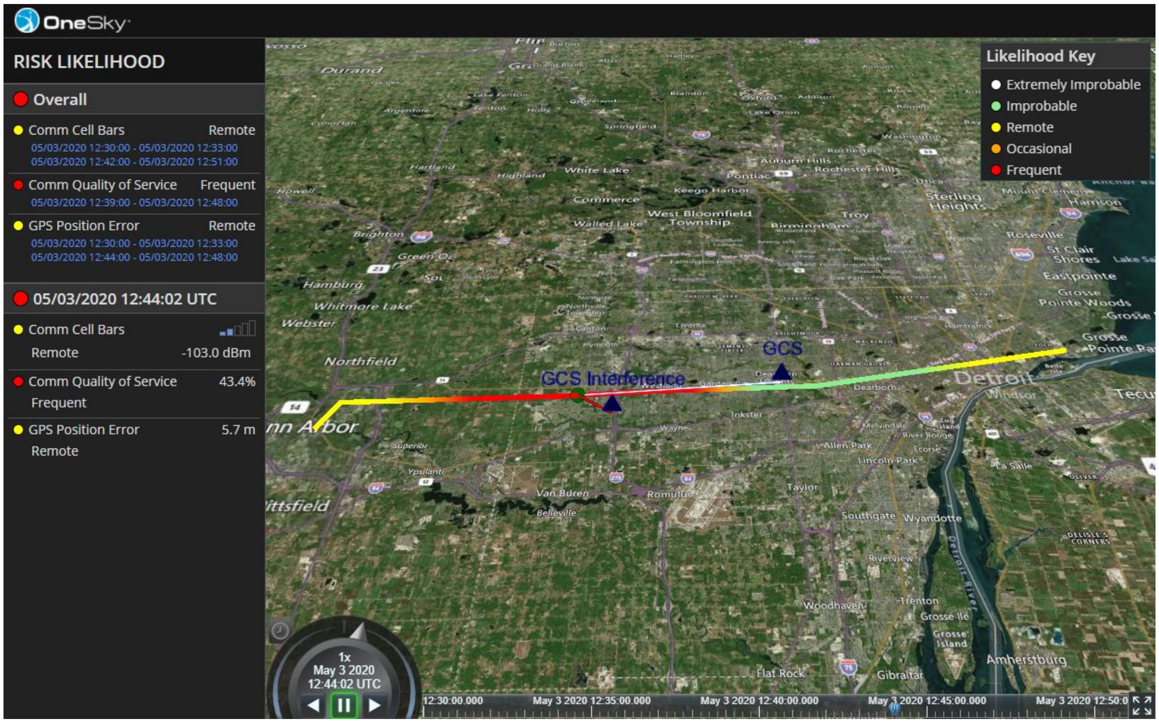
In this section, we examine visualizing risk likelihood in 3D space, over time. An example web application has been developed to demonstrate some possible mechanisms for understanding and sharing risk likelihood with stakeholders. We are using CesiumJS, an open-source time dynamic 3D globe, for geospatial visualizations.

We believe these are the fundamental questions to be answered for flight operations, both overall and at a given instant: What is the likelihood of risk? What are the components contributing to that likelihood? When and where is that likelihood encountered within the operational plan? How can this information be used in a way that aids automation? Answers to these questions enable stakeholders to mitigate or avoid conditions contributing to risk. Examples from our web application demonstrate how those questions might be answered.

In the application, a *Path flight* is a fixed 3D volume where an aircraft travels from one point to another within a predetermined flight corridor volume. It is anticipated that, within some tolerance, the aircraft's exact intended position is known beforehand for any given instant within the flight interval. Waypoints, and loiter stations may be planned as part of a path flight.

Example Web Application Layout and Components

The web application is primarily composed of an interactive 3D globe where relevant entities are displayed: a map layer, the flight geometry, the location of the GCS, and the locations of any GCS communications interference points. Users can zoom and pan the camera or lock onto any entity to track it throughout the operation. A timeline, clock, and animation speed controls are laid out along the bottom of the window. The clock can be animated forward and backward as desired. Figures 4 and 5 show the overall route and the route near the vehicles current position, respectively.


