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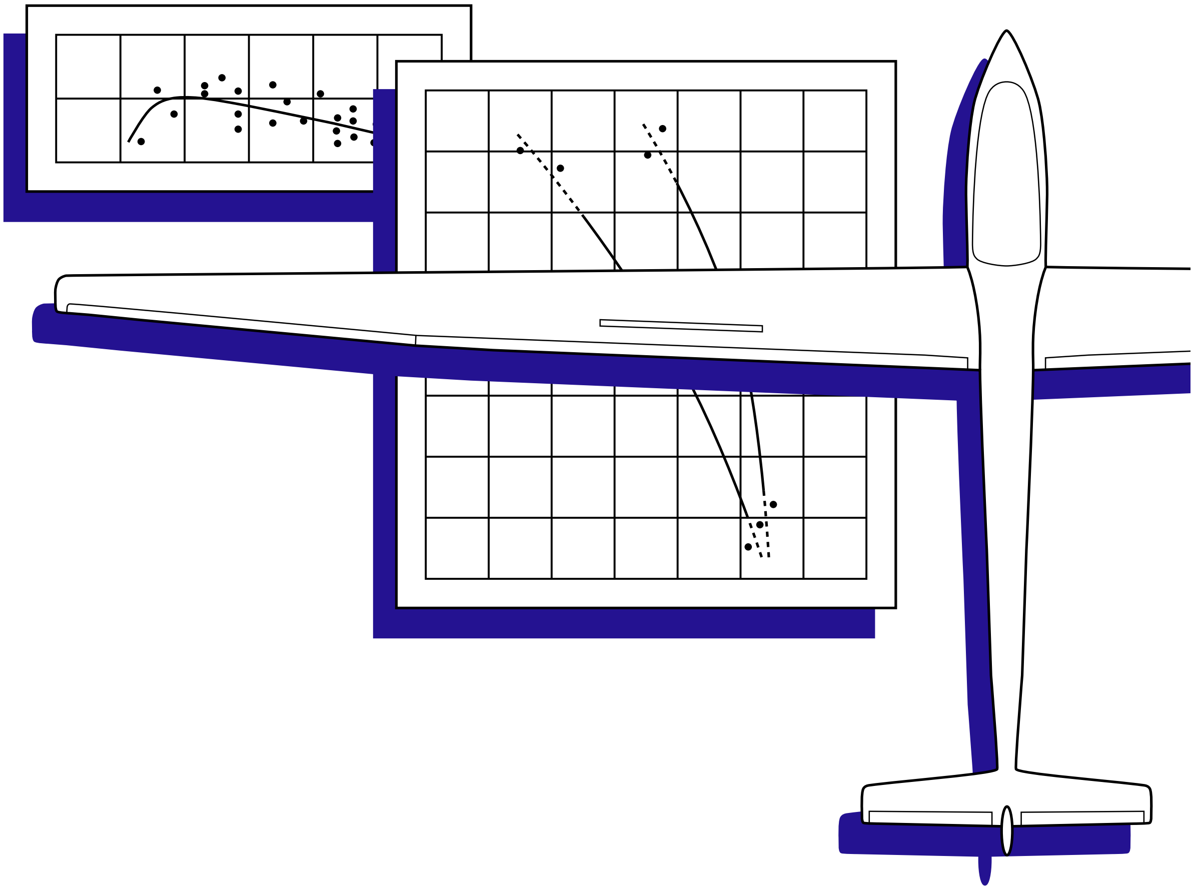

- **Collision threat identification**

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Organisation Scientifique et Technique Internationale du Vol à Voile
(International Scientific and Technical Organization for Gliding)
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Technical Soaring

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FLARM: Collision Threat Identification Influenced by Pilot's Mental Model of the Cockpit Display

