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Modifications to ACAS Safety Study Methods for Remotely Piloted Vehicles (RPVs)

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Summary

Estimating the relative safety of a Remotely Piloted Vehicle (RPV) equipped with ACAS will require several extensions to the methods developed in previous ACAS studies. This paper outlines several of these redesign issues. First, it may be necessary to compute the probability that an RPV will experience a critical encounter relative to that for a conventional aircraft. Performing a safety study on only the incremental impact of equipping an RPV with ACAS would circumvent this need. Additionally, methods are proposed to adapt existing encounter models to better represent the likely characteristics of encounters with RPVs. Finally, modifications to the level of detail included in dynamic simulations and fault trees are discussed. It is proposed to shift all dynamic elements out of the fault tree and into a new more complex Monte Carlo simulation.

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Modifications to ACAS Safety Study Methods
for Remotely Piloted Vehicles (RPVs)

1.0 Introduction and Background

1.1 This Information Paper provides an overview of several issues impacting the modeling and analysis methods applied to study ACAS on Remotely Piloted Vehicles (RPVs). The paper is intended to articulate the current status of such a study and to elicit feedback on the proposed methods or modifications to existing methods that are to be applied. The paper does not cover all issues that need to be resolved; rather, it exposes several of the issues thought to be most critical.

1.2 The relative safety of ACAS on conventional aircraft has been estimated through several detailed studies, the most recent of which was the ACASA study completed in 2002 [1]. Extensive notes on the development and execution of this study were archived [2] and subsequently re-examined. The results from ACASA informed States and ICAO regarding the potential safety benefits of equipping aircraft with ACAS.

1.3 Issues related to the use of ACAS on RPVs have been raised at several prior SICASP and SCRSP meetings [3], and a process for performing safety studies of ACAS on RPVs has been articulated in the ACAS Manual [4].

1.4 Starting in October, 2003, MIT Lincoln Laboratory was tasked by the US Air Force to begin a safety study of ACAS on the RQ-4A Global Hawk aircraft.

1.5 The RQ-4A can be flown autonomously from engine start to engine shutdown, with a remote operator able to intervene to tactically command speed, heading, altitude, and vertical speed using a computer interface and communication link. ACAS could potentially be operated in several modes on Global Hawk, including TA-only, RA response by the ground operator, or through an autonomous response to the RA performed on-board Global Hawk. It is generally accepted that a safety study will be required before Global Hawk will be allowed to use ACAS in any RA-producing mode.

1.6 Global Hawk flies a somewhat different flight profile than a conventional aircraft. Its climb rate at takeoff can be as large as 3800 ft/min to 5200 ft/min depending on gross weight. At the same time, the vehicle flies at a relatively slow airspeed, between 135 – 150 KCAS. This results in a flight path angle at takeoff that can exceed 20 degrees at light takeoff weights. Global Hawk also climbs to a cruising altitude of approximately FL650, where it may remain for over 24 hours. Latencies of several seconds between downlink and uplink of information and commands to the ground pilot may occur due to satellite links.

1.7 Lincoln Laboratory has begun reviewing the detailed working papers from the ACASA study to determine what features may be extended or modified for the Global Hawk study, and what features may require completely new modeling or analysis techniques. An overview of the major issues that have been identified from this review are discussed in this Information Paper.

1.8 As in the ACASA study, it is proposed to use a fast-time Monte Carlo simulation, with an encounter model as input. This simulation will provide details on the dynamic evolution of encounters with Global Hawk over a large number of types of encounters. Results can be summarized as a risk ratio, and individual problem encounters can be identified. Additionally, a fault tree model will be applied to examine the larger system-level impact of issues such as failure of ACAS to track an aircraft, or failure of a pilot to respond properly to ACAS RAs. This paper focuses on issues related to the encounter model, simulation, and the fault tree.