OneSky

RISK LIKELIHOOD

● Overall

● Comm Cell Bars Remote
05/03/2020 12:30:00 - 05/03/2020 12:33:00
05/03/2020 12:42:00 - 05/03/2020 12:51:00

● Comm Quality of Service Frequent
05/03/2020 12:39:00 - 05/03/2020 12:48:00

● GPS Position Error Remote
05/03/2020 12:30:00 - 05/03/2020 12:33:00
05/03/2020 12:44:00 - 05/03/2020 12:48:00

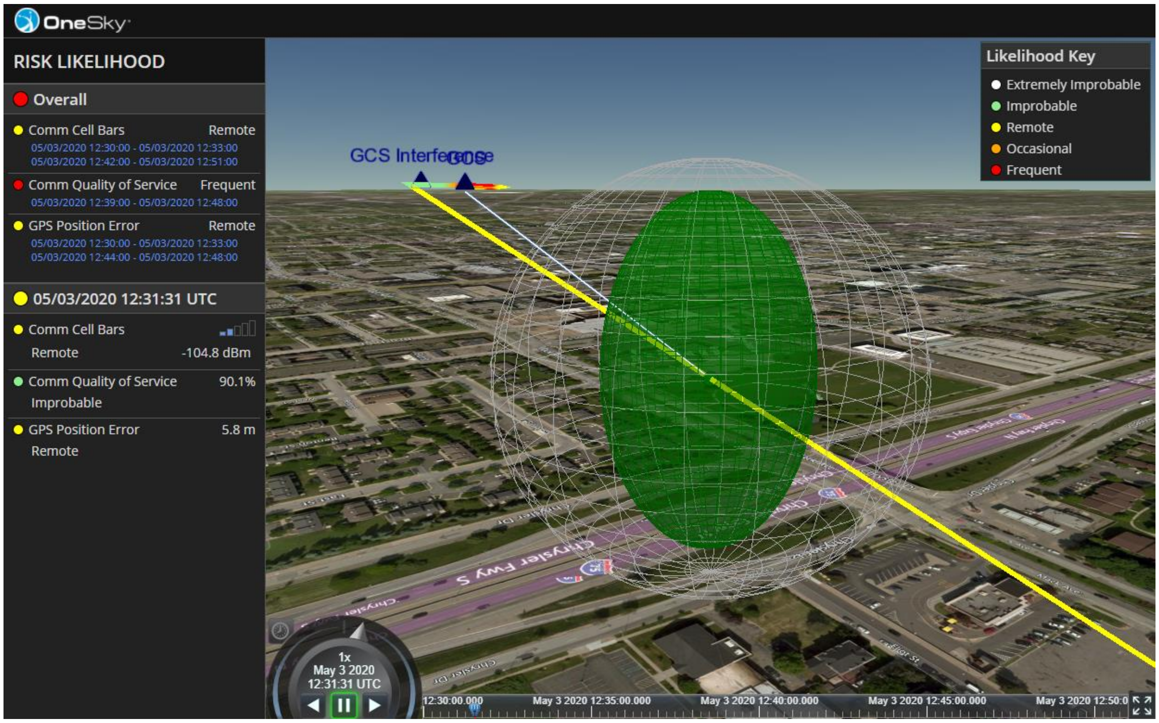
● 05/03/2020 12:44:02 UTC

● Comm Cell Bars
Remote -103.0 dBm

● Comm Quality of Service 43.4%
Frequent

● GPS Position Error 5.7 m
Remote

Figure 4. Example Web Application – Overall Route


OneSky

RISK LIKELIHOOD

● Overall

● Comm Cell Bars Remote
05/03/2020 12:30:00 - 05/03/2020 12:33:00
05/03/2020 12:42:00 - 05/03/2020 12:51:00

● Comm Quality of Service Frequent
05/03/2020 12:39:00 - 05/03/2020 12:48:00

● GPS Position Error Remote
05/03/2020 12:30:00 - 05/03/2020 12:33:00
05/03/2020 12:44:00 - 05/03/2020 12:48:00

