Analysis of mid-air close encounters in gliding competitions and proposal for a penalty based remediation

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1 Introduction

This technical report presents details of a system to analyse track information from gliders in competition to determine frequency of close encounters, being moments in which both aircraft are at a greatly elevated risk of mid-air collision. A set of data from previous FAI World Gliding Competitions is analysed using this system to provide insights on close encounter risk factors. Finally, a system is proposed to encourage safe competition flying by penalising pilots who frequently fly close to others.

1.1 Background

With WGC 2017 being held at the author's home club at Benalla, the unfortunate occurance of two mid-air collisions, and reported crowded airspace in several task days with relatively low ceilings, gave the authors the idea to make use of IGC flight logs to analyse the joint proximity of gliders participating in the competition.

An analysis system was implemented and results provided to WGC 2017 stewards and safety officers in an ad-hoc basis. Some of the results were presented to pilots of WGC 2017 in safety briefings.

Arising from the analysis capability and protest reports, were indications that particular pilots were engaging in risky behaviour. This led to the idea of introducing a scoring penalty system to shape behaviour away from that which results in 'near-misses'.

The proposed penalty system was implemented for testing and review purposes during WGC 2017.

1.2 Goals

The basic goals of the project are two-fold:

- Assess safety of gliding competitions;
- Improve safety, by using data products to help increase awareness of collision risk, and by shaping pilot behaviour by introducing a penalty system to discourage risky flying.

To achieve these goals, this study intends to use data from several previous FAI World Gliding Competitions to:

- Determine the typical risk level of competitions
- Classify risky behaviours or scenarios that frequently result in close encounters.
- Support identification of risk factors in tasking and general competition rules.
- Support development of a penalty scheme and show retrospectively, in previous competitions, how risky pilots could be identified and how penalties could have been applied.

1.3 Scope

As this is a preliminary study, several technical issues arising require more detailed work and are beyond the scope of this study:

- Aspect analysis (blind spots etc, higher risk)
- GPS/logger accuracy influence on results
- Detailed analysis of tasking involving AAT/AST, conflicting tasks, etc
- Optimal selection of suitable close encounter distance thresholds and times
- Optimal selection of penalty scoring parameters

These items are recommended topics for further study.

1.4 Acknowledgements

Matt Gage; Terry Cubley; John Orton

2 Proximity analysis calculations

Calculating close encounters can be performed from any source of time-stamped position information that is of sufficient data rate. IGC files, as used in all FAI gliding competitions, are a suitable source.

2.1 Source data

The competition data used in this analysis, and their short form labels, are listed below:

31st WGC 31st FAI World Gliding Championship, 2010, Prievidza Slovakia; comprising World, Club, and Standard classes.

32nd WGC 32nd FAI World Gliding Championship, 2012, Uvalde USA; comprising 15-meter, 18-meter and Open classes.

33rd WGC 33rd FAI World Gliding Championship, 2014, Leszno Poland; comprising 15-meter, 18-meter and Open classes.

34th WGC 34th FAI World Gliding Championship, 2017, Benalla Australia; comprising 15-meter, 18-meter and Open classes.

The IGC flight logs were downloaded from http://www.soaringspot.com and from http://wgc2017.org.

2.2 Close encounter detection

In developing the means of calculating close encounters, it is necessary to define a set of measures incrementally:

- Close encounters shall be measured for each pair of gliders flying concurrently, each second.
- The glider position is defined as the location of the logger as recorded by the IGC logger, or, where the logger rate is less than once per second or experiences bad fixes, an interpolated location is used. The interpolation scheme used is a Catmull-Rom interpolation of latitude, longitude, and altitude.
- Barometric altitude is used in calculating vertical separation since it is a more reliable measure of altitude than available from GNSS systems in loggers.
- Glider to glider separation is given by the distance between the positions of each glider, being the hypotenuse of the right angle triangle of relative horizontal distance, and relative vertical separation according to altitude.
- A threshold distance is applied to filter out separations not considered to be close encounters. Half of this threshold is also used to filter out vertical separations. The encounter envelope, therefore, appears as a sphere with truncated top and bottom, aligned with the Earth vertical axis.
- The threshold geometry is established to define an envelope that matches likely orientations of a glider in typical competition flight.
- Incursion distance is the deficit of the separation and the threshold distance.

- Further filtering, such as exclusion of team-mates, can additionally be applied if such information is known.

Interpolation resulting from low fix rate and fix dropouts introduces a source of error into the separation calculations, but is necessary to estimate the location of aircraft at equal times. Determining the impact of the interpolation error, and potential enhanced interpolators, is beyond the scope of this study.

More sophisticated proximity envelopes could be developed making use of each aircraft's attitude (particularly, bank angle). However, since attitude is not directly measured and recorded by conventional gliding loggers, such information would need to be estimated from wind-corrected paths.

2.3 Close encounter episodes

A close encounter is defined as a sequence no longer than a maximum time in which a pair of aircraft are in close encounter.

Because the filtering scheme is a discrete measure, it is possible for two aircraft to alternately fall within and outside the threshold over a short period of time. Consequently, the encounter detection algorithm allows for this switching within 10 seconds of the first incursion when considering to merge incursion events into the one encounter.

2.4 Implementation details

Computations detailed in this paper performed on an Intel i5-7200U PC with single core processing, with the analysis taking approximately 15 minutes to calculate statistics and 15 minutes to generate a multitude of plots.

Most of the statistics algorithms were implemented in the C++ language using the XCSoar (www.xcsoar.org) codebase and Perl language for postprocessing. This code will be made available for others to use under the Gnu Public License (GPL).

2.5 Algorithm parameters

Parameters of the algorithms used in this study were set as follows:

Threshold separation distance 30 meters

Threshold separation height 15 meters

Maximum encounter time 45 seconds

Encounter hysteresis time 10 seconds

3 Proximity analysis results

For the present study, close encounters between team-mates were not excluded from the statistics. Close encounters for this study include interactions between all competition aircraft across all classes flown on a given day.

3.1 Insights: basics

Using proximity statistics of competition flight logs, it is possible to determine the close encounter frequency during gliding competitions. This can be used to determine several trends:

Individual competitions Were some competitions higher risk than others? Is there an annual trend?

Number of competitors How do close encounters relate to the number of competitors?

Task duration Are close encounters more frequent as tasks get longer or shorter? How much of the total close encounter time is per instance of competition day, and how much is incremental in time? In other words, is the risk due to flying a competition day, or does the duration of the task increase or decrease the risk?

Competition class Does the manoeuvrability and glide performance of different classes influence close encounter frequency?

3.1.1 Flight time

Close encounter statistics were calculated for each task day of the four competitions under investigation. Figure 1 shows the total flight time (number of aircraft-hours) flown for each competition day, as well as the average flight time per aircraft. Although the total flight time varies considerably due to tasking and number of classes included each day, the average flight time per aircraft per day is approximately four hours.

Also observable in these statistics is a slight increase in the number of total flight hours per competition day each time the WGC is held. The increased participation rate increases the potential for close encounters simply because the number of aircraft to aircraft interactions increases as the square of the number of participants.

3.1.2 Task duration

In order to assess the effect of task duration on close encounter rates, the average flight time of flights within a class per day is used as a proxy measure for task duration. Figure 2 shows the average flight time for all classes, all competition days under investigation. A linear regression fit of the data is also shown, and shows that task duration has almost no effect on close encounter rates.

Potential effects of task duration on close encounter rates include:

- Longer tasks increases separation (improves situation)
- Longer tasks increases total exposure (worse if there is an encounter rate per time)
- Longer tasks decreases ability to separate start window times

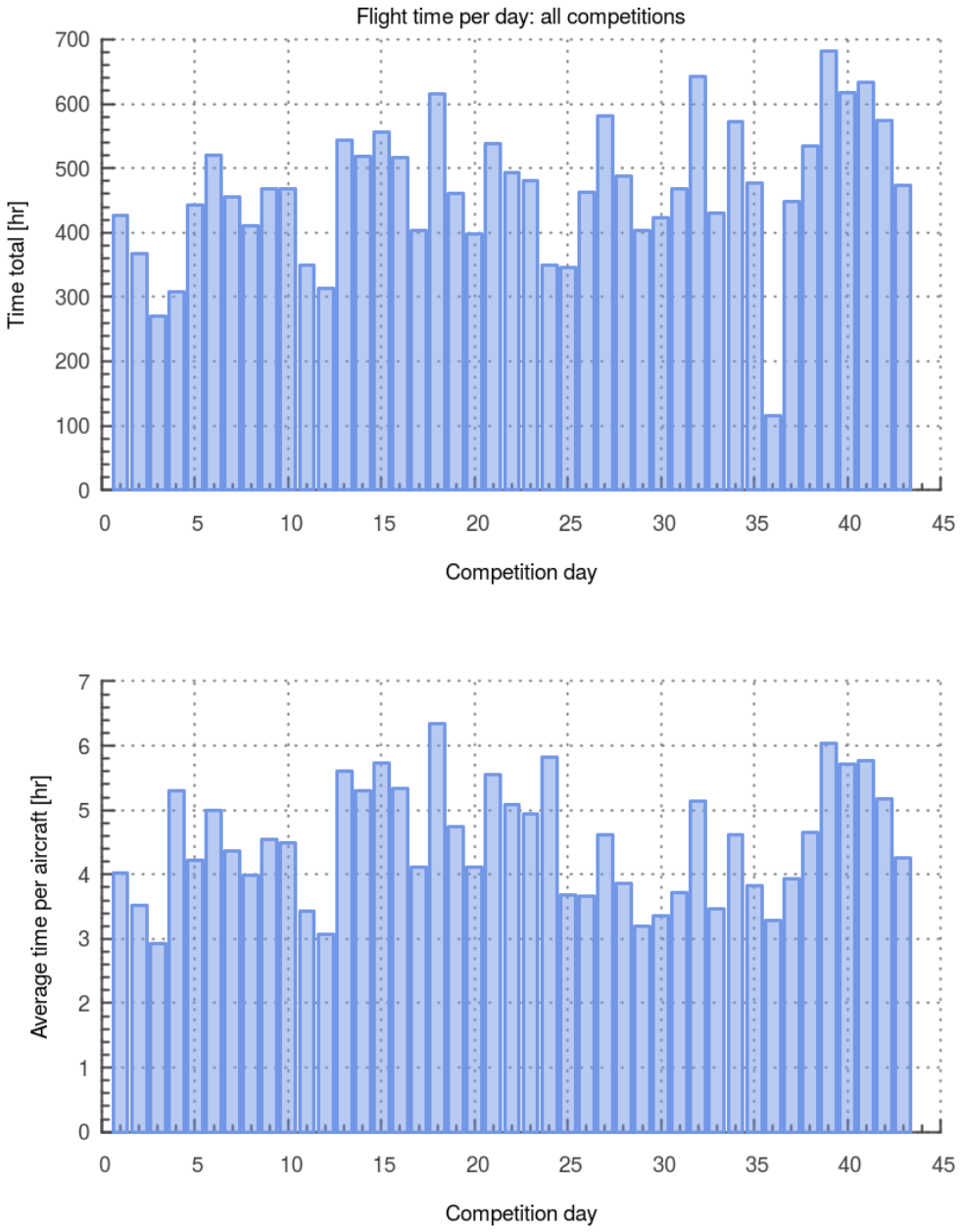

Figure 1: Flight times, all competitions

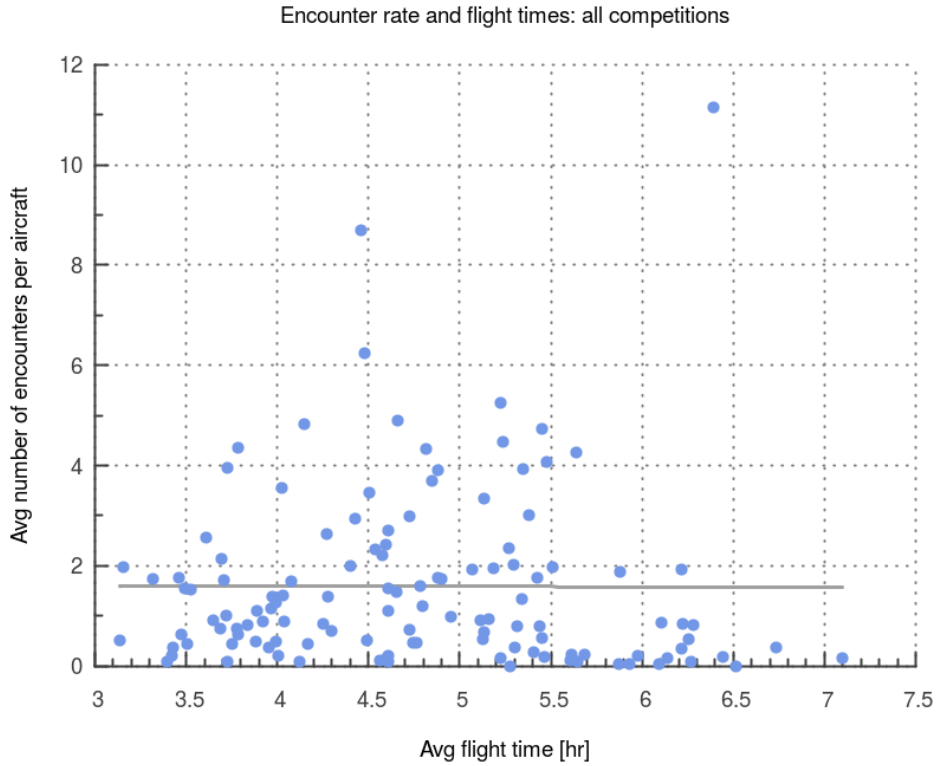

Figure 2: Close encounter rates and flight times, all competitions

These factors may each influence the encounter rates. Speculation as to why the task duration does not have a significant effect on encounter rates is beyond the scope of this study.

3.1.3 Close encounter time

The accumulated duration of close encounters, as shown in Figure 3, shows a very large variation both across competitions, and from day to day. There appears to not be a strong relationship between day of task and close encounter frequency — indicating that the risk level is not affected significantly by pilot competition currency or fatigue.

Figure 4 shows how close encounter time are correlated with total, and per aircraft flight time per day. The data shows a large scatter, indicating only a weak reduction in the close encounter exposure as flight time increases. There is therefore no clear evidence in this data set that longer duration tasks reduces the risk of collision.