2.0 Summary of Prior ACASA Safety Modeling and RPV Differences

2.1 Figure 1 shows a schematic of the major processes that may succeed or fail in preventing a Near Mid-Air Collision (NMAC), defined here, as in the ACASA study, as passing within 500 ft laterally and 100 ft vertically of another aircraft. The figure does not imply a specific order of events or magnitude of effect; it is meant to be conceptual. First, begin at the left side of the figure, considering all possible encounters that may occur between two aircraft. Many of these encounters are benign in that the aircraft pass well separated from one another. This can be attributed mainly to the design of airspace and air traffic control procedures. Should aircraft not be projected to pass well separated from one another, ATC typically issues a tactical vector to the pilot to change speed, heading, or to restrict his or her altitude. This solves the majority of potential conflicts. Should a conflict persist (or be missed by ATC), it is possible that visual acquisition by one pilot of the other aircraft may occur, in which case an evasive maneuver can be performed. Fourth, if ACAS is present on one or both aircraft, a TA or RA may prompt visual acquisition and/or advise a vertical maneuver to avoid a collision. Should all of the prior methods fail, it is still possible that the two aircraft will avoid an NMAC simply due to chance. Should all methods and chance fail, then an NMAC occurs.

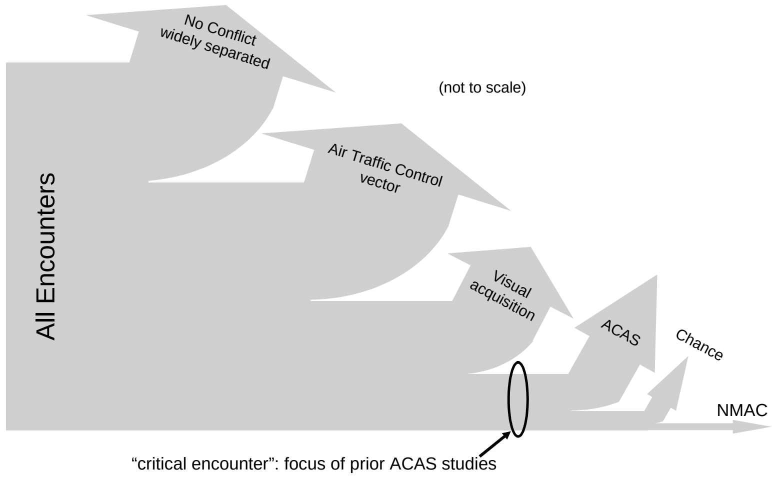

Figure 1: Opportunities to Prevent a Near Mid-Air Collision

2.2 The encounter model used in ACASA modeled the types and frequencies of what are termed here "critical encounters". That is, those encounters for which only ACAS or chance would prevent an NMAC. Airspace structure, ATC vectors, or unprompted visual acquisition were assumed to have already failed by the time that any simulations or fault trees began. ACASA, then, examined the risk of NMAC when the ACAS branch was present in Figure 1 relative to the risk of NMAC when the ACAS branch was not present. Events upstream of the circle shown in Fig. 1 were irrelevant.

2.3 Figure 2 shows a distribution of the various probabilities and encounter types leading up to an NMAC. The circle on the left shows the probability of a Critical Encounter occurring, P(CE). P(CE) is a function of the airspace structure, procedures, ATC clearances, and unprompted visual acquisition. When a Critical Encounter occurs, there is some mix of encounter types, shown schematically in the center circle. This encounter mix was generated through modeling and analysis of observed radar data in the ACASA study. Finally, given an encounter mix, a fast-time simulation was used to estimate the probability of an NMAC occurring, P(NMAC | CE). The encounter mix was adjusted so that P(NMAC | CE) when ACAS was not present resulted in a reasonable baseline NMAC risk value [5]. Note that the overall probability of an NMAC is given by P(NMAC) = P(NMAC | CE) P(CE).