● 05/03/2020 12:31:31 UTC

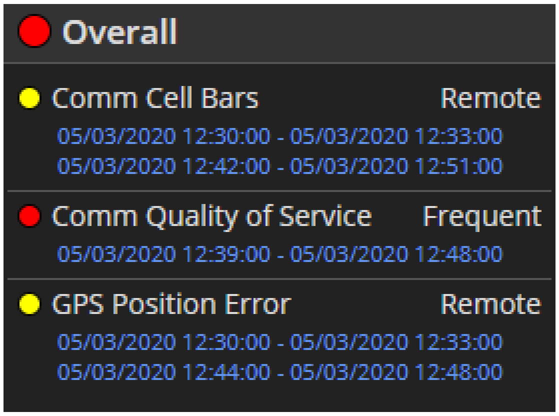
● Comm Cell Bars
Remote -104.8 dBm

● Comm Quality of Service 90.1%
Improbable

● GPS Position Error 5.8 m
Remote

Figure 5. Example Web Application – Overall Route, at Vehicle Position

The Overall Risk Likelihood panel in the top left corner of the application (Figures 4 and 5) shows the overall likelihood of risk for the operation. This panel presents the risk likelihood that a stakeholder may need to make a fly / no-fly decision, based on the output from Equation 3. This panel, enlarged in Figure 6, contains the components of risk likelihood for the entire flight. These components are: Communication Signal Strength (Cell Bars), Communication Quality of Service, and GPS Position Error. Each component includes a timestamp stating when the maximum likelihood level for the risk component is predicted to begin. The values in this panel are static, they do not change unless the flight plan changes. This panel represents a look at the entire flight with respect to each individual metric of interest.



🔴 Overall

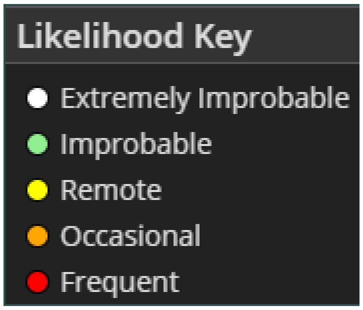
🟡 Comm Cell Bars — Remote
05/03/2020 12:30:00 - 05/03/2020 12:33:00
05/03/2020 12:42:00 - 05/03/2020 12:51:00

🔴 Comm Quality of Service — Frequent
05/03/2020 12:39:00 - 05/03/2020 12:48:00

🟡 GPS Position Error — Remote
05/03/2020 12:30:00 - 05/03/2020 12:33:00
05/03/2020 12:44:00 - 05/03/2020 12:48:00

Figure 6. Components of Risk Likelihood

A likelihood indicator in the form of a colored circle is placed in the panel header, where the color of the circle represents the aggregate likelihood for the entire route, for all metrics in that panel. Each component of risk likelihood includes a likelihood indicator as well, showing the maximum likelihood level for that metric during the entire operation. To better understand the likelihood colors, a Likelihood Key panel is added for reference; see Figure 7. This information is taken from Table C2.

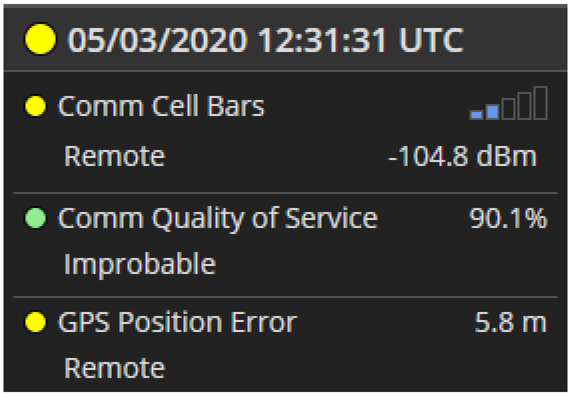


Likelihood Key

⚪ Extremely Improbable
🟢 Improbable
🟡 Remote
🟠 Occasional
🔴 Frequent

Figure 7. Risk Likelihood Color Mappings

The Instantaneous Risk Likelihood panel, Figure 8, is situated beneath the Overall Risk Likelihood panel. This panel's header displays the current scenario time in UTC as the timeline clock ticks. It includes an aggregate likelihood indicator for all metrics for that instant in time. Inside the panel body, each metric's analytical value is listed, along with its risk likelihood indicator signal strength in dBm, communication quality of service in percent, and position error in meters.



● 05/03/2020 12:31:31 UTC

● Comm Cell Bars
Remote -104.8 dBm

● Comm Quality of Service 90.1%
Improbable

● GPS Position Error 5.8 m
Remote

Figure 8. Instantaneous Risk Likelihood

The panels answer the fundamental questions of what the likelihood of risk is, what its components are, and when that likelihood will be encountered; both overall and at any instant. The information in the panels alone is valuable, and when combined with interactive 3D visualizations, stakeholders gain an even greater understanding of risk within the airspace. The next sections examine the visualizations for each component of risk.