3.1.4 Close encounter duration

Figure 5 shows the frequency distribution of encounter duration across all competition days. This shows that the bulk of close encounters are fleeting (within 5 seconds), but there are a significant number of longer encounters up to 20 seconds. Some of these longer encounters may be between team-mates.

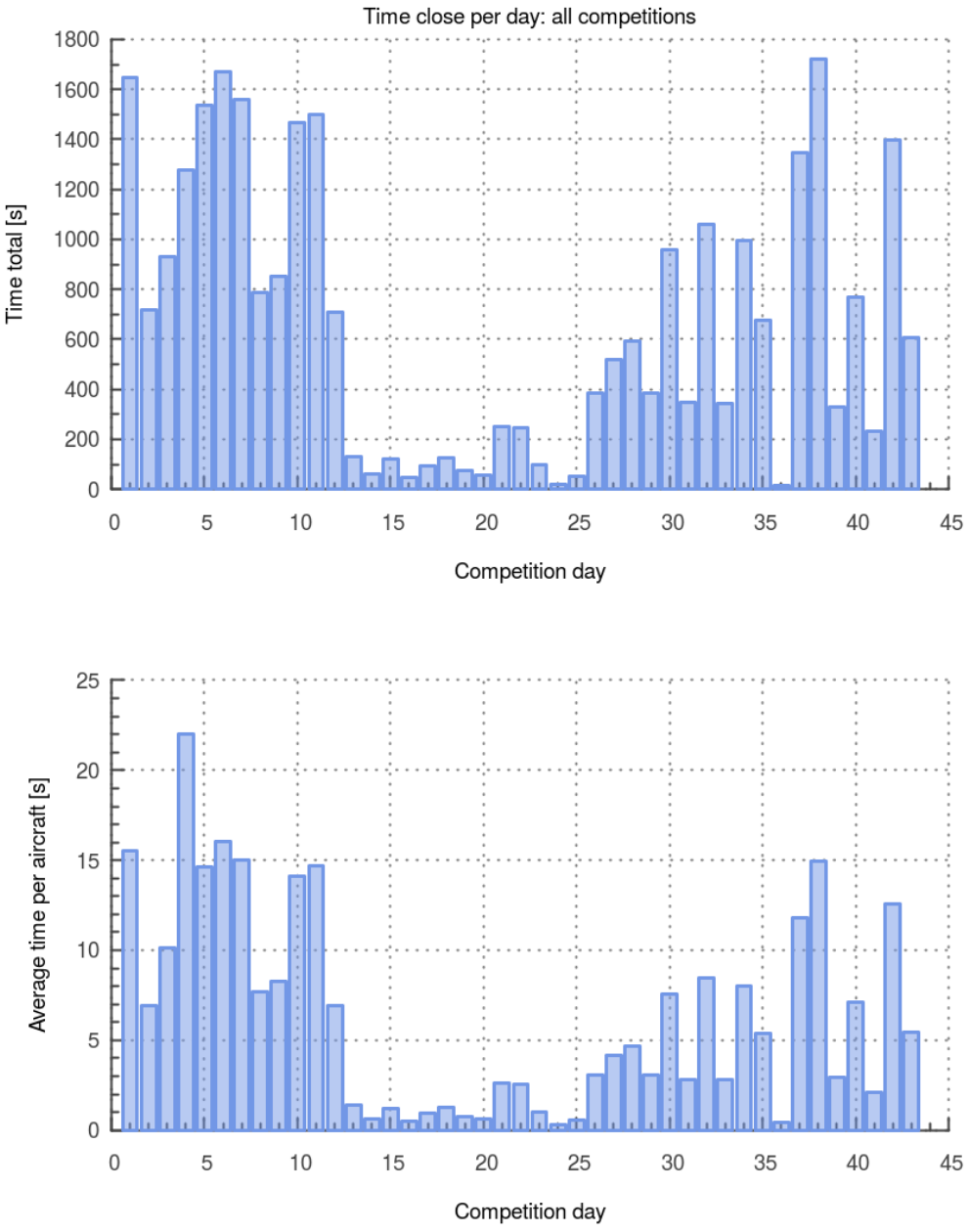

Figure 3: Close encounter times and flight times, all competitions

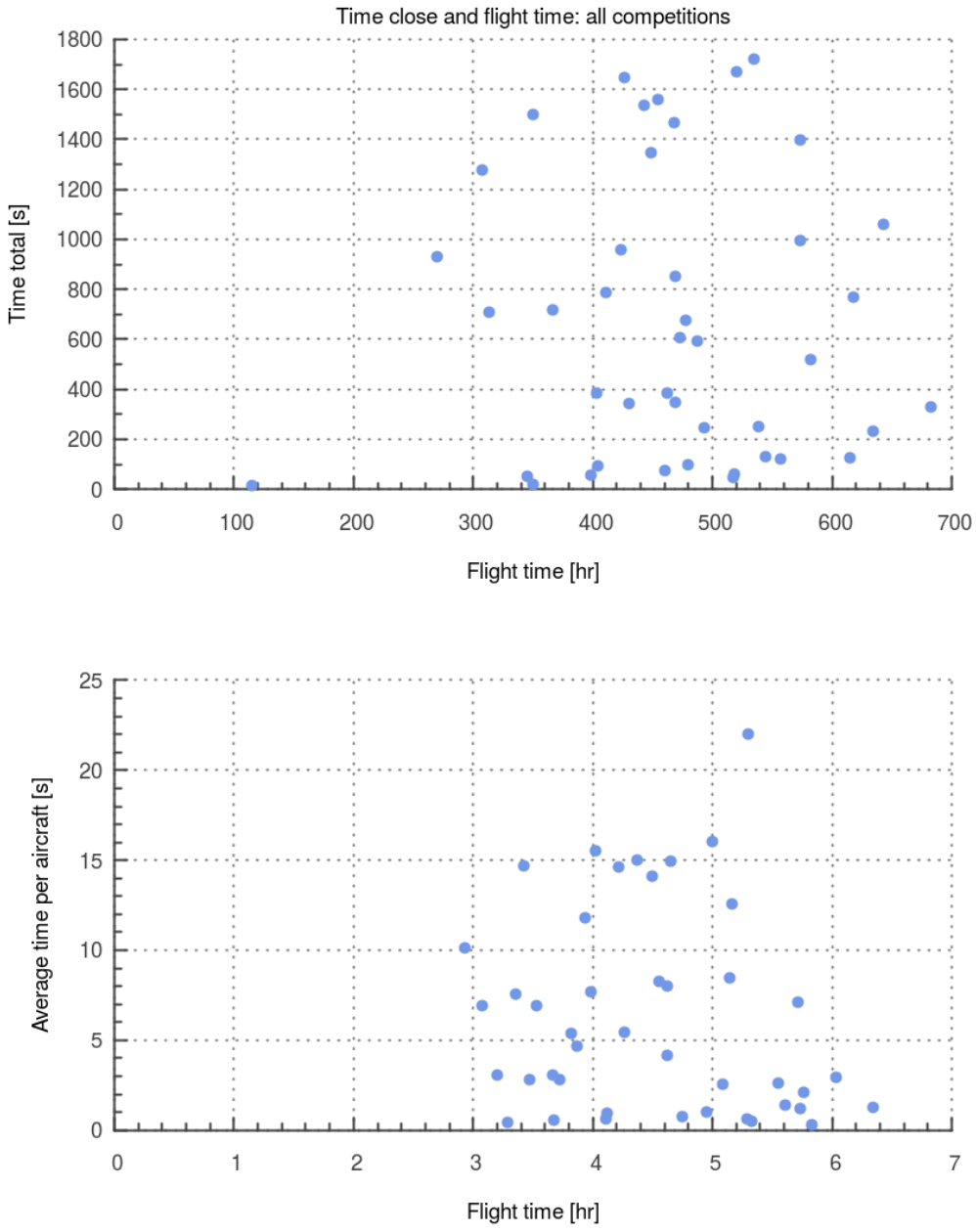

Figure 4: Scatter plot of close encounter time with flight time, all competitions

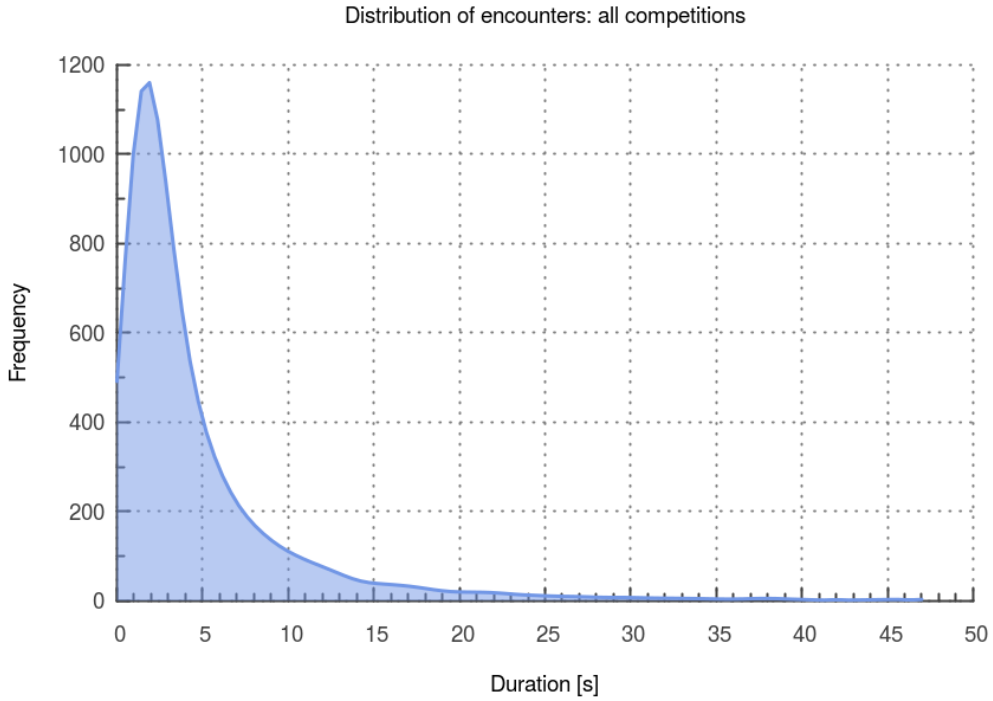

Figure 5: Frequency of close encounters duration, all competitions

3.1.5 Competition class

The effects of competition class on close encounter rates are difficult to assess accurately because each class typically involve different numbers of aircraft, and further study involving more historical data is advised. Nevertheless, the close encounter rate per aircraft within each class (that is, the number of close encounters involving any aircraft within a class, divided by the number of aircraft in the class), provides a simple measure to indicate differences.

Figure 6 show the close encounter rates per aircraft separated by class, for all competition days under investigation. The bar indicates the average value for each class. It is notable that higher performance aircraft are associated with lower close encounter rates.

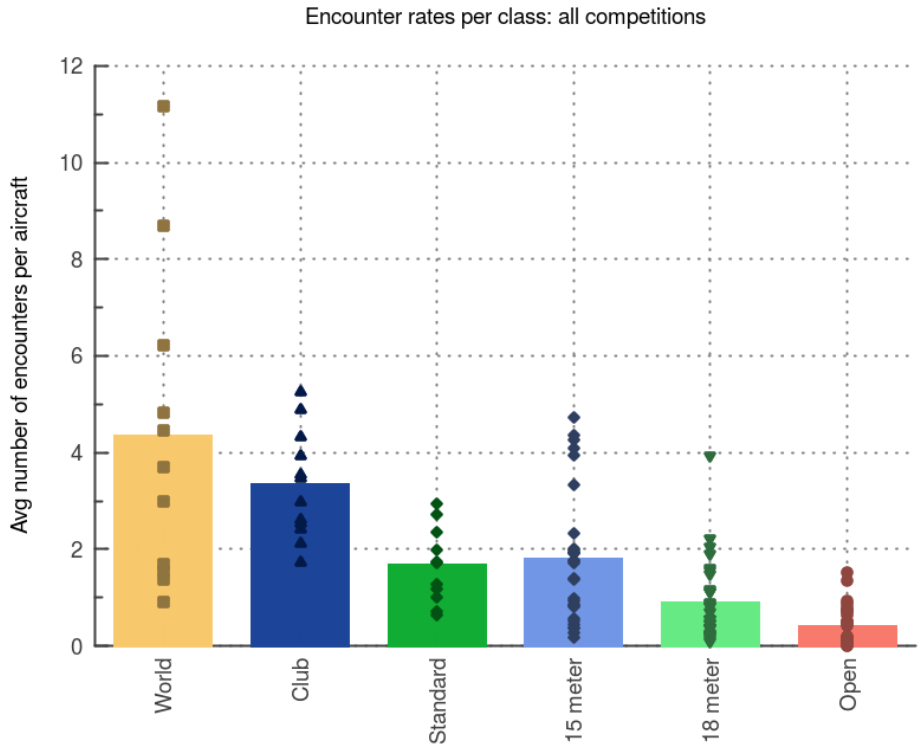

Figure 6: Close encounter rates per class, all competitions

The potential effects of classes on close encounter rates include:

- Lower performance may encourage gaggle flying
- Higher manoeuvrability may encourage risky behaviours
- Longer wingspans may reduce pilot appetite for close flying

There is insufficient data to speculate further on effect of class on risk.

3.2 Insights: contributing factors

Using proximity statistics of competition flight logs, it is possible to perform quantitative analysis to provide insights into potential contributing factors to high close encounter frequency during gliding competitions.

Candidate factors that can be explored include:

Individual pilot behaviour Are some pilots more frequently involved in close encounters? This is expanded on in Section 5.

Soaring conditions Intuitively, if the convection ceiling is low then one would anticipate more gaggle flying and expect higher risk. This hypothesis can be tested.

Site factors Are some sites better suited to uncrowded competitions?

Task types Assigned Area Tasks (AAT) and Assigned Speed Tasks (AST) may have a different effect on glider spacing and close encounter frequency. Because in a given day, there may be a mix of AAT and AST, the present study excluded investigation of task type as beyond the scope of the work.

Phase of task How much of the close encounter risk occurs during the start gaggle?