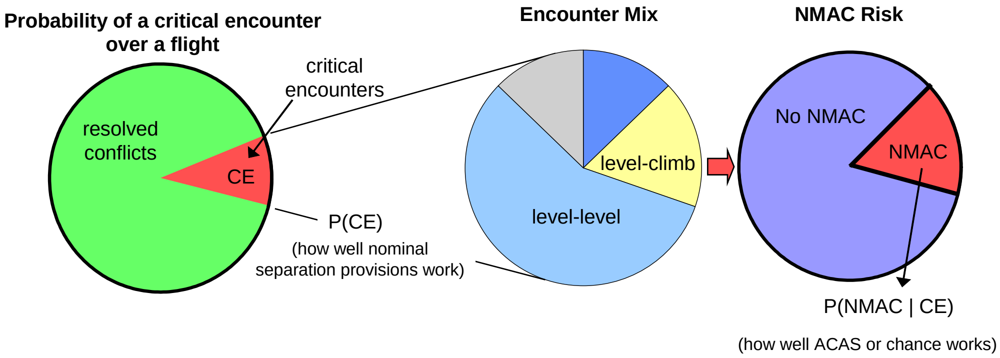

Figure 2: Generation of Probability of NMAC

2.4 Figure 3 shows how the risk ratio was formed in the ACASA study. The top row repeats what was shown in Figure 2, for a case in which ACAS is not fitted. The bottom row shows a similar calculation but in the case where ACAS is fitted. Note that the presence of ACAS has no effect on P(CE) or on the encounter mix: it was assumed that ACAS does not affect the upstream opportunities (ATC vectors, unprompted visual acquisition) to avoid an NMAC. The bottom-right circle shows that with ACAS, some NMACs that would have occurred are resolved, some are unresolved, and some new NMACs may be induced.

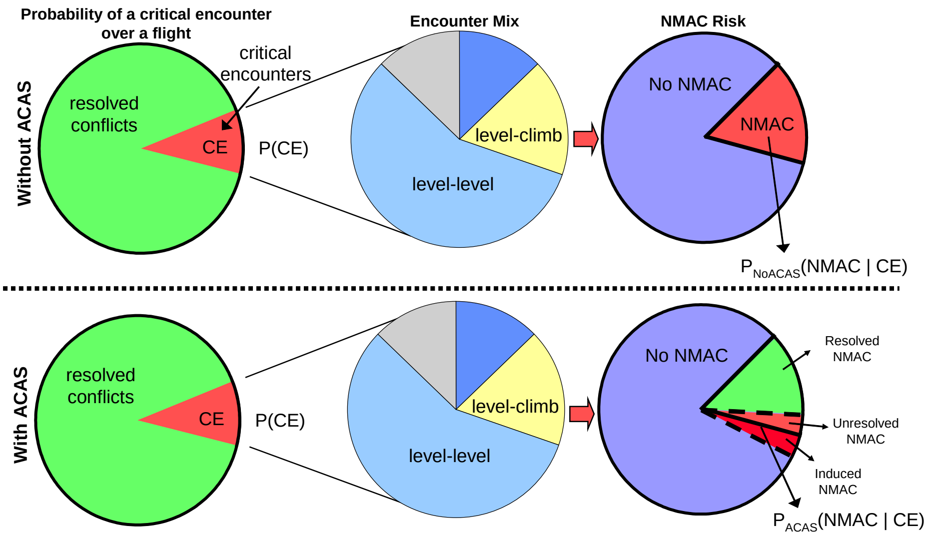

Figure 3: Schematic of the Computation of Risk Ratio

2.5 The risk ratio is then given by:

$$\text{risk ratio} = \frac{P_{ACAS}(NMAC)}{P_{NoACAS}(NMAC)} = \frac{P_{ACAS}(NMAC \mid CE)\,P(CE)}{P_{NoACAS}(NMAC \mid CE)\,P(CE)}$$

$$= \frac{P_{ACAS}(NMAC \mid CE)}{P_{NoACAS}(NMAC \mid CE)}$$

2.6 Note that P(CE) drops out of the equation for risk ratio, and P(CE) need not be computed. Rather, all that is needed is to compute the two conditional probabilities shown schematically by the rightmost circles in Figure 3, based on the encounter mix that has been generated.