Visualizing Risk Likelihood Along a Path Flight

A path flight is depicted by a colored line as shown in Figure 9. The line color indicates the aggregated metric risk likelihood level for the flight at each timestep along the flight. In Figure 9, the flight from Detroit to Ann Arbor has an overall likelihood level of Frequent. The likelihood key shows that Frequent is depicted by the color red. Comm Quality of Service is the offending metric, as shown in the Overall Likelihood panel in Figure 6.

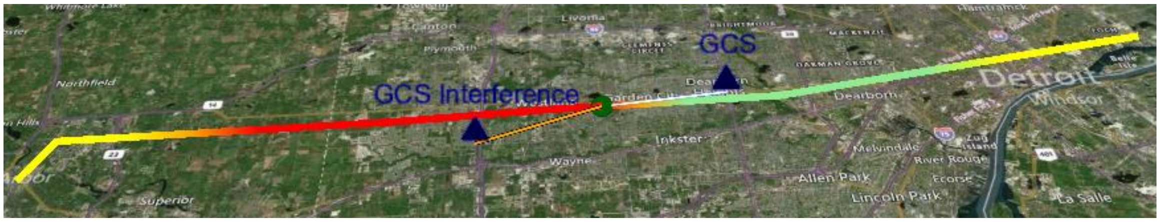


Figure 9. Flight Path Colored Line

In Figure 9, the aircraft departs Detroit, on the right side of the image, travelling east to west. Initially, the risk likelihood level is Remote as indicated by the yellow path segment. The level drops to Improbable, (light green) as the aircraft approaches the GCS. As the aircraft passes the GCS, and moves toward a source of interference, the path turns yellow and then red. Finally, after leaving the area of interference, it returns to yellow

This view shows the geometry of aggregated risk likelihood along the flight route. It gives stakeholders the opportunity to change the time, geometry, comms equipment, emergency procedures or other flight attributes.

Aggregate metric visualizations show the effect of all metrics on the risk likelihood for the flight. At any point along the route, any metric can be affecting the route's risk likelihood level and thus causing the color indicator to reflect that state.

Visualizing Individual Metrics

Navigation Position Error. In a path flight, the anticipated position of the aircraft, at a given instant, is marked with a green dot. As the time progresses, the green dot is animated to show the current position, giving the effect of the dot traveling along the path. The dot represents the ideal aircraft position if no GPS position errors were to exist.

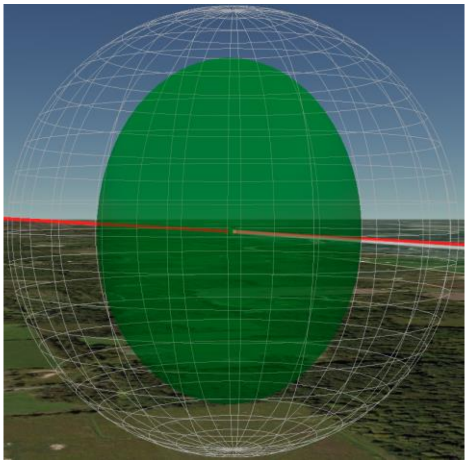
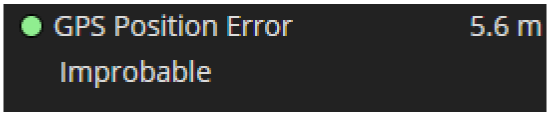


Figure 10, Navigation Error Ellipsoid

A translucent green ellipsoid surrounds the current vehicle position. The ellipsoid shows the volume of the 95% confidence GPS position error along the major and semi-major axes of the flight path, see Figure 10. The axes are represented by the East-North-Up coordinate system but can be rotated to any frame desired. Because of the positioning error, the aircraft can be anywhere inside the bounding error ellipsoid. Outside of the ellipsoid, a wireframe sphere is included to show the operator's chosen threshold for position error. In this example, that threshold is six meters, and the wireframe sphere is drawn with a six-meter radius. As the timeline clock ticks, the error ellipsoid shrinks and grows, showing the instantaneous position error volume.

The instantaneous likelihood of GPS Position Error risk is shown in the instantaneous likelihood panel along with the current GPS position error, see Figure 11.