3.2.1 Weather (working ceiling)

Gaggle flying is typically regarded as being more common when weather conditions are weak, such as when convection is weak, the working height is low, and without the presence of cumulus. Because weaker conditions are usually accompanied by a lower working height, all the competition aircraft are squashed into a smaller volume and therefore more likely to have close encounters.

Without performing a more detailed analysis of average climb rates of gliders during the competition, an initial investigation of the effect of weather on close encounter frequency was performed by considering the distribution of close encounter times with maximum height in all competitions, as shown in Figure 7.

This shows that for moderate ceiling heights, there is not a strong relationship between close encounter time and maximum height; but at heights above 3000 m, the data shows the close encounter rate decreases dramatically. From the competitions sampled in this study, however, such conditions all occurred at a common site, Uvalde USA, and therefore there may be other site-specific reasons for the lower close encounter rate than altitude. More study would need to be done to be more confident in this factor, but weather is also not a controllable factor anyway.

3.2.2 Geographical distribution

Competition sites, their local geography, airspace and weather, offer different levels of freedom for task-setters to physically separate the classes by having them fly in different bulk directions. Figures 8 through to 11 show the geographical distribution of close encounter points for each of the WGC competitions investigated.

The high concentration of encounters near the competition site can be readily observed in these figures. Also notable is that some sites have differing levels of constraint on allowable tasking regions.

3.2.3 Glider spacing

In order to assess whether site constraints and tasking separation has an effect on encounter frequency, the average spacing between gliders can be calculated during each competition day and used as a measure of how well separated the classes are in space and time. Figure 12 shows how total close encounter time per aircraft varies with the average glider spacing.

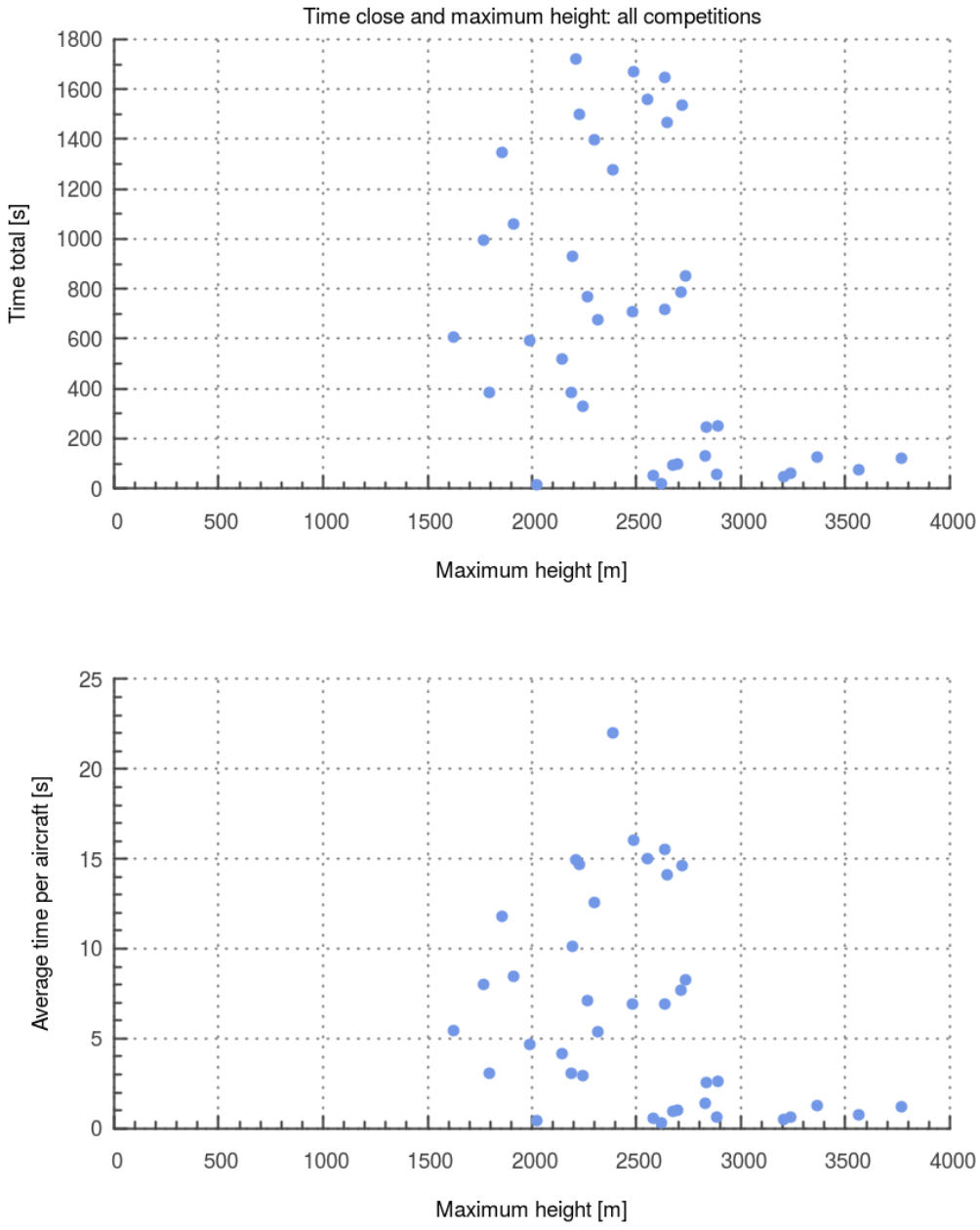

Figure 7: Scatter plot of close encounter time with maximum height, all competitions