2.7 Next, consider the case of an RPV such as Global Hawk. Recalling the branches in Figure 1, there may now be differences in each branch between what happens with the RPV vs. what happens with a conventional aircraft. The RPV may be strategically flown in a more segregated manner, reducing the likelihood of a close encounter, and ATC vectors may be issued differently or be responded to differently than for a conventional aircraft. Visual acquisition will certainly differ, as there will be either no visual acquisition from the RPV, or visual acquisition based on some type of new sensors and possibly additional algorithms. As discussed earlier, the RPV may also fly a different flight profile than a conventional aircraft, leading to a different encounter mix.

2.8 The implication of the issues in paragraph 2.7 are that P(CE) and the encounter mix are in general different for an RPV than they are for a typical conventional aircraft. By studying only the incremental effect on safety of equipping with ACAS, it is possible to avoid estimating P(CE), as was the case in ACASA and in the equation given in paragraph 2.5. If a safety study of RPVs is performed to analyze the risk ratio between the RPV with ACAS vs. the RPV without ACAS, then at a minimum it is likely that a new encounter mix model will be required.

2.9 Should an overall relative risk estimate be required relative to conventional aircraft, however, it will be necessary to examine the difference in P(CE) between conventional aircraft and RPVs. The risk ratio calculation will require the following equation, where P(CE) must now be estimated for both RPVs and conventional aircraft. This would result in a significantly more complex problem than has been addressed before.

$$\text{risk ratio} = \frac{P_{RPV}(NMAC)}{P_{conventional}(NMAC)} = \frac{P_{RPV}(NMAC \mid CE)\;\; P_{RPV}(CE)}{P_{conventional}(NMAC \mid CE)\;\; P_{conventional}(CE)}$$

3.0 Proposed Vertical Profile Model Modifications for Global Hawk

3.1 As discussed in Section 2, at a minimum a new encounter mix must be developed for RPVs. The ICAO and ACASA Encounter models are comprised of tables that describe the initial encounter situation between two aircraft, including data such as whether the aircraft are level or climbing, the vertical speed, and whether the aircraft turn during the encounter [6,7]. Corresponding to each type of encounter in the table is a probability that serves to weigh a given encounter type relative to the others. The encounter data was compiled from filtering observations of actual aircraft tracks in radar data.

3.2 Because there is not enough radar data of Global Hawk flying in the vicinity of other aircraft from which to compile a similar table of encounters, it is necessary to make appropriate extensions of the original encounter tables to apply them to Global Hawk.

3.3 The basic proposal for the Global Hawk extension is to assume that the ACASA (or ICAO) encounter model defines a background distribution of air traffic flying various trajectories which Global Hawk will fly through. The probability of a certain type of encounter occurring depends on the probability that Global Hawk is flying a certain flight profile and on the conditional probability of encountering another aircraft in some flight profile given Global Hawk's behavior. Let *AB* represent a joint event in which Global Hawk is flying vertical profile *A* (e.g., climbing) and another conventional aircraft is flying vertical profile *B* (e.g., level). Then,

$$P(AB) = P(B \mid A)\, P_{GH}(A)$$

3.4 We assume that $P_{GH}(A)$ will be specified from the concept of operations for Global Hawk for the safety study. This may be based on the anticipated fraction of time that Global Hawk will spend in a certain flight profile, for example. This concept of operations is currently being developed.

3.5 $P(B \mid A)$ can be obtained from the ICAO or ACASA encounter models by reversing the above relationship, based on conventional aircraft:

$$P(B \mid A) = P(AB) \,/\, P(A)$$

where $P(AB)$ is the value given in the table cell corresponding to encounter type *AB* and $P(A)$ is the sum of all conventional encounter probabilities in which at least one aircraft is flying profile *A*.