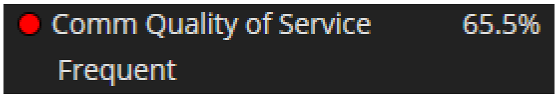
● GPS Position Error 5.6 m

Improbable

Figure 11, Instantaneous Navigation Risk Likelihood

Communications Quality of Service. In a path flight, as the aircraft travels along the route, a white translucent line appears when the communications Quality of Service (QoS) likelihood level is high, specifically: Occasional or Frequent. See Figure 12. The line connects the aircraft and the transmitter, in this case the GCS. The line directly illustrates the entities involved as the scene is animated. The white line disappears when the QoS instantaneous likelihood drops below Occasional. When an interference source is present, a line connects the vehicle and that interferer, showing that geometry. The GCS-vehicle line is colored to show the instantaneous risk likelihood associated with that interference.

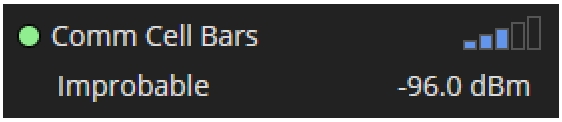
Figure 12, Instantaneous Communications Quality of Service



● Comm Quality of Service 65.5%
Frequent

Figure 13, Instantaneous Communications QoS Risk Likelihood

Communications Signal Strength at the Receiver. Communications signal strength from the GCS transmitter is measured as decibel-milliwatts received at the aircraft. The raw value is shown in the instantaneous likelihood panel, see Figure 14. It is also translated to a "cell bars" signal strength graphic, common to most devices. Five empty cell bars are shown. As the received power increases, the cell bars fill to indicate signal strength. As with the other metrics, the instantaneous likelihood of signal strength risk is shown using the likelihood color indicator.



● Comm Cell Bars
Improbable -96.0 dBm

Figure 14, Instantaneous Communications Signal Strength Risk Likelihood

Visualizing Risk over an Area

Sometimes, it is valuable to assess risk likelihood over large areas. For example, fleet operators may benefit from large scale risk analysis versus generating individual flight risk assessments. Airspace supervisors and those concerned with asset protection from air operations may benefit from understanding the likelihood of successful air operations over a given area.

Area risk analysis may also offer time savings. If likelihood is low enough (in combination with severity determinations as part of the total ORA) across the entire operational timeline, further analysis may not be required. When likelihood is not low, subdivisions of the area may be scrutinized to determine which operations are at risk.

The following series of figures shows how risk likelihood may change for a given area of operations of time. In Figure 15, the area has been divided into small grid cells. Each cell is colored based on the aggregate risk likelihood at that time, evaluated at the center of the cell. At the given time, a small portion of the eastern section of the area shows high likelihood of risk. In this case, GPS navigation accuracy is diminished.

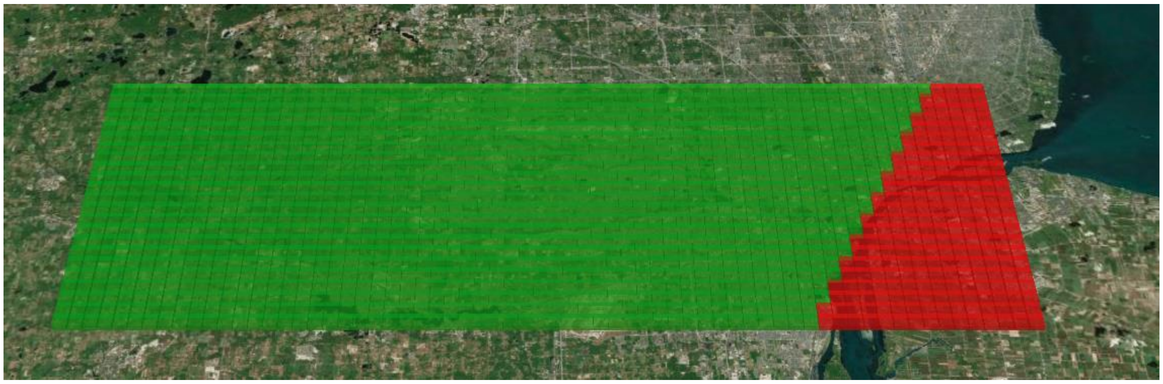


Figure 15, Large Area Instantaneous Risk Likelihood

Over time however, the areas of risk likelihood will change. Figures 16 and 17 show the progression of risk likelihood over a 30-minute period.