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Abstract

During the last decade, low-cost collision alerting systems have become available to assist glider pilots in their task of seeing and avoiding other traffic. These systems present pilots with traffic information on different displays. Previous work by the authors shows that many glider pilots make systematic errors in interpreting traffic information shown on one such display, the popular FLARM display. This is the case whenever the pitch angle, bank angle or drift angle deviate from zero. In this paper data from the aforementioned research are analyzed using analytical modeling of the pilots' mental models in order to explain these systematic errors. Results show that the majority of glider pilots rely on a glider-fixed reference system when interpreting the traffic indications on the FLARM display. This is attributed to the available in-cockpit clues on the display. Since the data displayed on the FLARM display are actually derived from a FLARM-specific coordinate system — and is not glider-fixed — it is only natural that many pilots make systematic errors in predicting the position of traffic shown on the display. At the end of the paper possible courses of action to reduce these interpretation errors are discussed.

Introduction

Gliding is an air sports activity that is mostly carried out under visual flight rules. Consequently, in most airspace classes glider pilots are responsible for visually detecting and avoiding other traffic [1, section 2.6]. In order to support glider pilots in their task of seeing and avoiding other traffic, low-cost collision alerting systems (CASs) have become available [2].

The FLARM collision alerting system

By far the most popular CAS in gliding is the FLARM system. It represents a quasi-standard in the German gliding community [3]. The system relies on participating aircraft being equipped with a cooperative FLARM transceiver unit. This transceiver unit detects the glider's own position using a Global Positioning System (GPS) module and broadcasts this position to other aircraft using a proprietary radio protocol [4]. At the same time, the transceiver receives position reports from other aircraft within range. These position reports are then assessed for collision threats [5]. Directional information to the nearest or most threatening traffic known is displayed on a simple display unit, as shown in Fig. 1.

This display shows the directional information in terms of polar coordinates. A circular array of light-emitting diodes (LEDs)

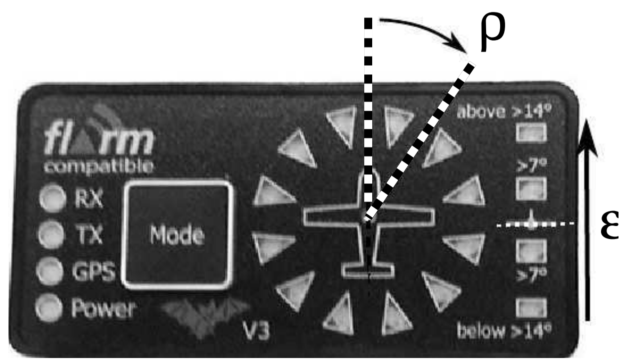


Fig. 1: FLARM display

displays the relative bearing ρ between the glider's ground track and the traffic's direction, as projected into the horizontal plane. The elevation ε of the traffic represents its angular distance above or below the horizon, as seen from the pilot's point of view in her or his own glider. This *FLARM coordinate system* can be also described with an analogy from the field of geography. The glider is located at the center of a globe in this analogy.

The globe's equatorial plane (EP) is parallel to the horizontal plane and its zero-meridian passes through the glider's ground track. The traffic's bearing ρ is represented by longitude and its elevation ε by latitude. Figure 2a illustrates this analogy.

However, this coordinate system is *not* self-evident from the graphical clues provided by the display. The FLARM display shows the top view of an airplane at the center of the circular LED array. Using the concept of pictorial realism [6], a user might assume that her or his own glider's wingplane represents the polar coordinate system's EP. Similarly, the sketched airplane points to the top of the LED circle, suggesting that the glider's longitudinal axis passes through the zero-meridian. The polar coordinate system, which is suggested by the display's in-cockpit visual clues, is a *glider-fixed polar coordinate system* (Fig. 2b). When comparing Figs. 2a and 2b it is evident that these coordinate systems do not necessarily coincide.

The question of "why does FLARM rely on this non-intuitive FLARM coordinate system?" might arise. A major advantage of this coordinate system is that all indications can be calculated from GPS measurements alone. No data about the glider's own attitude or the traffic's attitude are required for these indications. Therefore, the FLARM transceiver units do not need to be equipped with attitude sensors and can be marketed at a lower price. Low costs, along with the benefit of receiving collision alerts, are considered to be driving factors in the rapid distribution of low-cost CASs in parts of Europe [7, p. 103].