3.6 Probabilities for other parameters, such as vertical rate or ground speed, are chosen independently for each aircraft in the ICAO and ACASA models. There is therefore no need to make additional modifications to this process: the values for the conventional aircraft will be selected as before, and values for Global Hawk will need to be specified from a new RPV-specific probability table defined in the concept of operations.

3.7 To summarize, the required data to form a Global Hawk encounter model includes:

1) Tables of conventional encounter types and their probabilities. This is readily available from the ACASA study and from the ICAO encounter model. From these data, the conditional probabilities of aircraft flying different trajectories can be computed as described in 3.5 above.

2) Probability of Global Hawk flying a particular vertical profile in that airspace. This will require further assumptions regarding how often Global Hawk will level off vs. continue its climb to cruising altitude, etc.

3.8 A demonstration of the modification technique to the ICAO encounter model for an assumed Global Hawk flight profile is provided in the Appendix to this paper.

4.0 Altitude Layer Probability Issues for Global Hawk

4.1 ACAS safety studies use an encounter model in which a key parameter is the altitude layer in which a critical encounter occurs. Each altitude layer has a corresponding weight so that risk ratios from all altitudes can be combined into a single overall risk ratio. Altitude layer weights were obtained from observational data that generated a statistical model of how often critical encounters occurred in these altitude layers.

4.2 Because Global Hawk flies a different flight profile from a conventional aircraft (namely, it spends the majority of its time above FL 410), the relative weights of critical encounters at different altitudes will vary from the ICAO or ACASA models that were based on conventional air traffic.

4.3 One possible method to handle this difference is to examine performance in each altitude layer in isolation. The safety study then becomes one in which the relative safety of the RPV is assessed in each altitude layer separately; the relative risks of NMAC in each layer are not combined together with different weights as was done in ACASA. This isolation method is proposed for the current RPV safety study, as it greatly simplifies the effort and avoids making several necessary but debatable assumptions. Ideally, favorable risk ratios would be obtained in each altitude layer. Combining altitude layer risk ratios would only be necessary if the risk ratio in some layers is not favorable -- so that the relative benefit in some layers can be weighed against the increased risk in others.

4.4 If a single overall risk ratio is required, additional modeling will be required. It may be possible to build a statistical altitude layer model based on assumptions of the amount of time the RPV will spend within each altitude layer, its average speed, and the background rate at which traffic encounters occur. However, for the reasons stated in the previous paragraph, such a modeling effort is not expected to be required.

5.0 Simulation and Fault Tree Modifications for Global Hawk

5.1 Prior studies of ACAS risk ratio have used a combination of two evaluation tools: dynamic fast-time Monte Carlo simulation of aircraft encounters, and static system-level fault trees [1]. The Monte Carlo simulation focused on ACAS collision avoidance logic performance using specific pilot response and aircraft dynamic models. All other considerations (e.g., failure to track, visual conditions, aircraft equipage) were placed in the fault tree.

5.2 The models used to perform safety assessment have grown significantly in complexity. The fault tree used in 1983 had 15 input probabilities; the latest ACASA study fault tree required 61 inputs.

5.3 Some of this complexity is due to a need to model dynamic events, such as visual acquisition prompted by a TA or RA. For several reasons, these non-logic dynamic events were incorporated into the fault trees rather than into the dynamic simulation. This makes the Monte Carlo simulations simple and therefore facilitates running many simulations in a reasonable amount of time. It also enables trade studies of varying event probabilities to be computed instantaneously in the fault tree as opposed to requiring a complete re-run of the Monte Carlo simulation. However, it also means that the fault tree becomes extremely complex, due to the fact that fault trees are inherently inefficient at representing dynamic events, especially when the order of events is important.

5.4 Fault trees constructed to date have focused on the very specific problem of modeling ACAS safety in conventional aircraft. The trees would require significant modification to incorporate issues such as one-sided visual acquisition (because there is no possibility of visual acquisition from Global Hawk). The trees are also not amenable to improving the accuracy of visual acquisition models, because the trees are not able to take into account dynamic factors such as target size, distance, and whether it is within the windscreen field of view. The incorporation of future sense-and-avoid systems into the fault tree would also be a complex task.