Figure 16, Large Area Instantaneous Risk Likelihood – Time Advancing 1

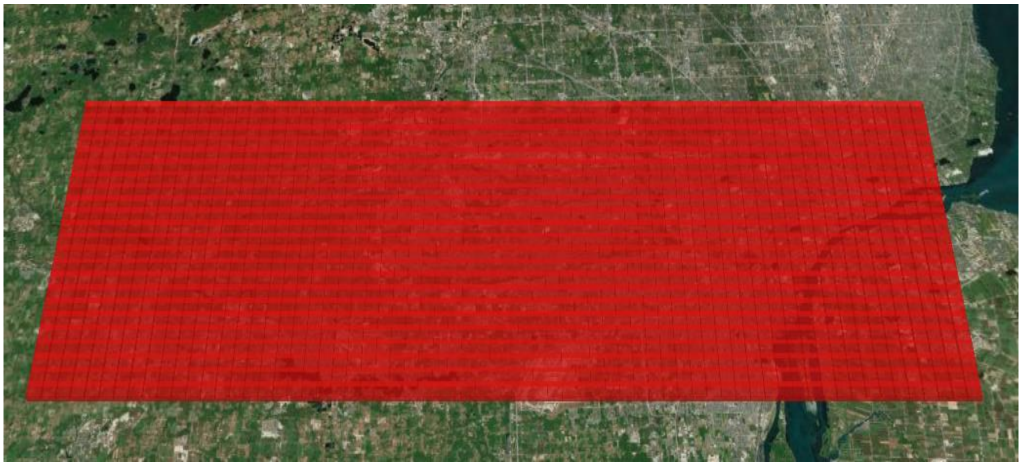


Figure 17, Large Area Instantaneous Risk Likelihood – Time Advancing 2

Communicating Risk to Stakeholders

Stakeholders may need to collaborate to determine steps to take once risk likelihood is identified. Decisions to accept, mitigate or avoid risk can be made much easier when interested parties have the relevant information immediately available. A web application certainly enables that information sharing, especially as it is tailored towards individual and group needs. An Application Programming Interface (API) to share this information is also essential to enable automation.

Sometimes, an exportable document may be desired to share information with stakeholders who do not have access to the application. A stakeholder, such as an insurance provider, may require documentation of the risk analysis and mitigation plan. We imagine such a document would list the overall risk likelihood along with its aggregate component. Timestamps and locations of predicted risk would be documented. Screen captures of 3D visualizations, like those in this paper, would also likely be included to assist with visualizing high-risk portions of an operation.

Understanding risk, and the likelihood of a specific event occurring can be greatly enhanced by visualization. There are various things that can be visualized, analytical results, risk severity, likelihood, and operational statuses. Combining these visualizations into a cohesive, actionable set of information, that does not clutter the screen or confuse the user is a challenge that must be met. Meeting this challenge will allow an effective path for human intervention where required, on the road to automation of operational risk assessments.

DEVELOPING A RELIABLE RISK ASSESSMENT PROCESS

Working with Operators to Develop Tuned Risk Assessments

Developing algorithms that can assess risk likelihood can only go so far. Every algorithm must be tested in operations to make it useful. Our algorithms are no exception and in fact we rely on operational parameters to determine acceptable results. Our risk likelihood algorithms vary by analytical type (navigation, communications, etc.) and the constraints operators put on them. For example, in a communications scenario you may not have connectivity for a short duration of time and, while that is something the algorithm would catch, it may not be something to report or act on to an operator. Temporary communication outages may be fine for a given flight plan. This type of information is needed to 'tune' the algorithms to make them useful not only for operations, but for understanding in a larger context, leading to BVLOS approvals. OneSky is working with operators to make this critical information a part of the risk likelihood algorithmic picture.

Working with the CAAs to implement automated risk analysis pipelines

As risk likelihood moves toward automation, making up a small piece of the approval process, we must also think about the larger picture. BVLOS approvals are complex and can be different for individual CAAs. Just as working with operators can improve the risk picture for flights, working with CAAs can help with the automation process. We fully expect that different authorities will want differing levels of visualization, APIs and reporting for approvals. Working to find the best automation process for CAAs, with the right content needed for their approval is key to making automated BVLOS approval a reality. To that end, we expect differences in visualization and reporting to be the norm and we recommend designing approval processes that allow for this inevitability.