This paper's authors and their colleagues have found that glider pilots make systematic errors in estimating traffic positions whenever the FLARM coordinate system and glider-fixed coordinate system do not coincide [8]. The data from their experiment suggest that at least some glider pilots use a glider-fixed coordinate system. So far this has been attributed to the concept of pictorial realism [6], which results in glider pilots gaining a false understanding of how the FLARM CAS operates. However, the previous work does not disclose how *each individual pilot* believes the FLARM CAS to work. It is only logical to ask the question of how each glider pilot *believes* the system to operate.

Mental models

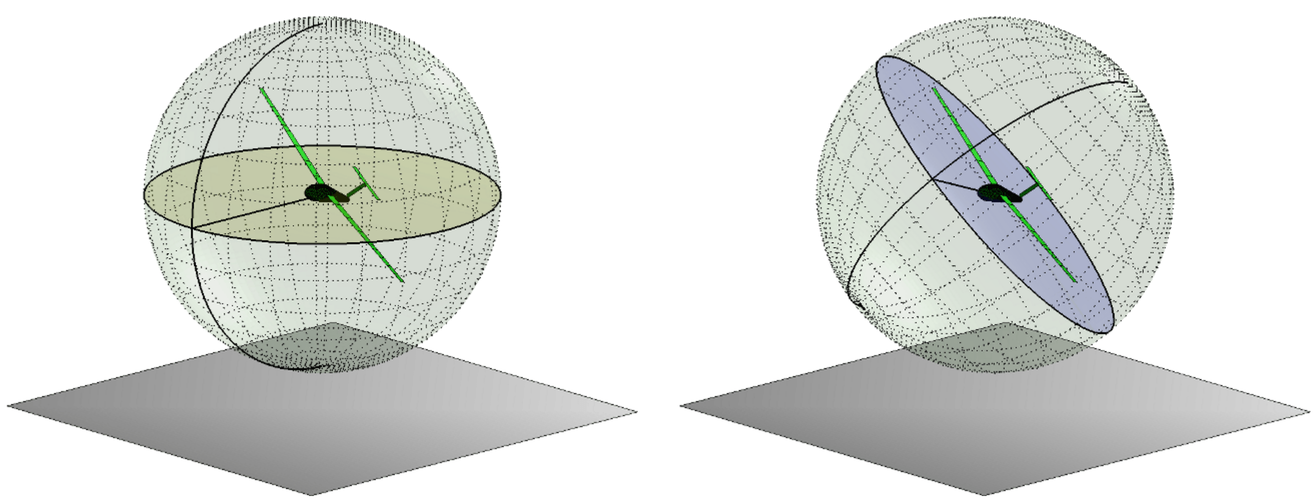
The problem of how a pilot believes a certain aircraft system to operate is a question of mental models (MMs). When interacting with any system, humans form a model of how this system works and what its purpose is. These MMs can take many shapes. One extreme of a MM is a mere "black box," where simple rules of thumb are applied to relate input and output and where the user has no deeper understanding of a system's internal characteristics. The opposite extreme may be a user who has a detailed and intricate understanding of the internal technical workings of a system.

According to Rouse and Morris "mental models are the mechanisms whereby humans are able to generate descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions of future system states" [9, p. 7]. Consequently, pilots form MMs of systems with which they interact, such as CASs. Wickens, Lee, Liu and Gordon Becker mention that often-times display design shapes the MMs of a system developed by its users [10, chap. 8].

Empirical identification of MMs is a task prone with difficulties. Uncovering all details of how any given person models a technical system would be a task nearly impossible. Yet, several methods are available to identify MMs.

Direct inquiry requires interviewing the participant on how she or he believes a system to operate. It can only provide results which the participant is able to verbalize [9, pp. 13–16].