5.5 Computational power has grown by over two orders of magnitude since the 1980s. This suggests that it would be possible today to develop a Monte Carlo simulation 100 times more complex as that used in the 1980s and still be able to obtain results in a reasonable amount of time.

5.6 Lincoln Laboratory is therefore proposing making several significant changes to the level of detail in the Monte Carlo and fault tree models to be used to evaluate ACAS on Global Hawk. It is proposed to shift all dynamic elements that currently reside in the fault tree, into the Monte Carlo simulation. This includes visual acquisition and air traffic control response. The shift of these elements into the dynamic simulation will enable using more sophisticated models, and will also allow the simulation to study events occurring before or after an RA is issued in more detail than was possible before. The fault tree will retain static events (static within the timescale of a single encounter between two aircraft) such as aircraft equipage, visual / instrument conditions, and equipment functionality (e.g., failure to supply Mode C altitude information).

5.7 Future sense-and-avoid systems that are proposed can be introduced into the dynamic simulation in a similar manner, without requiring a major redesign of the fault tree. At a high level, each system that senses aircraft state and provides information to the pilot can be incorporated in a similar manner in the dynamic simulation. This includes ACAS, visual acquisition, air traffic control, and other new sense-and-avoid systems.

5.8 It is understood that these modifications will slow down the Monte Carlo simulation. We do not believe that the growth in computation time will be excessive, and the fault tree will be streamlined and considerably simplified. Running trade studies of varying parameters (e.g., visual acquisition performance) will require re-running the Monte Carlo simulation, but again this is not expected to be a major barrier.

5.9 The new modeling approach (where visual acquisition and air traffic control response are placed in the dynamic simulation) can be validated against the prior fault tree model. Validation can be achieved by setting the dynamic visual acquisition and air traffic control models to act in an identical manner to their behavior in the prior fault tree. That is, in each simulation run, there will be a simple probability test to determine whether visual acquisition or air traffic control intervention will take place, just as was done in the fault tree. Should visual acquisition occur, for example, then the simulation will be terminated as a miss case, as was done in the prior fault tree. Once the overall model has been validated in this manner, more advanced visual acquisition and air traffic control models may be injected as needed.

6.0 Conclusion

The panel is invited to consider and discuss the modifications that are proposed here relating to encounter modeling, altitude layer weights, and simulation / fault tree design for a safety study of ACAS in RPVs. Of special interest are any concerns or identified errors in assumption or methodology that should be addressed before beginning to implement these modifications.

Appendix: Example Encounter Model Modification for Global Hawk

Table 1 shows the ICAO encounter model that defines vertical profile classes as specified in [6]. The "Before" and "After" columns refer to each aircraft's vertical profile before and after the closest point of approach. For example, in Altitude Layers 1-3, the probability of a level-level vs. transition-level encounter that crosses in altitude (Class #3) is 0.00049.

Table 1: ICAO Encounter Model Vertical Profile Classes [6]

(L = Level, T = Transitioning)

	Aircraft 1		Aircraft 2		Altitude	Layer 1-3	Layer 4-6
Class	Before	After	Before	After	Crossing	Probability	Probability
1	L	L	T	T	Y	0.00502	0.00319
2	L	L	L	T	Y	0.00030	0.00018
3	L	L	T	L	Y	0.00049	0.00009
4	T	T	T	T	Y	0.00355	0.00270
5	L	T	T	T	Y	0.00059	0.00022
6	T	T	T	L	Y	0.00074	0.00018
7	L	T	L	T	Y	0.00002	0.00003
8	L	T	T	L	Y	0.00006	0.00003
9	T	L	T	L	Y	0.00006	0.00003
10	L	L	L	L	N	0.36846	0.10693
11	L	L	T	T	N	0.26939	0.41990
12	L	L	L	T	N	0.06476	0.02217
13	L	L	T	L	N	0.07127	0.22038
14	T	T	T	T	N	0.13219	0.08476
15	L	T	T	T	N	0.02750	0.02869
16	T	T	T	L	N	0.03578	0.06781
17	L	T	L	T	N	0.00296	0.00098
18	L	T	T	L	N	0.00503	0.00522
19	T	L	T	L	N	0.01183	0.03651