Standardization of algorithms and data to provide consistent risk assessments

As the automation process grows, many vendors will be providing pieces that are needed to flow into the approval chain. Vendors will have different internal methods for producing what each considers the best result for their application. However, to be able to reproduce an approval request's analysis, and effectively make a judgement on the flight plan, we are recommending that standard data and algorithms be used to produce operational risk assessments. When everyone participating in the approval chain is using standardized methods, the results from the analysis can be assured.

This necessarily ties into the idea of a common data infrastructure, used by participating Supplemental Data Service Providers (SDSPs). Vetted, approved data for use by SDSPs employing standard algorithms help legitimize BVLOS automated approvals. As such, we are recommending an approach whereby a common data pipeline is accessible by authorized users in the BVLOS automated approval chain.

CONCLUSIONS

In this paper, we have begun to outline the process for automating BVLOS flight approvals, by showing how an Operational Risk Assessment can be aided by analytics. Risk assessments contain both a severity and a likelihood component, and we have shown how analytical techniques can be applied to determine risk likelihood for flight routes. Risk severity is necessarily tied to the flight CONOPS and has not been dealt with in this paper. We have showed how to combine multiple analytical metrics into a single, aggregate risk likelihood value for the entire flight.

A fault tree analysis technique was provided to understand the depth to which some analytics must be understood, to provide a reliable and accurate risk assessment. The ability to automate tasks for which data and algorithms exist, can greatly reduce the amount of time spent performing the risk assessment.

To make automated risk assessments usable by operators and other stakeholders, the results must be easily understood and transportable to other platforms. This paper’s sections on visualization techniques looks at ways which allow for both high-level, actionable results and the ability to look at each metric in depth.

Finally, we know this process will take many parties and require consideration and agreement along the way. We have touched on a few topics that we already know will need to be addressed as we move toward more automation, such as working with operators, ANSPs and CAAs. Realistically, if there are to be large scale flights from the UAV and UAM community, we must tackle the ORA completion time problem, and move towards an automated assessment capability, where humans in the loop can make quick, accurate decisions for flights at scale, on a routine basis.

APPENDIX A: ALARM LIMITS

Alarm Limits define the upper limit of protection level that is allowed for a given runway approach.

GNSS differential corrections that create a position error that exceeds a given protection level creates an availability hazard since the approach cannot be completed. If the protection level is less than the alarm limit, but the actual error (caused by unknown sources) is greater than the alarm limit, the corrections are considered Hazardous and Misleading Information (HMI).

GBAS and SBAS approaches are designed with the Alarm Limit in mind to ensure that the intended flight path, with the alarm limit as a buffer, does not breach the obstacle clearance surface throughout the approach.

To mitigate the threat of GPS errors, the protection levels and alarm limits are continuously calculated and monitored during approaches, to ensure that protection levels remain below the alarm limits. If this limit is exceeded, then the GPS system is not accurate enough to be used, the approach must be conducted visually or other navigation aids such as ILS.

However, HMI is considered a high-impact threat, since during these events, the position errors are beyond both the protection level and the alert limit. Since these errors are unaccounted and exceed the operational limitations (i.e., the aircraft could breach the obstacle clearance surface), the GNSS error threat is unmitigated. The residual risk of these occurrences must be estimated and judged for acceptability.

Although UAS systems do not currently use the concept of protection levels and alarm limits, the flight intents in a USS do fulfill the role of accommodating aircraft position variation induced by pilot maneuvers, aircraft dynamics, and navigation errors. The boundaries of the flight intent should accommodate the size of expected position errors.

APPENDIX B: ERRORS DUE TO CONSTELLATION GEOMETRY

Figure 1 denotes a simple notional fault tree, that focuses on GNSS errors for brevity. A top tier hazard “Controlled Flight into Static Object” is identified, as well as different subcomponents that can lead to this type of hazard. Erroneously entered flight plan could intersect a building; a correctly entered, but outdated, flight plan is entered; excessive navigation errors during flight; and other factors can lead to this type of hazard.