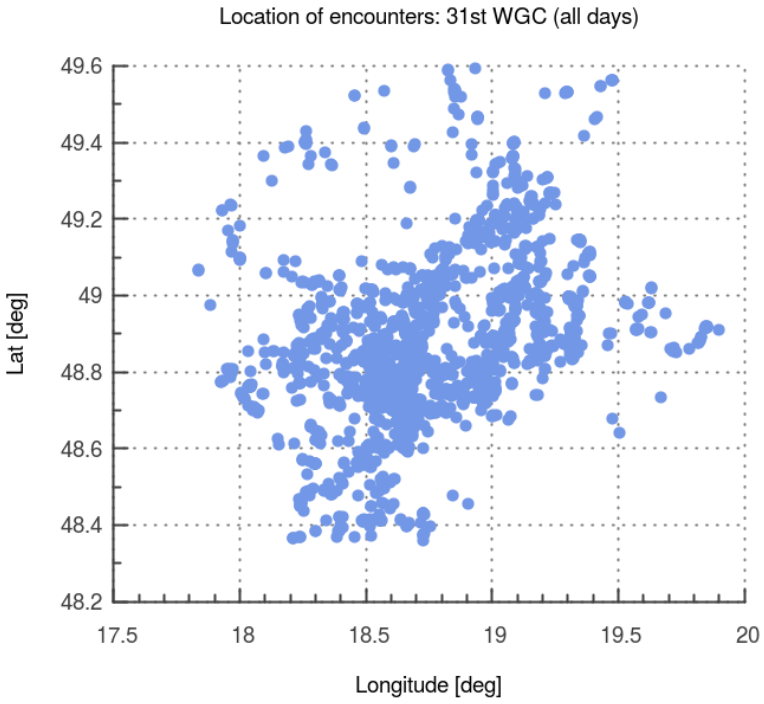

Figure 8: Distribution of close encounters with location, 31st WGC

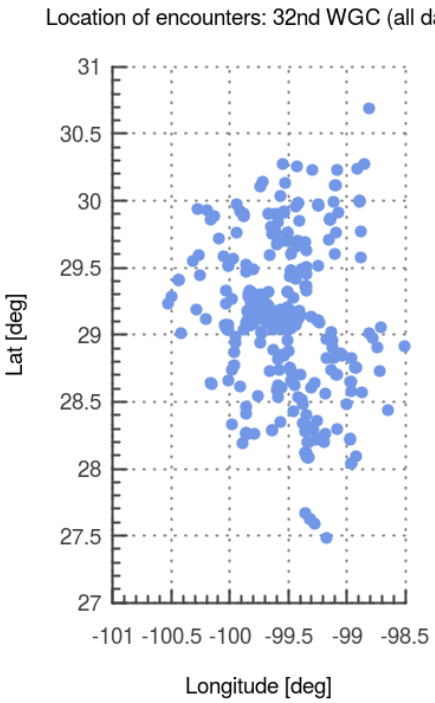

Figure 9: Distribution of close encounters with location, 32nd WGC

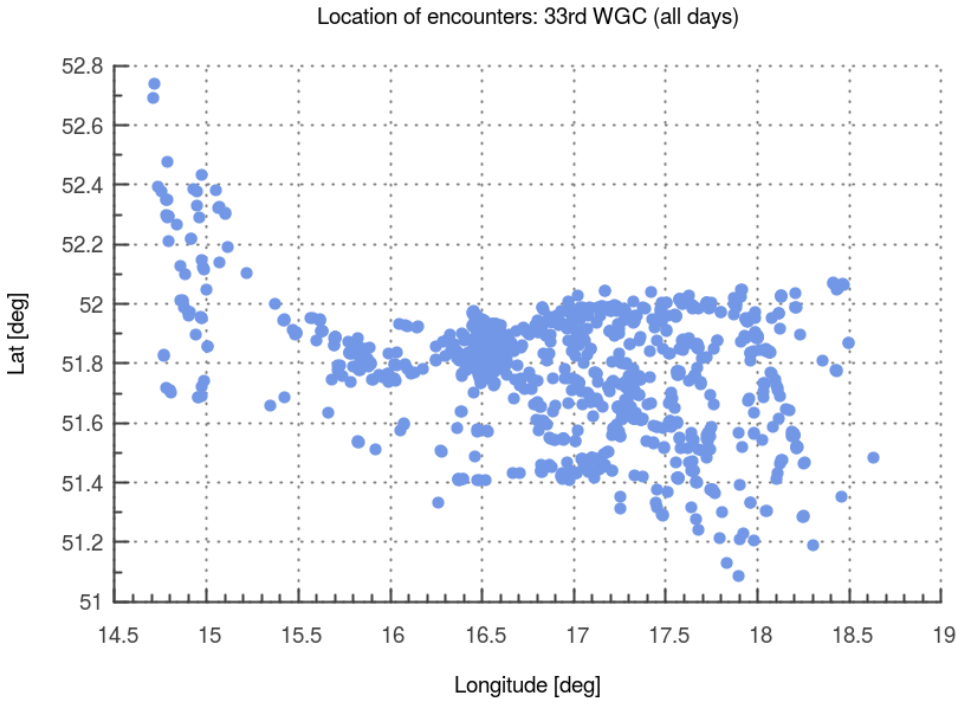

Figure 10: Distribution of close encounters with location, 33rd WGC

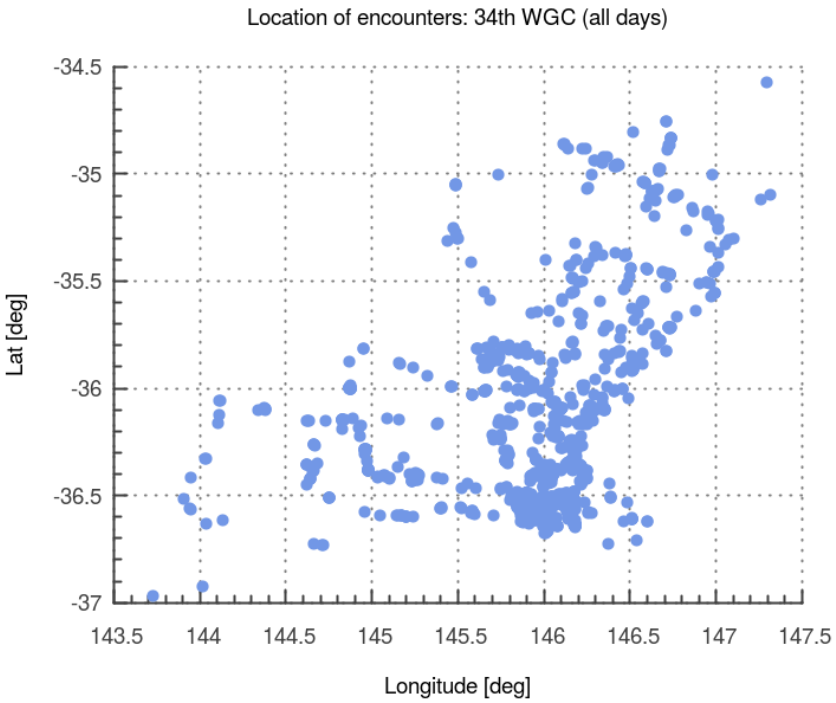

Figure 11: Distribution of close encounters with location, 34th WGC

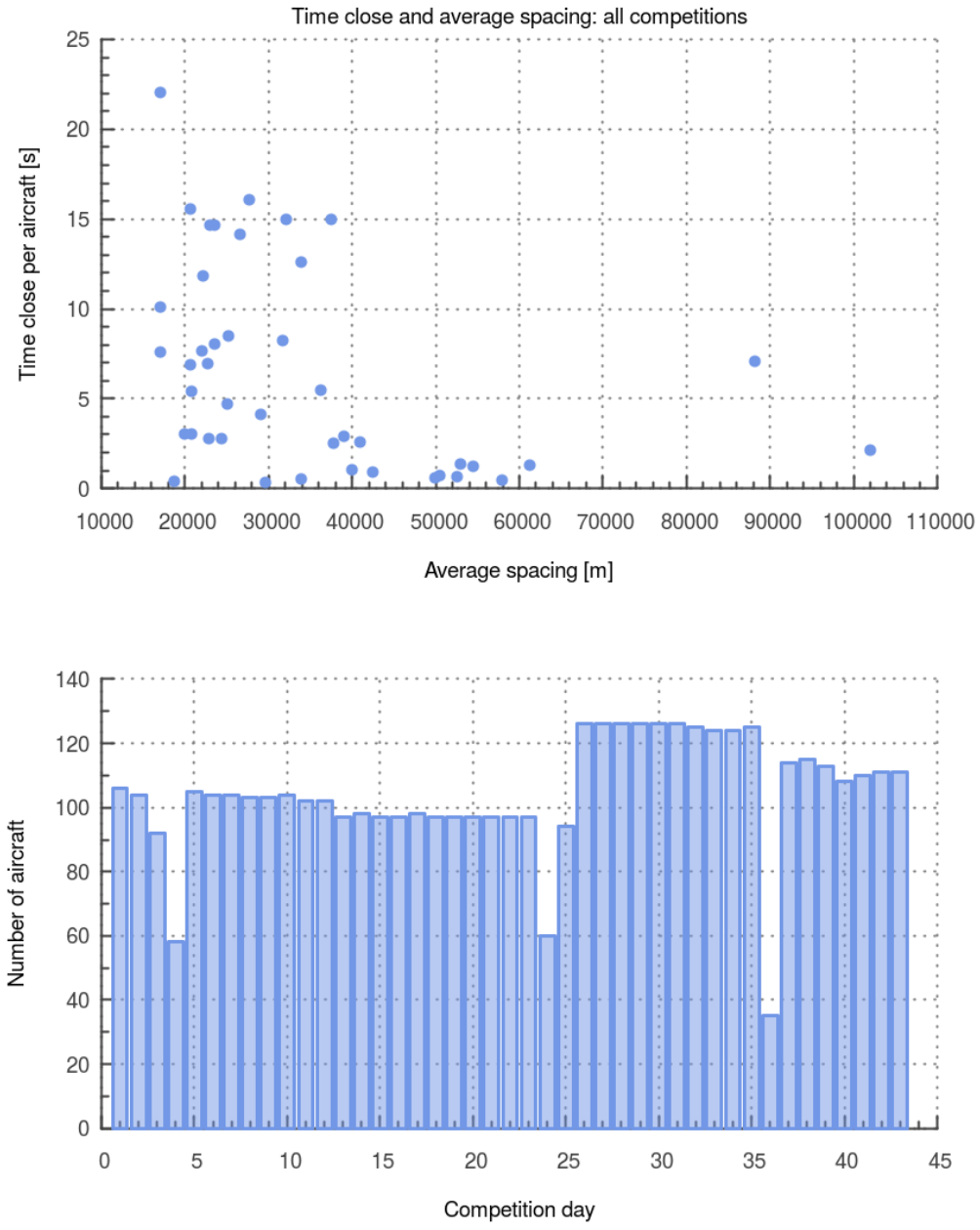

Figure 12: Close encounter time and average spacing, all competitions

From this figure it can be observed that there is a strong trend that increasing average spacing decreases the close encounter frequency; though it is also notable that for even small average spacing values, there are many competition days that have a low frequency of close encounters.

This indicates that whilst task spacing is a very important factor that can drive down close encounter frequency, it is also possible to achieve low frequency of close encounters by other means.

Although task separation, longer distance tasks and use of AAT can all encourage greater separation between gliders, it is well-known that none of these factors are entirely effective at eliminating gaggle behaviour particularly during the pre-start and post-start phase. This may explain why the data shows a few competition days of higher number of close encounters despite having a very large average glider separation.

3.2.4 Task time and altitude

Figure 13 shows the distribution of close encounter events during a typical task day (34th WGC day 71G) with each point representing the task time of day of the encounter and the altitude at which it occurs.

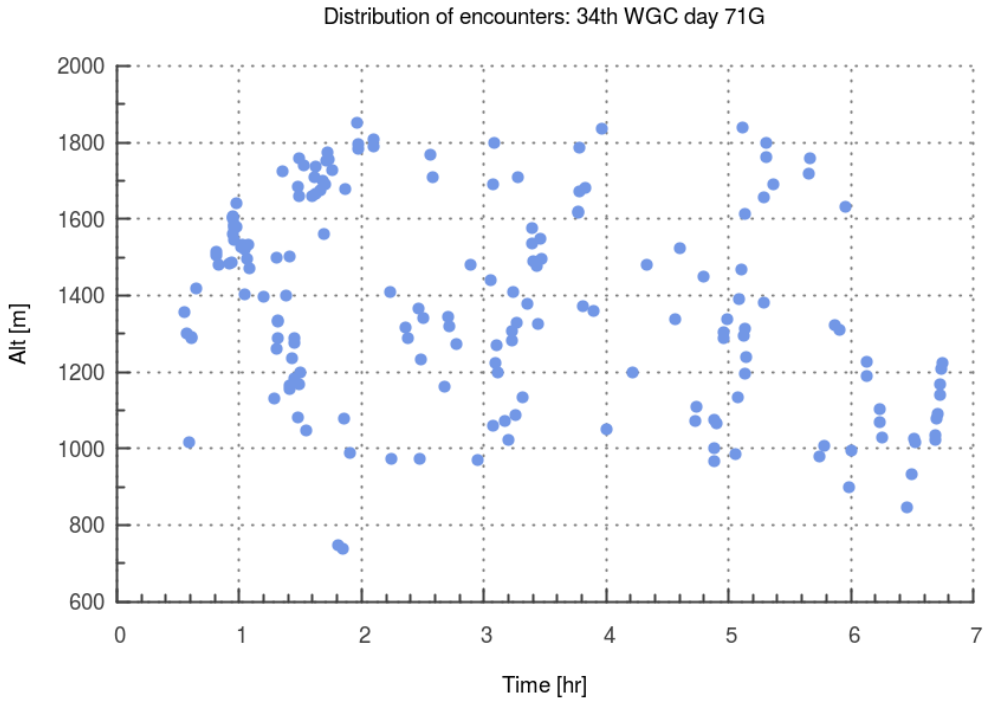

Figure 13: Distribution of close encounters with task time and altitude, 34th WGC day 71G

There is a peak of encounter frequency at the start of task, likely due to a combination of factors:

- At this stage of the competition day, all aircraft in all classes are confined to a relatively small area near the competition launch site location.
- The effect of having separation of tasks for each class is weakest in this period.

During the task start phase, the encounter altitude tends to increase in time as the just-launched gliders tend to climb in a gaggle together.

It is also noteworthy that high concentration of encounters occurs after task start, where gaggle and close following behaviour is likely to occur — in this phase, the aircraft within a class haven't had sufficient time to spread out naturally from competitive differences in performance.

After task start, there are several clusters of higher concentrations of encounters where gaggles form. This varies from the start and post-start gaggle pattern in that the encounters occur at a larger range of heights.

Figure 14 shows the density of encounter events across altitude for the same day (again, 34th WGC day 71G). This pattern is typical for the competitions investigated in this study. Generally, encounter concentration occur in a bell-curve centered in the typical working height band of the gliders.

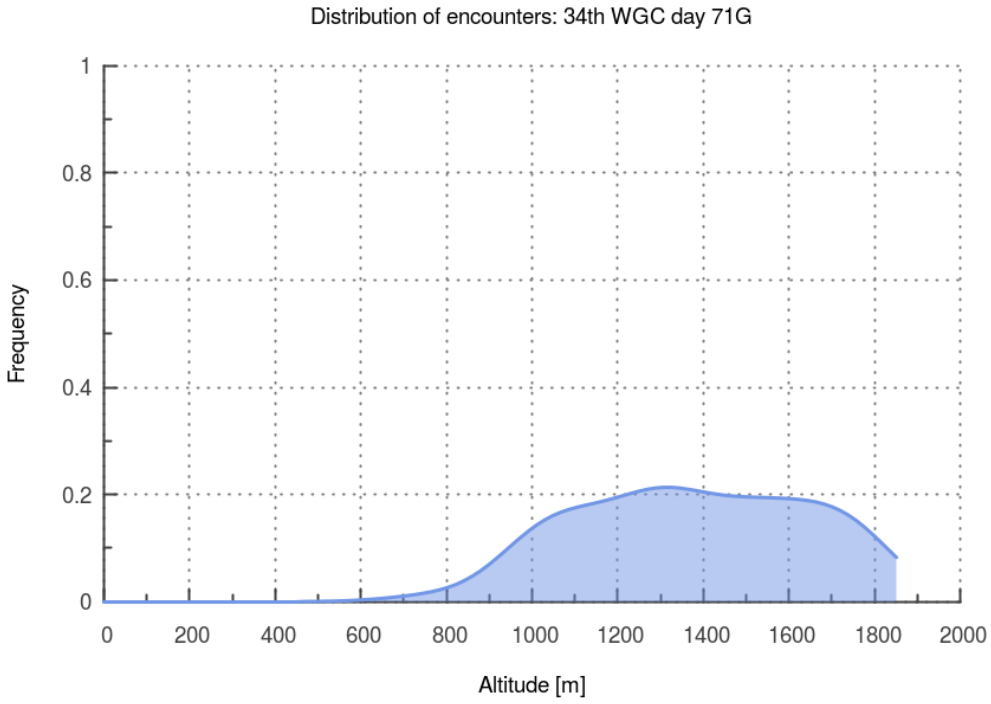

Figure 14: Frequency of close encounters with altitude, 34th WGC day 71G

Figure 15 shows the density of encounter events across task time of day for the same day. This pattern is typical for the competitions investigated in this study. Generally, the largest peak concentration occurs during pre-start and post-start gaggles, with often a series of smaller peaks later in the task day.

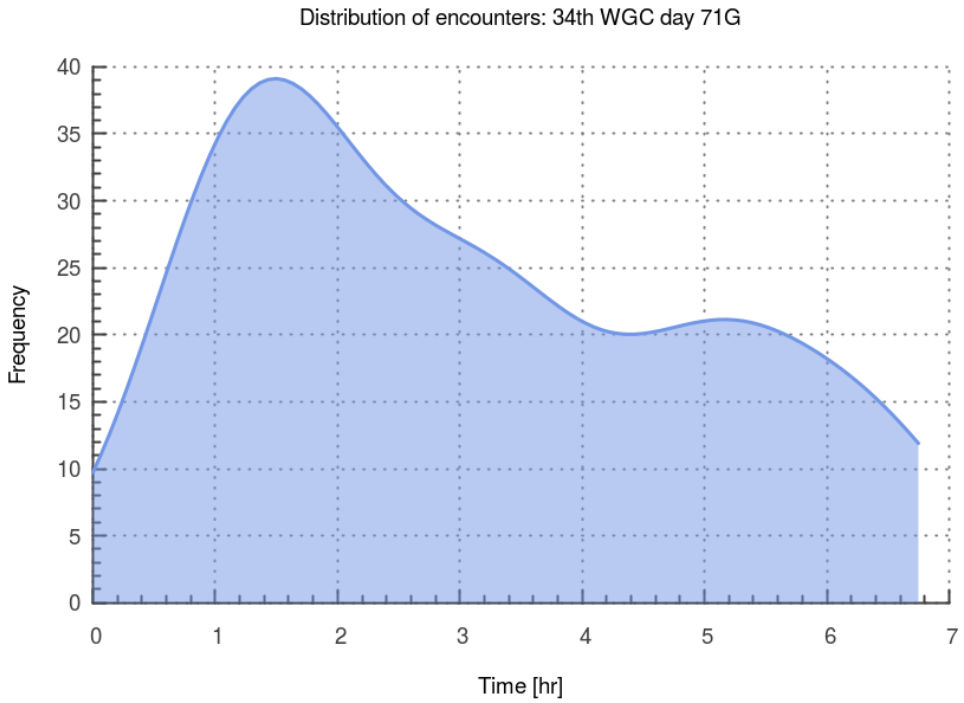

Figure 15: Frequency of close encounters with task time, 34th WGC day 71G

4 Encounter analysis

A secondary product from performing close encounter analysis is the set of identified close encounter episodes that can be extracted for review. This enables the production, automatically, of graphcs, animations, and flight reconstructions (such as using third party flight simulations such as SilentWings) in order to illustrate what occurred.

4.1 Applications of encounter extraction

One application of this type of product is to assist competition officers to resolve disputes or investigate protests about reported near-misses or particular pilots. It would be difficult if not impossible to develop an algorithm that attempts to identify deliberate risky behaviour, but inspection of an encounter by a competition officer may be used in assessing some degree of fault.

Secondly, the set of close encounter episodes can be analysed to determine common factors about the episodes themselves. This may lead to improve awareness of which situations and pilot actions result in close encounters.

Determining what type of close encounter patterns are highest risk of mid-air collision is beyond the scope of this report.

Note: flight reconstruction is not able to be performed accurately without an IMU, but some information about airspeed and bank angle can be inferred from the trace.

4.2 Encounter patterns classifier

A simple technique was developed to classify the types of close encounters by assigning labels to each involved aircraft based on its basic turning state:

- At each second, the turn mode (climb, possible transition to cruise, cruise, possible transition to climb) is calculated based on the previous state and current turn rate.
- This turn mode is converted to a letter or symbol:

  C Climb; circling

  X Possible transition to cruise; exit

  G Glide; cruise

  E Possible transition to climb; entering
- This symbol is appended to a list if it varies from the previous symbol

The turn mode logic from XCSoar was used in this implementation.

At the first point of incursion, each aircraft then has a sequence of symbols representing its pattern of flight. For example, 'GEC' would indicate the glider was in cruise, then entered climb, then was established in climb.

Joining these sequences together with a dash produces an identifier for the joint encounter. These identifiers are referred to as an encounter pattern.

4.3 Frequency of encounter patterns

The encounter patterns corresponding to all close encounters in the investigated competitions were collected, and sorted to identify the most frequent patterns. Figure 16 shows these patterns ranked by frequency.