Empirical modeling indirectly infers characteristics of a MM



(a) FLARM polar coordinate system

(b) glider-fixed polar coordinate system

Fig. 2: Orientation of polar coordinate systems while maneuvering.

based on experimental results. For example, when comparing the performance of multiple groups while performing the same experimental task, one might infer that a superior MM is developed by the group with the best performance. However, this does not provide direct insight into the MM [9, pp. 10–11].

Analytical modeling requires making multiple "educated guesses" about how a MM might look. These multiple guesses are then compared to the experimental data and the best-fitting guess is selected as being the most-likely MM. However, it cannot be said with certainty that the best-fitting MM reflects the actual MM of the participant [9, pp. 10–11].

Empirical modeling of pilots interacting with the FLARM display is used by Mehringskötter [11]. Since the results of this study were unsatisfactory, he recommends that future work use analytical modeling [section 6.5.1.1]. Therefore, an analytical modeling approach is chosen in the paper at hand.

Hypothesis

MMs are expected to vary between glider pilots. However, the authors' previous work suggests that MMs based on the glider-fixed coordinate system are most frequent [8]. This leads to the following hypothesis.

> **Hypothesis:** Mental models based on the *glider-fixed polar coordinate system* are most frequently found in glider pilots using the FLARM CAS's display.

Method

In the presented approach an explorative analysis is conducted. The analyzed data set was previously gathered and analyzed by the authors and their colleagues [8]. The paper at hand extends this analysis to the concept of MMs. First, multiple possible MMs are proposed using analytical modeling. Following this, a method for assessing the quality of how each proposed MM predicts the participants' answers is proposed. Then the best-fitting MM for each participant is selected. Afterwards, the distribution of best-fitting MMs is analyzed in regard to the hypothesis presented.

Description of the experiment

Due to the fact that data from the experiment of the authors' previous research are utilized, the environment in which these data were gathered is briefly presented. For a more detailed description of the experimental setup the reader is referred to the aforementioned study [8].

Equipment

The experiment was performed in the Diamond DA 40-180 flight simulator of the Institute of Flight Systems and Automatic Control at Technische Universität Darmstadt [12]. As the glider pilot participants did *not* have to perform a flight task, the simulator merely served to provide static visual immersion into different flight scenarios. The simulator's out-the-window (OTW) view was provided using the Diamond Global Canvas Visual System image generation software [13]. The projection screen was gridded into 50 cells (see Fig. 3) and each cell was marked with an alphanumeric identifier.

Fig. 3: Flight simulator cockpit with gridded projection screen.

At the cockpit's center, above the audio panel, an external FLARM display V3 [14] was installed. It sat atop the audio panel and beneath the standby instruments.

The participants were handed a touch screen monitor [15] to perform their experimental task. Participants loosely placed the monitor on their laps. On this monitor (Fig. 4), an answer grid analogous to the grid in the OTW view, was shown.

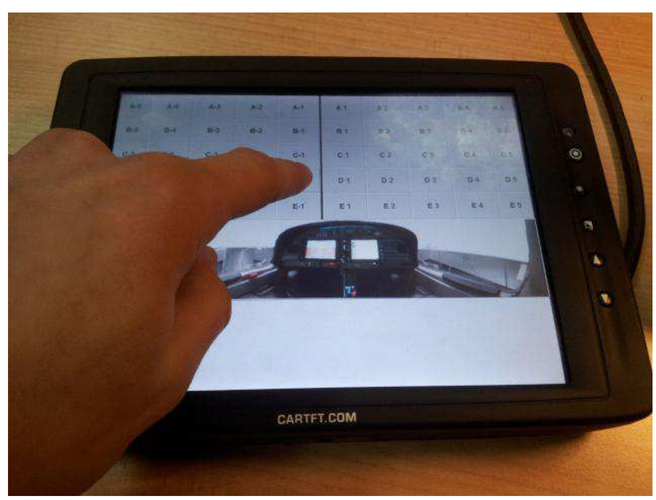


Fig. 4: Touch screen monitor with answer grid.