Navigation errors have their own set of causes such as hardware and software issues; a user misinterpreting altitude; or GNSS errors. Focusing in on GNSS errors, there are several more subcategories that contribute to position errors, for brevity, we limited the scope of the top tier hazard due to position errors caused by the geometry (and number) of satellites tracked:

- Radio Frequency Interference (RFI) presence
- Ionospheric Scintillation
- GNSS Constellation Geometry

Radio Frequency Interference

RFI impacts GNSS receivers by creating noise that either intentionally, or unintentionally inhibits receivers’ ability to track GNSS satellites. The amount of attenuation of the carrier to noise levels depends on the strength of the noise and distance between the receiver and source. The effect of RFI can range from a negligible reduction in carrier to noise density ration (CN0), to inability to track a subset of visible satellites (those with lower CN0 values), to a complete loss of lock on all satellites.

Even though illegal, “personal privacy device” (PPD) jammers are relatively simple and cheap to obtain. Noisy communication equipment and frequency harmonics from other signals can also cause GNSS interference. RFI is likely to be encountered in cities and should be addressed in the CONOPS and ORA. The simplest mitigation method is keeping away from busy roadways and buildings, either horizontally or vertically. Complex hardware mitigation techniques are possible such as dual antenna anti-jamming receivers, directional antennas, and the like.[8]

The operational environment and duration of the mission will affect the likelihood of encountering RFI. It is unlikely that applicants will know some (or any) of the RFI sources in each operational area ahead of time. A site assessment can enable applicants to empirically determine the likelihood of encountering RFI during missions, but that will have its own set of limitations and costs.

Alternatively, instead of avoiding RFI, this hazard can be mitigated by detecting and executing a pre-planned response, such as diversion to an alternate waypoint far away from RFI sources or using alternative forms of navigation.[8]

Ionospheric Scintillation

Another phenomenon that challenges receivers tracking ability is ionospheric scintillation. The interaction of solar ejecta with the Earth’s magnetic field creates masses of free electrons in our ionosphere. Depending on the Earth’s latitude, time of day, and solar activity, GNSS signals that propagate through the ionosphere may not only cause pseudorange delays, but also the possibility of CN0 fading on the order of 25 dB[9].

In mid-latitudes such as the contiguous United States, scintillation is not a concern, but low latitude areas must assess and mitigate this threat. The geo-magnetic equator is particularly susceptible to this fading effect, as it can result in poor geometry or complete loss of position estimates.

GNSS Constellation Geometry

Even under perfect environmental conditions, clock errors in both GNSS receivers and satellites will result in an overall position error that depends on the geometry of the satellite constellation. Variations of this Dilution of Precision (DOP) and User Range Errors (URE) can be calculated based on satellite ephemeris information.[8] A set of satellites widely distributed across the sky (in both elevation and azimuth) will produce better position estimates than a set grouped close together.

More satellites will improve the DOP to varying degrees, and this is another reason why the previous two hazards discussed are important to consider. In addition, artificial masks along the horizon are commonly deployed by end-users to sacrifice the DOP to mask out multipath at launch and landing locations. Buildings that block the line-of-sight vector to satellites also affect the DOP, as well as forecasted (or unannounced) satellite outages.

Though the constellation cannot be controlled by GNSS end-users, several factors are known in advance to calculate and review the DOP in advance of missions:

- Satellite ephemeris data
- Aircraft flight plan

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[8] https://teddriver.net/Papers/Understanding%20GPS%20Navigation%20in%20Contested%20Environments.pdf

[9] https://web.stanford.edu/group/scpnt/gpslab/pubs/papers/Seo_IONGNSS_2008.pdf

- Satellite outage notifications (such as NANU's)
- 3D building data (used to determine line-of-sight vectors to aircraft)

To mitigate errors due to poor satellite constellations, operators could select a maximum allowable DOP parameter as a pre-flight check, and/or actively monitor the DOP and execute a response if a threshold is exceeded.

APPENDIX C: RISK TABLES

These tables here are typical for risk severity and risk likelihood.

Table C1. Severity Definitions

Severity Level	Severity of Occurring Hazard	Value
Catastrophic	Multiple fatalities, equipment, infrastructure and destruction	5
Hazardous	Large reduction in safety margins, possible fatalities	4
Major	Significant reduction in safety margins	3
Minor	Nuisance, minor incident	2
Negligible	Little or no negative consequence	1

Table C2. Likelihood Definitions

Likelihood Level	Definition	Value
Frequent	Likely to occur many times	5
Occasional	Likely to occur sometimes	4
Remote	Unlikely, but possible to occur	3
Improbable	Very unlikely to occur	2
Extremely Improbable	Almost inconceivable to occur	1