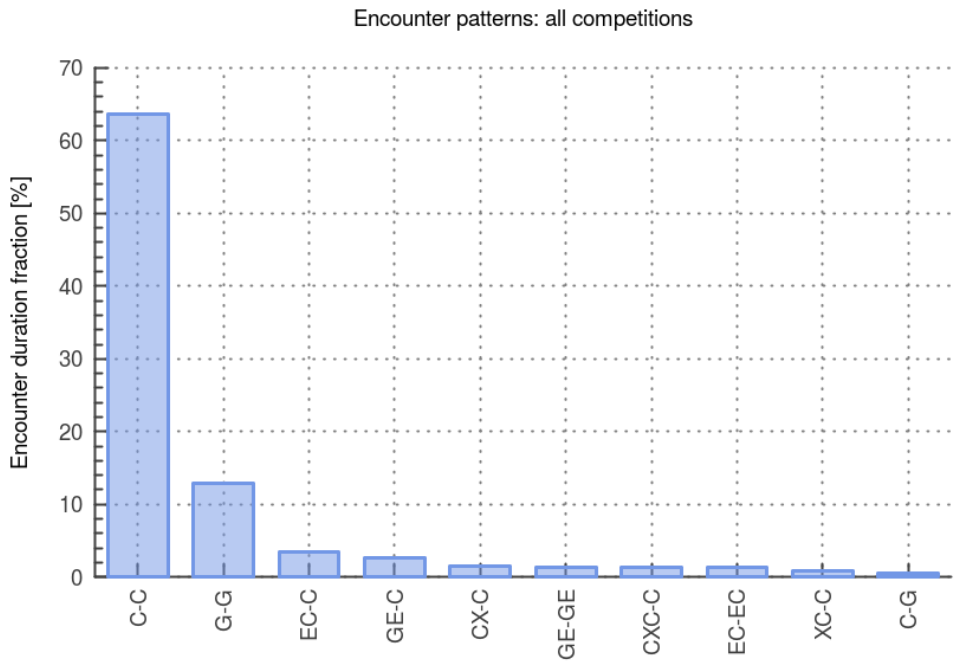

Figure 16: Ranking of encounter patterns, all competitions

The most frequent patterns are as follows:

C-C Both aircraft circling (64%)

G-G Both aircraft gliding (13%)

EC-C One aircraft entering then circling, the other circling (3.5%)

GE-C One aircraft gliding then entering, the other circling (2.7%)

CX-C One aircraft circling then exiting, the other circling (1.5%)

Combined, transition to and from climb makes up around 7.7% of the encounters.

4.4 Encounter pattern examples

Figures 17 and 18 show an example of a close encounter where both aircraft are climbing.

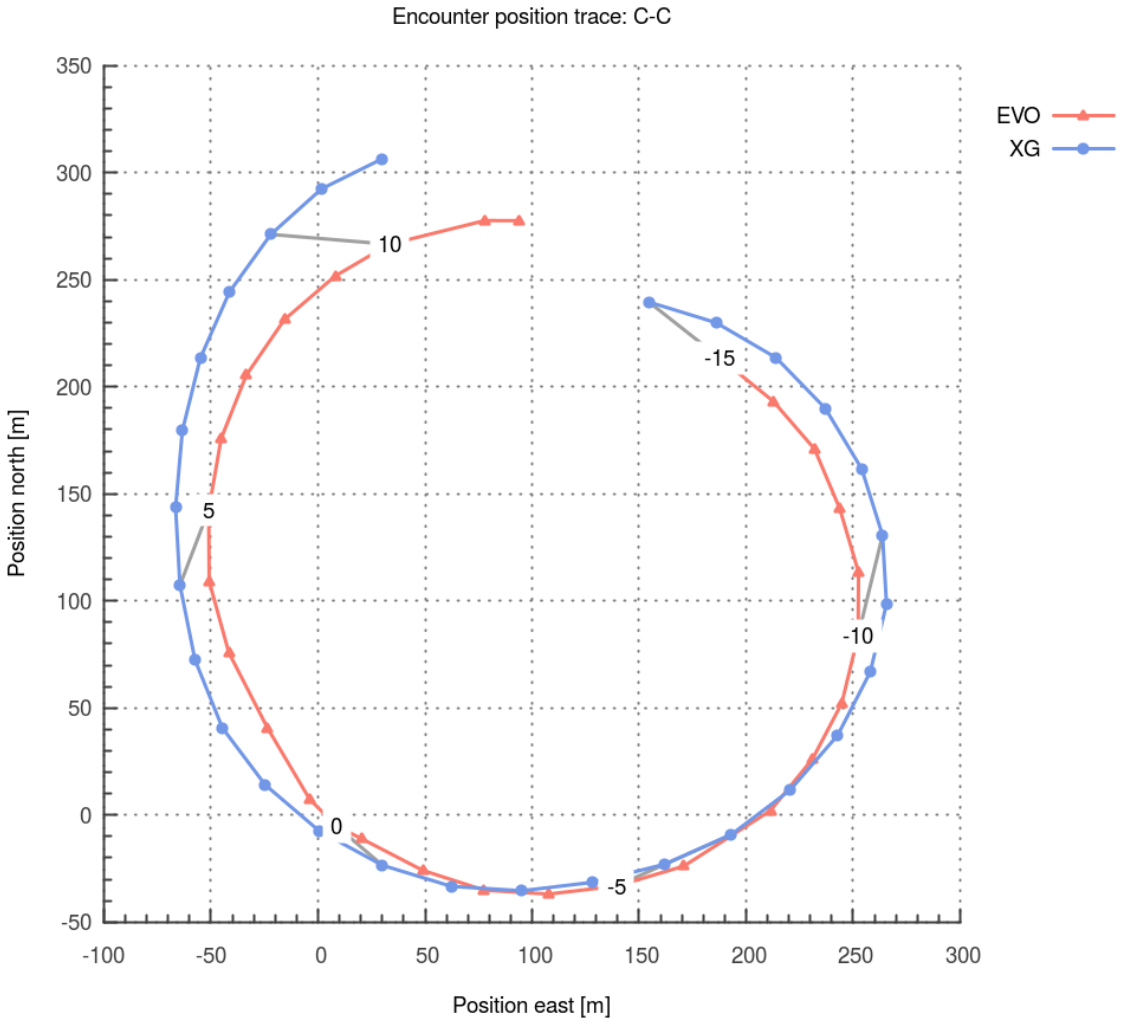

Figure 17: Typical encounter position trace (adjusted for wind), climb-climb

Figures 19 and 20 show an example of a close encounter where both aircraft are gliding.

Figures 21 and 22 show an example of a close encounter where one aircraft is climbing, the other is in glide and joins the climb.

Figures 23 and 24 show an example of a close encounter where both aircraft are climbing, and one departs.