Recalling Section 3, if we are given a Global Hawk profile, say B, then the probability of encounter class AB is

$$\mathrm{P}(AB) = P(A \mid B)\, P_{GH}(B)$$

where $P_{GH}(B)$ is the probability that Global Hawk flies profile B. We compute $P(A \mid B)$ from the values in Table 1 using

$$P(A \mid B) = P(AB) \,/\, P(B)$$

where $P(B)$ is the probability that either aircraft flies profile B in Table 1.

For example, the probability of either aircraft flying an LT profile can be found by summing all probabilities for classes that include at least one LT: this includes classes 2, 5, 7, 8, 12, 15, 17, and 18. The four profile probabilities[1] then are:

$$P(\mathrm{LL}) = 0.780$$
$$P(\mathrm{TT}) = 0.475$$
$$P(\mathrm{TL}) = 0.125$$
$$P(\mathrm{LT}) = 0.100$$

Next, we can find conditional probabilities that one aircraft will fly profile A given that the other aircraft flies profile B. Two examples (using values for altitude-crossing geometries) are:

$$P(\mathrm{LL} \mid \mathrm{TL}) = P(\mathrm{LL,TL}) \,/\, P(\mathrm{TL}) = (0.00049)/(0.125) = 0.00392$$
$$P(\mathrm{TL} \mid \mathrm{LL}) = P(\mathrm{LL,TL}) \,/\, P(\mathrm{LL}) = (0.00049)/(0.78) = 0.00063$$

All other combinations of conditional probabilities are similarly computed.

The computations to this point have been independent of anything that Global Hawk may do; they simply serve to generate probabilities that will be needed later. The above computations need only be done once, and would apply to any future analyses that may be required.

Now, we come to the part that does depend on Global Hawk's flight profile. Assume that in Altitude Layers 1-3 Global Hawk has the following vertical profile frequencies (these are entirely hypothetical at the moment; actual values would depend on the Global Hawk concept of operations):

$$P_{GH}(\mathrm{LL}) = 0.200$$
$$P_{GH}(\mathrm{TT}) = 0.700$$
$$P_{GH}(\mathrm{TL}) = 0.075$$
$$P_{GH}(\mathrm{LT}) = 0.025$$

[1] Note: there is no problem that these probabilities sum to greater than one, because they are not mutually exclusive events.

We then use the equation above to find the resultant joint probability of an encounter with a specific Global Hawk profile. For example, an encounter between a conventional aircraft flying LL and Global Hawk flying TL in an altitude-crossing encounter has probability:

$$
\begin{aligned}
P(\text{LL,TL}) &= P(\text{LL} \mid \text{TL})\, P_{GH}(\text{TL}) \\
&= (0.00392)(0.075) \\
&= 0.000294
\end{aligned}
$$

Alternatively, an encounter between a conventional aircraft flying TL and Global Hawk flying LL in an altitude-crossing encounter has probability:

$$
\begin{aligned}
P(\text{TL,LL}) &= P(\text{TL} \mid \text{LL})\, P_{GH}(\text{LL}) \\
&= (0.00063)(0.20) \\
&= 0.000126
\end{aligned}
$$

We must be careful to distinguish (TL,LL) from (LL,TL) – the second profile listed within each parentheses corresponds to the one flown by Global Hawk. Unlike the earlier analyses, it will be important to keep track of which of the two aircraft in the encounter is the RPV.

A similar set of calculations would be performed for every other possible combination of encounters between Global Hawk and a conventional aircraft. A parallel set of modifications can be performed on the ACASA vertical profile model as well [7].