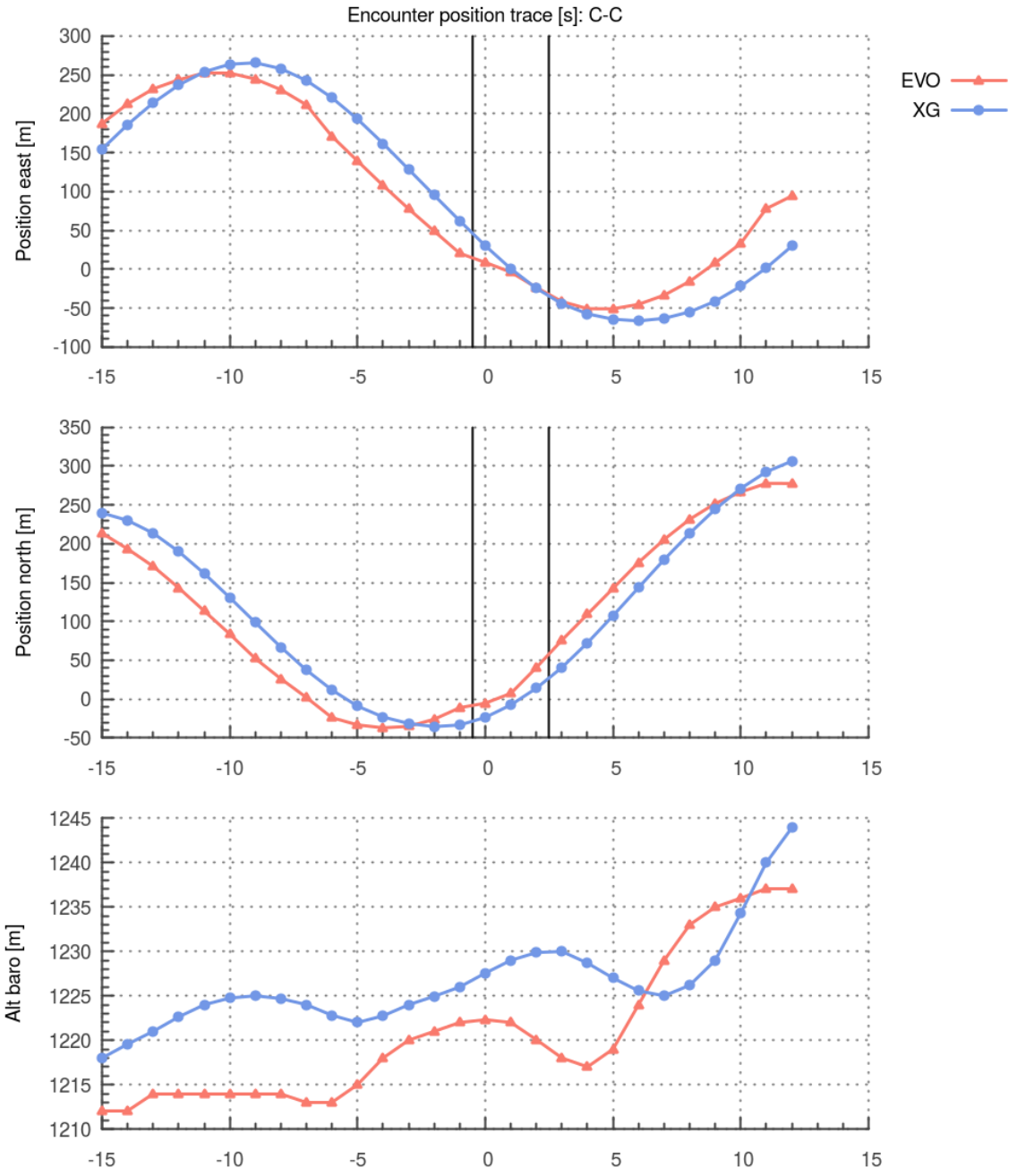

Figure 18: Typical encounter trace, climb-climb

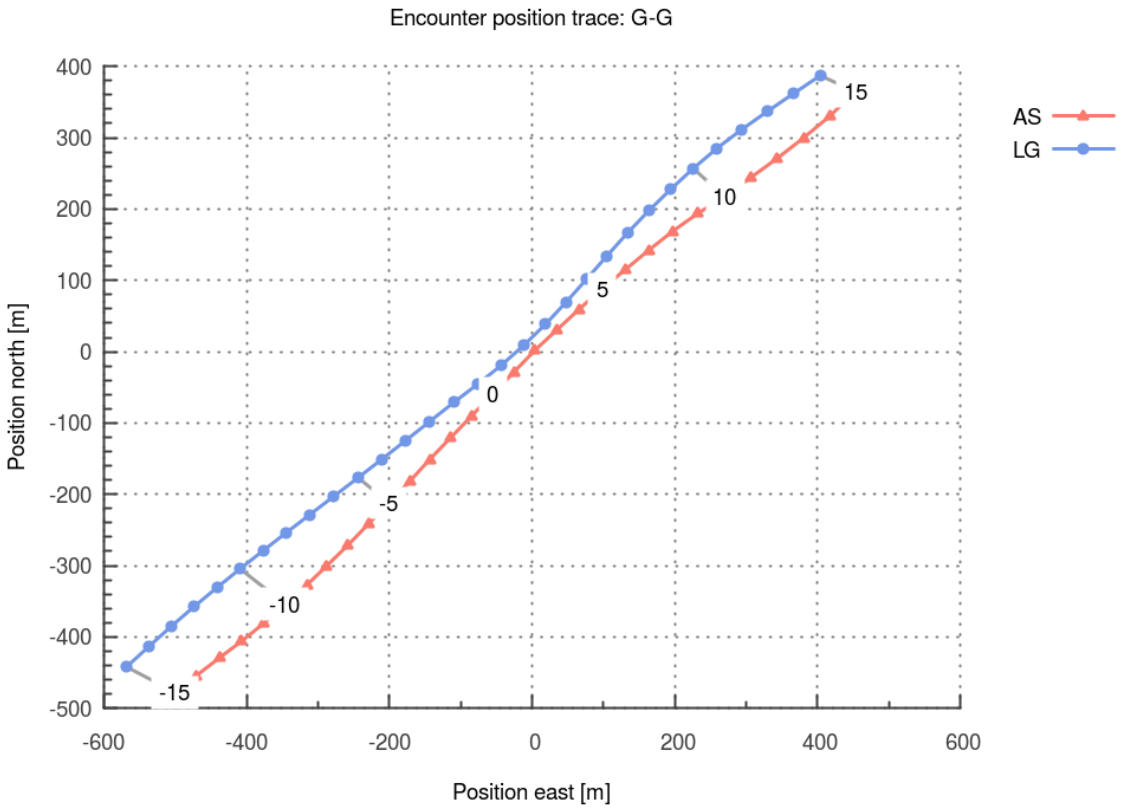

Figure 19: Typical encounter position trace (adjusted for wind), cruise-cruise

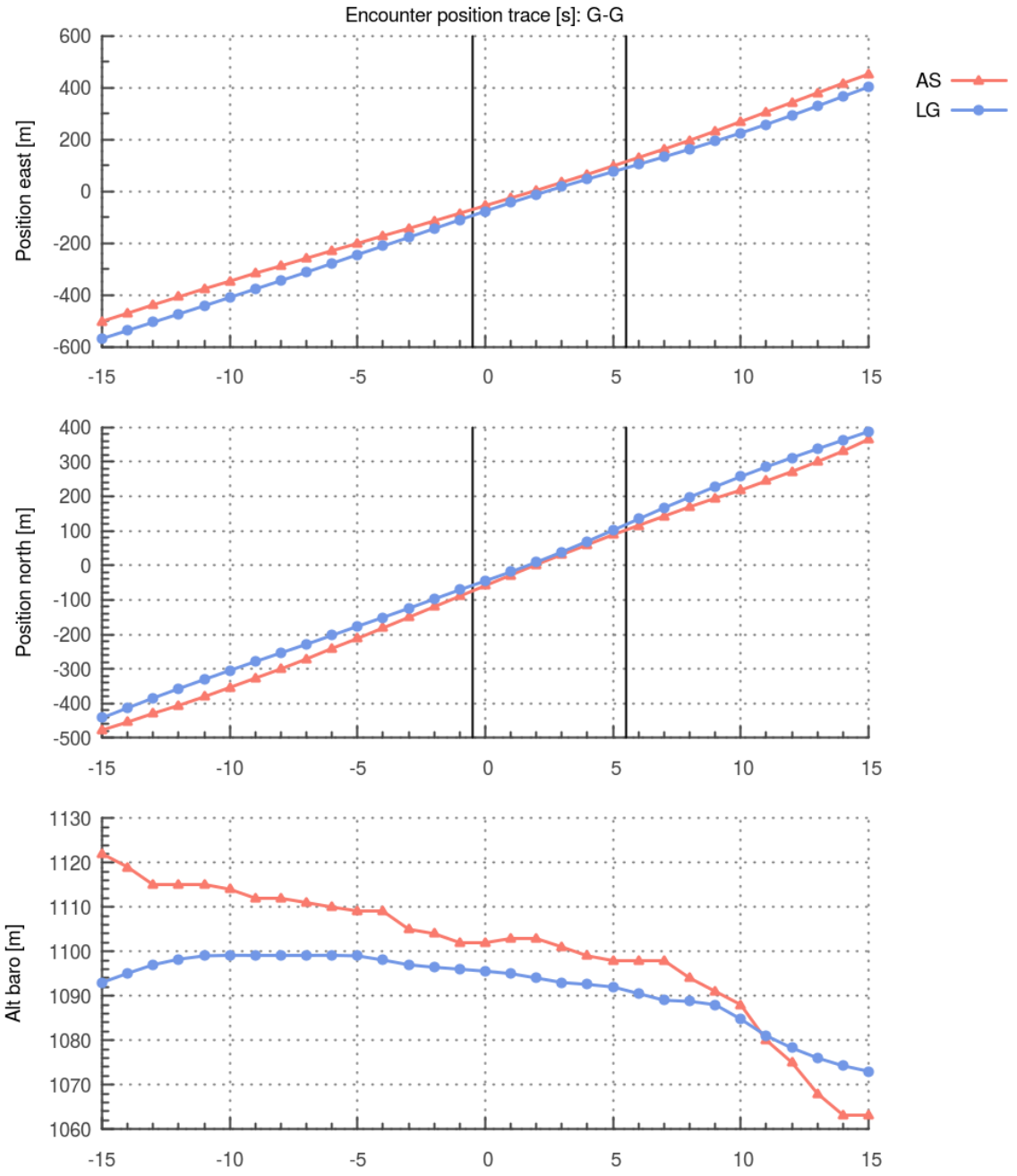

Figure 20: Typical encounter trace, cruise-cruise

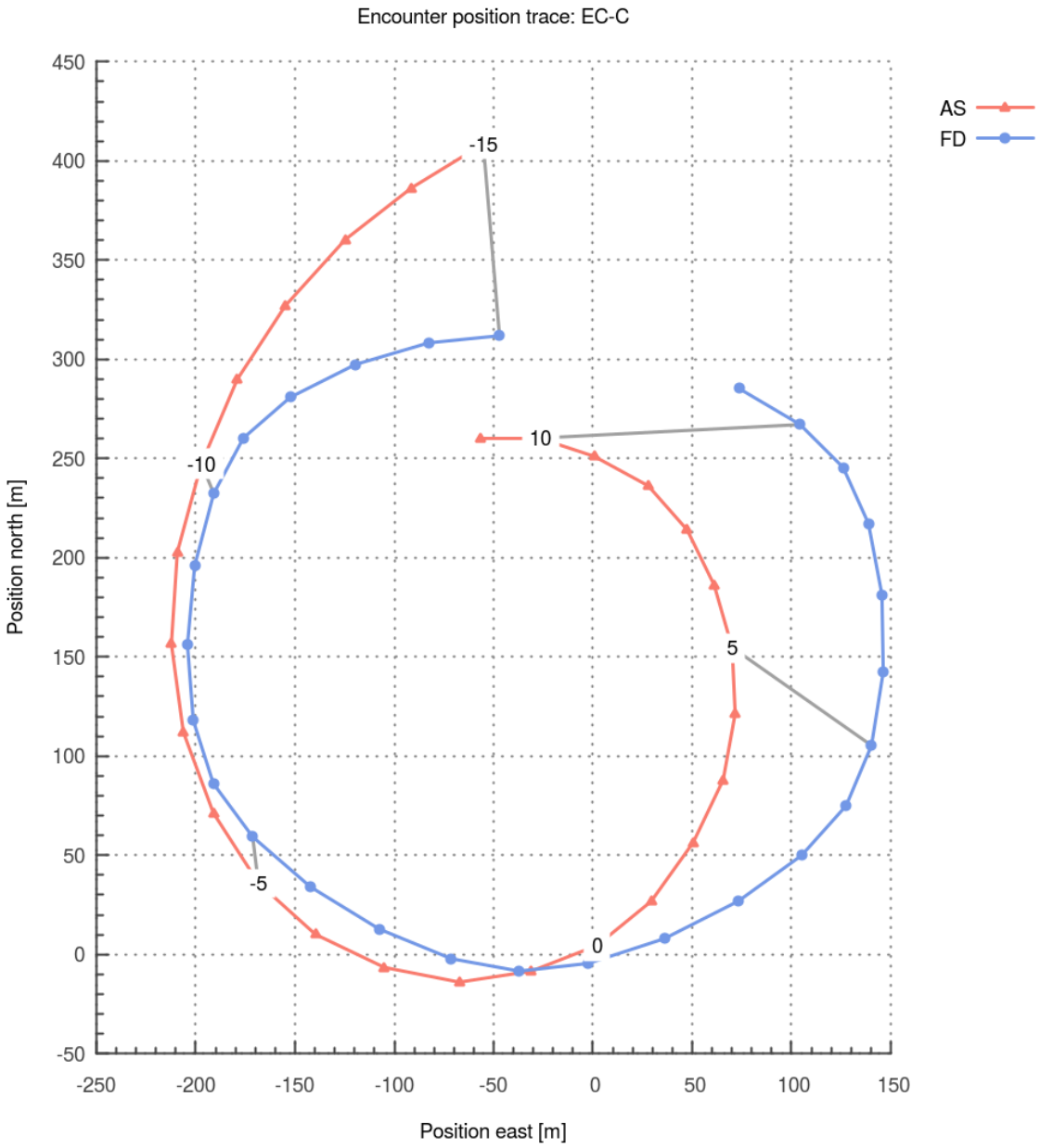

Figure 21: Typical encounter position trace (adjusted for wind), joining-climb

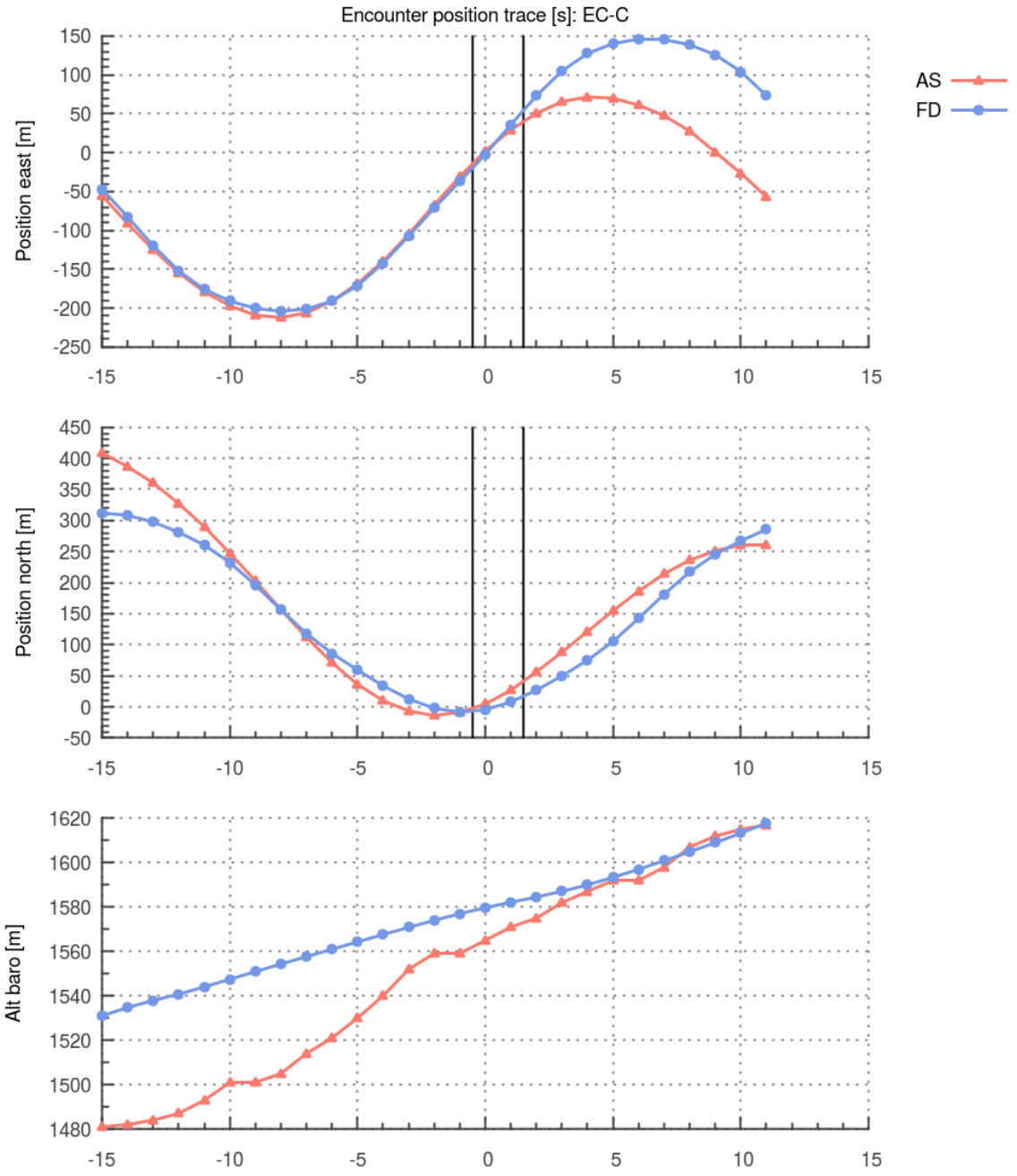

Figure 22: Typical encounter trace, joining-climb

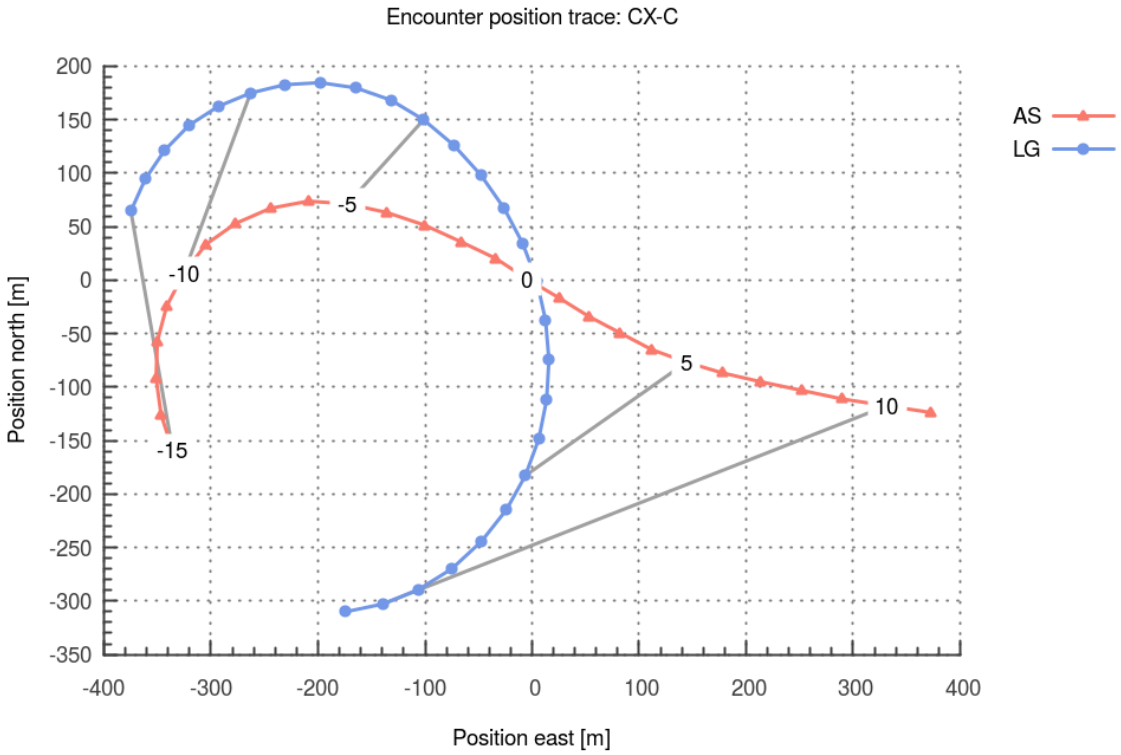

Figure 23: Typical encounter position trace (adjusted for wind), exit-climb

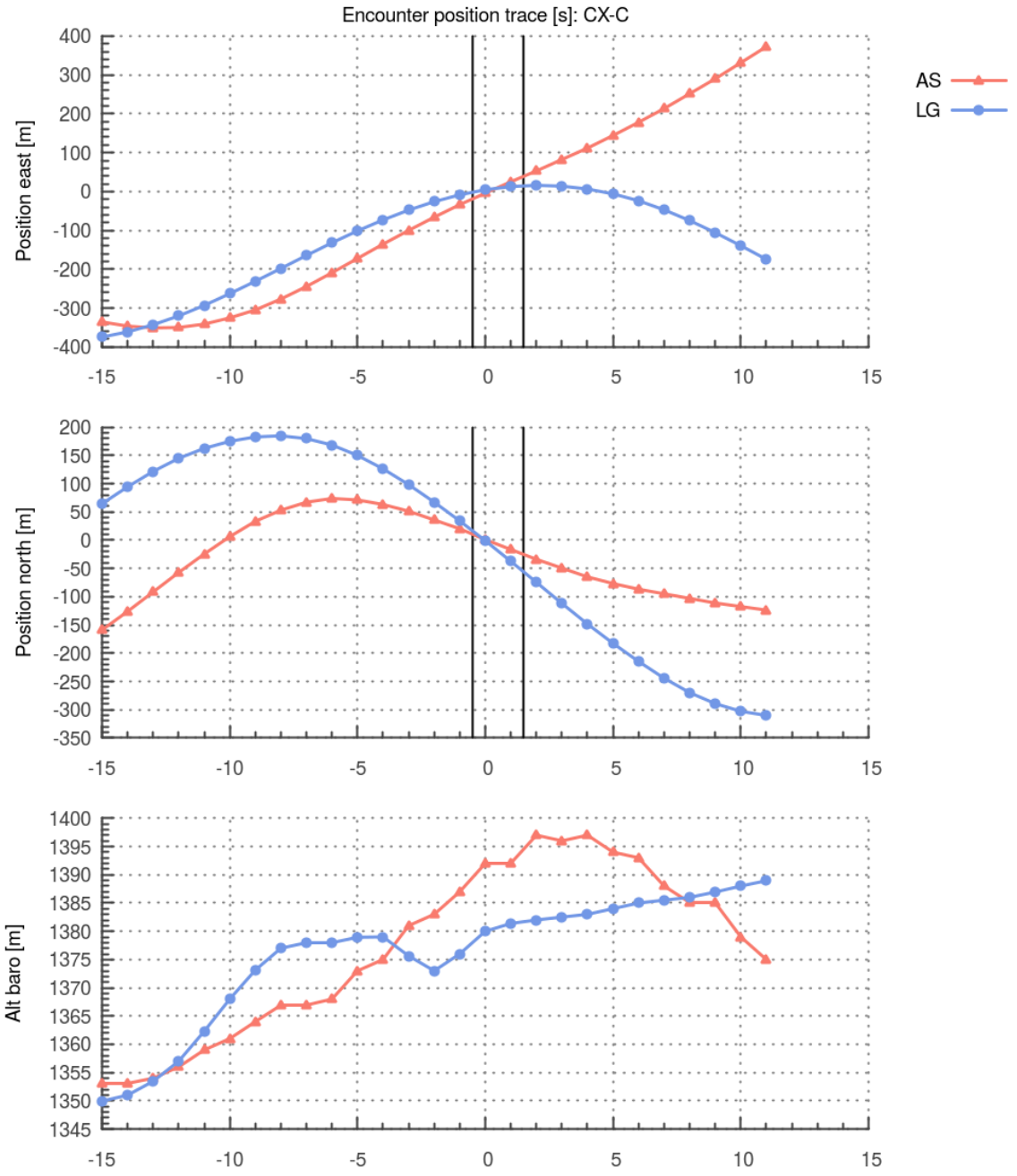

Figure 24: Typical encounter trace, exit-climb

Figures 25 and 26 show an example of a close encounter where both aircraft are climbing, and one straightens out as if to depart but re-joins.

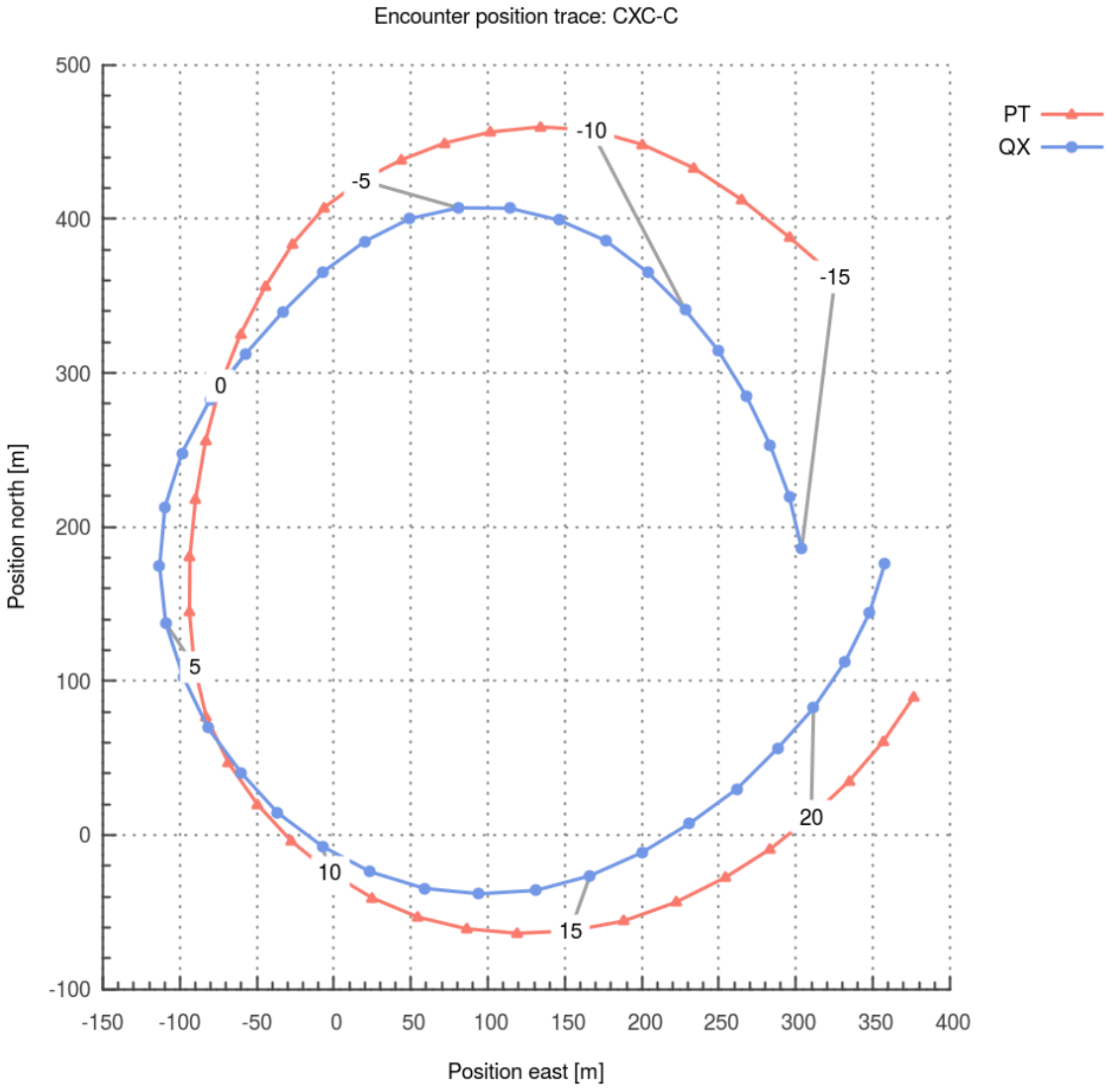

Figure 25: Typical encounter position trace (adjusted for wind), climb wide-climb

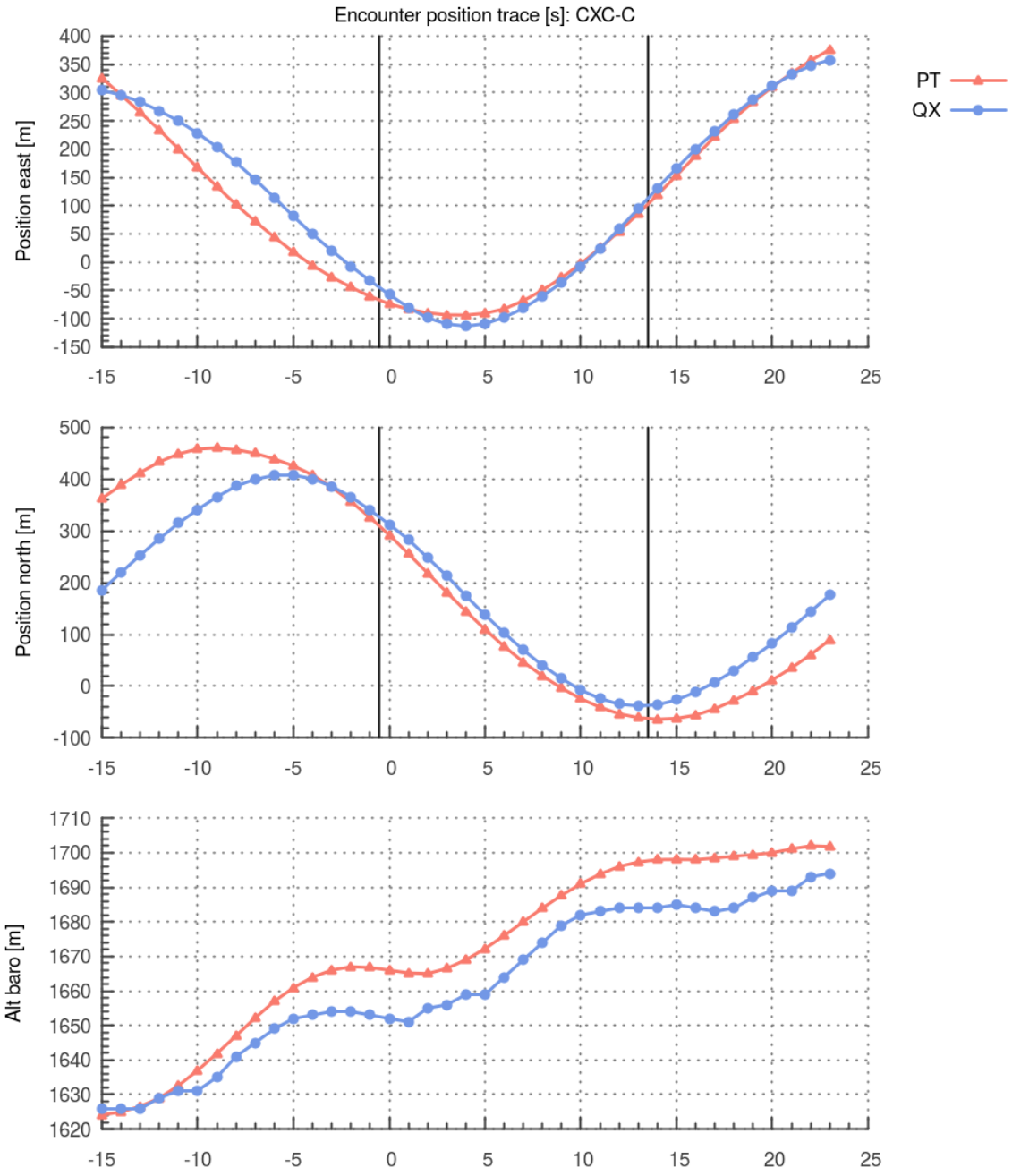

Figure 26: Typical encounter trace, climb wide-climb

5 Penalty schemes

Just as penalties are applied to pilots and teams for infringements of competition rules, to encourage proper sporting behaviour, fairness and safety, it is possible to apply penalties to pilots to discourage flying styles that result in high close encounter rates.

This approaches the safety problem from an economists perspective, in which undesirable behaviour is effectively taxed. The idea is to shape behaviour by introducing a consequence on scores for a pilot to have elevated close encounter rates.

5.1 Penalty system design

Considerations that need to be made when introducing such a system include:

Ease of calculation Software such as that produced for this study allows for rapid and essentially no-cost calculation of penalties.

Robustness to abuse The system should be designed to be difficult to exploit by pilots wishing to manipulate scores unfairly.

Precision The system should be insensitive to numerical or algorithmic faults that might produce anomalous scores.

Fairness Pilots who are flying safely should not be penalised, even if they are involved in close encounters with more risky pilots.

Potential abuse of penalty schemes could include:

- 'Ganging up' to knock points off someone
- Boxing someone in; cutting them off

This list is not exhaustive, so it is recommended that further study should be conducted to test the system and anticipate challenges.

5.2 Penalty system measures

Measures available to a close encounter penalty system include:

- Accumulated depth of incursion
- Integral of depth of incursion
- Closing speed within incursion zone
- Number of aircraft affected by close encounters involving a particular pilot
- Number of close encounters by a particular pilot

For this study, the accumulated depth of incursion is used as the primary penalty measure. For a particular pilot, the incursion penalty is the sum for all close encounter episodes, of the incursion to the minimum separation within each episode.

In order to eliminate penalties from safer pilots, an incursion depth allowance can be introduced, with incursion distance up to this value subtracted from the penalty score.

5.3 Administration of penalties

It is possible to have the penalty system switch-in only once a certain total number of encounters has been exceeded. That way, if everyone is behaving well, there is no impact on scoring.

Penalty analysis do be performed live, in real time, if gliders in the competition were equipped with tracking systems that are sufficiently reliable and high enough rate; it would then be possible to issue alerts to pilots of danger and warnings to pilots that are considered to be contributing to high close encounter rates.

Another consideration that needs to be taken into account when designing a penalty function is the psychology of pilots. If the penalty function and particularly, choice of allowance, is too selective and only issues penalties very rarely, the pilots may be willing to risk incurring the penalty and therefore the system would not be effective in shaping behaviour.

5.4 Distribution of penalties

Figure 27 shows the frequency distribution of daily penalties (accumulated incursions) for all of the competitions under investigation. This data, calculated for no incursion allowance, shows that just under half of pilot days have no incursions; and 90% of pilots have accumulated incursions less than 100 m.

This limiting value of 100 m might be a suitable value for the incursion allowance, though the most appropriate number should ideally be tuned from further analysis alongwith the other parameters of the algorithm such as separation threshold.

5.5 Example penalties

Figure 28 show example penalty measures for one competition day. It is noteworthy that the three measures presented, incursion depth, number of encounters, and number of affected aircraft, all mark a similar set of pilots.

Any of these measures or a combination of them could be used to form a penalty function. Indeed, using a combination of measures may be useful to make the system more robust to abuse and tolerant of algorithmic anomalies.

5.6 Consistency of penalty measures

Despite each penalty measure being based on different calculations, and having different inherent meaning, they are somewhat mutually correlated. Figure 29 shows how the number of encounters and number of affected aircraft relate to incursion depth.

Note that number of encounters is strongly correlated to incursion depth and may be considered more or less equivalent. Incursion depth is potentially a superior measure as it takes the severity of the close encounter into account.

The number of affected aircraft are strongly correlated to accumulated incursion depth for lower incursion rates, but rounds off at high incursion rates (due to the number of aircraft available to be affected being limited by the number of aircraft in the class).

Nevertheless, it is notable that pilots that are involved in high encounter rates tend to have higher incursions, and affect more of their competitors, than do everyone else. In other words,

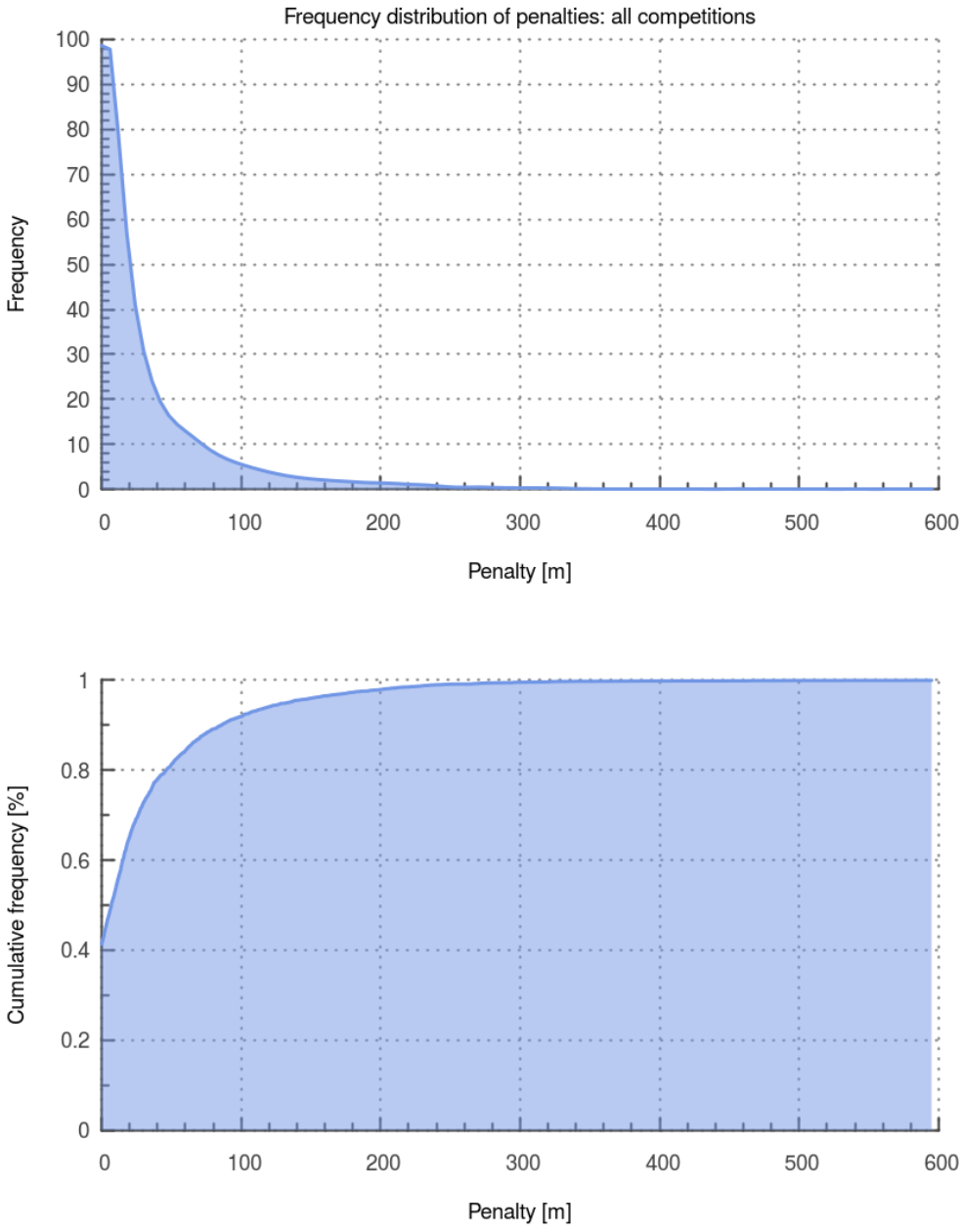

Figure 27: Frequency of penalty scores, all competitions

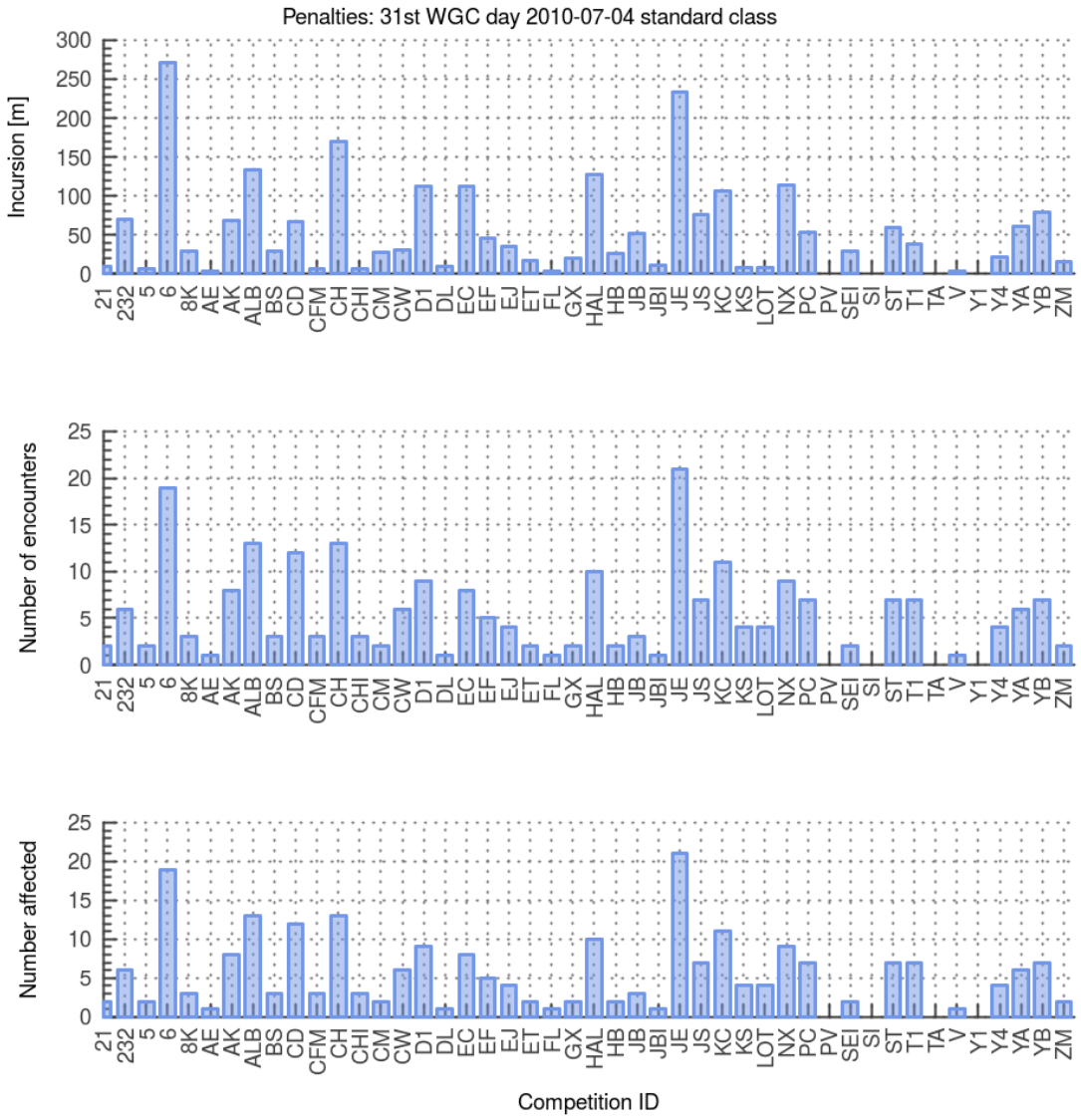

Figure 28: Example penalties, 31st WGC day 2010-07-04 Standard class

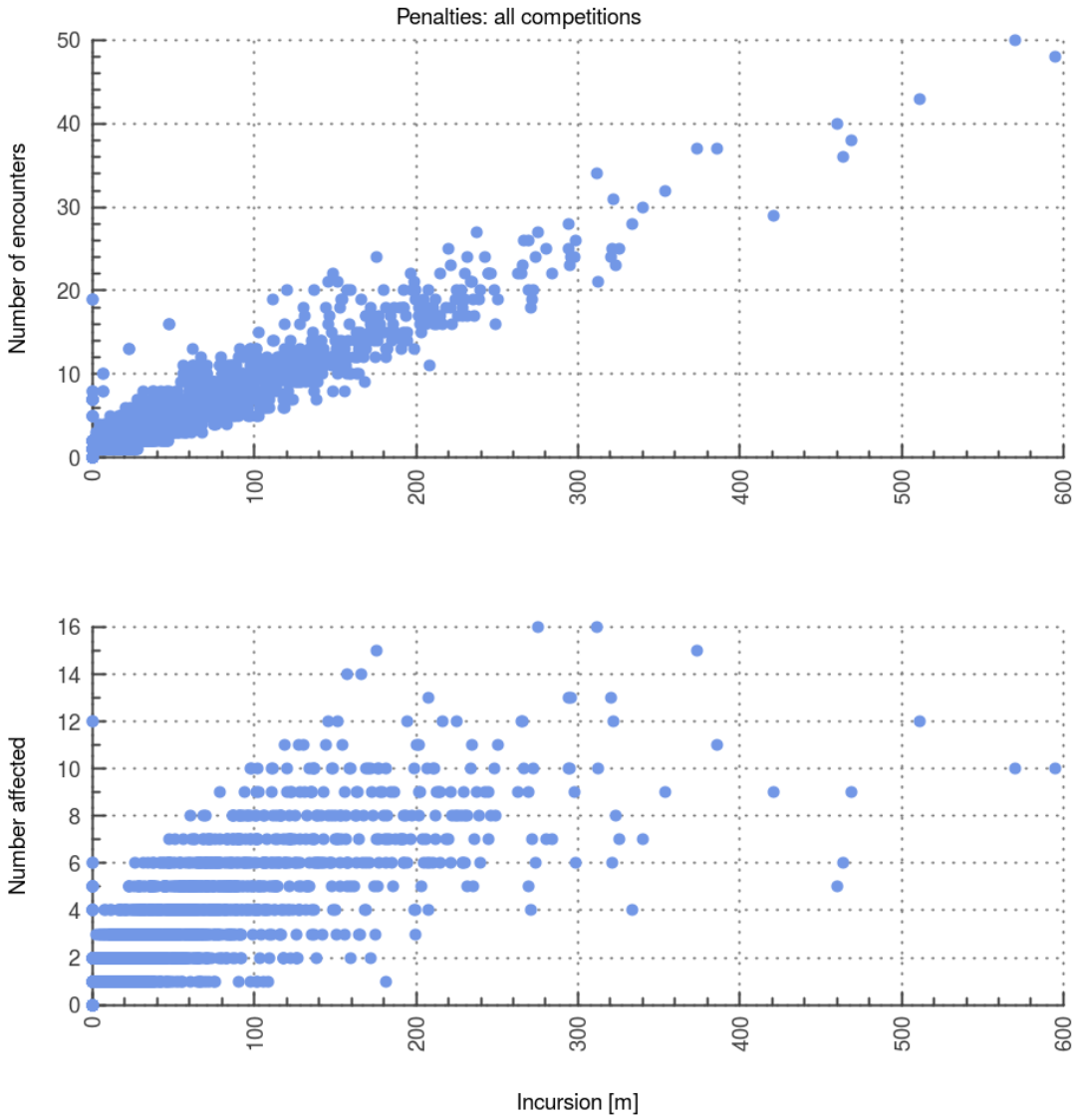

Figure 29: Penalty measures, all competitions

the results suggest that pilots that are involved in agressive or risky flying tend to spread their risk around, and clearly cannot be due to team flying.

6 Summary and recommendations

6.1 Summary of findings

Findings of the study, based on data from four previous World Gliding Competitions, includes:

- The trend towards greater competition numbers each competition year is likely to weakly increase the close encounter rate.
- Sites with very high working ceilings and freedom to task in all directions offer higher safety.
- Most close encounters are within a few seconds, but a significant number extend for 20 or so seconds.
- Pre-start and post-start phases are the most risky, but the risk of close encounters persists throughout tasks.
- Both aircraft circling is by far the most frequent close encounter pattern (approximately 64%).
- Both aircraft cruising is the second most frequent close encounter pattern (approximately 13%).
- Combined modes where one aircraft climbs and one transitions to and from climb make up around 7.7% of the encounters.

6.2 Administrative recommendations

1. Loggers should use 1 second fix rate always.
    - This avoids the need to interpolate between points, and the consequent error.
    - High data rate improves fidelity of source data in the event of accident investigation
2. Perform collision risk analysis (as described here) daily during competitions and make available to stewards and safety officers for monitor. This can be done automatically, that is, by incorporating it into scoring (e.g. SeeYou) or results publication systems (e.g. www.soaringspot.com). Because the software upon which this study is based is open-source, other organisations may use it as the basis or as a reference in developing their own implementation.
3. Trial use of penalty system or live use of close encounter system daily during competitions to caution risky pilots.

Rolling out a penalty system such as proposed here requires the formation of a team (sub-committee or tiger-team) with the resources to carefully test the logic of the scheme, look for potential drawbacks, guard against potential abuse, and to tune the parameters of the algorithms.

6.3 Task setting officers

This study has shown the benefit of separating tasks across classes as much as possible to increase average aircraft separation.

- If it is not possible to separate the tasks on a particular day, consideration should be made to reduce the number of classes that fly.
- Physically separate start sectors (more)
- Separate start times as much as possible

Further analysis of historical data could be used to generate guidelines to enable these factors to be used in making judgements by competition officers.

6.4 Study recommendations

Being a preliminary study, this work could be improved by more rigorous statistical analysis using a larger data set, such as adding data from regional competitions.

There would be benefit to reviewing the limitations of the study listed in Section 1.3 to identify work of priority and interest. Other enhancements could include:

- Making use of GNSS estimated position error. Note that for vehicles close to each other, they are likely to have similar satellite visibility, subject to similar atmospheric effects, and therefore have similar position error — meaning that their relative separation error is likely to be smaller than the position error magnitude.
- Making use of expected barometric error due to pressure sensor calibration drift and position error (variation due to cockpit interior static pressure).
- Incorporation of closing speed (the rate of change of separation distance) in identifying risky encounters
- Use information from the glider class or type to select appropriate distance thresholds based on the expected wing span of each aircraft.
- Extend the encounter classification system presented in Section 4.2 to perform more detailed classifications than is possible only using turn rate information.

Such work might be suitable to be performed by a student under sponsorship and guidance.