Participants

A total of $N = 43$ glider pilots participated in the experiment. Three participants were female and 40 were male. Out of the 43 participants, nine were student pilots in the pre-solo and post-solo phases of their flight training. Nine further participants held flight instructor ratings with limited or full privileges. The remaining 25 participants were regularly licensed glider pilots without instructor privileges. The participants had a mean flight experience of $M = 224.8\,\mathrm{hr}$ with a standard deviation $SD = 190.7\,\mathrm{hr}$. On average they were $M = 25.6$ years old with an $SD = 10.7$ years.

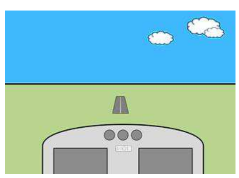
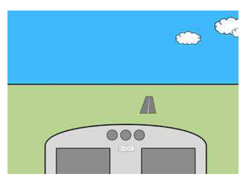
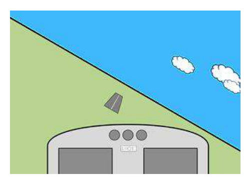
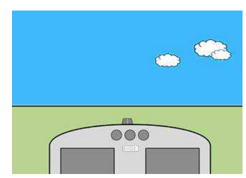
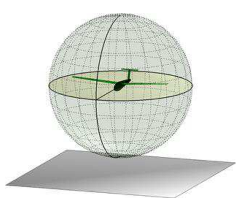
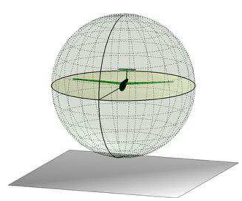
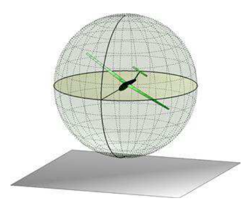
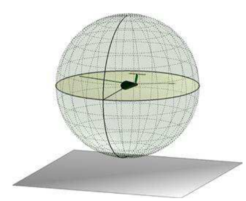
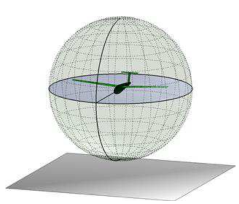
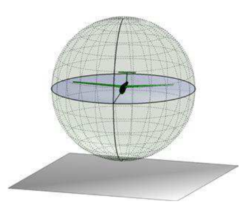
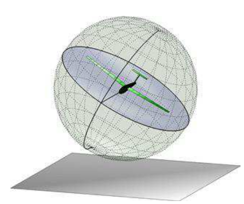
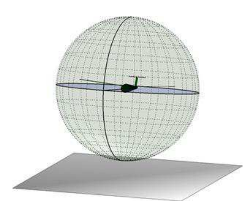
Experimental procedure

Each participant was seated on the left-hand seat of the flight simulator. There they were briefed on their experimental task (see the following section). A computer then randomized the order of four different factor levels of the flight condition. Each factor level of the flight condition had a unique combination of bank angle Φ, pitch angle Θ and drift angle ν. Details of these factor levels are provided in Table 1.

The simulator was then configured and "frozen" in the first factor level of the flight condition. A practice run, where participants familiarized themselves with their experimental task, was performed. During this practice run participants performed the task for five signals. These signals were shown on the FLARM display for 7 s. Between two signals was a pause of 2 s duration. Answers to their experimental task were not recorded during the practice run. Following this, the first experimental run was performed. It was identical to the practice run with two exceptions. Participants performed their task for 25 signals and their answers were now recorded.

Once the trial and experimental runs for the first factor level of the flight condition were completed, the procedure was repeated for the second factor level. Again, trial and experimental runs were performed. This procedure was reiterated for all four factor levels of the flight condition. At the end of the experiment a total of 100 answers (one answer per combination of flight condition factor level and FLARM signal) per participant were recorded.

Table 1: Characteristics of different factor levels of flight condition.

Flight condition:	Straight and level flight	Horizontal flight with crosswind from left	Left-hand turning flight	Climbing flight
Cockpit visual scene				
Orientation of FLARM coordinate system				
Orientation of glider-fixed coordinate system				
Bank angle Φ (deg.)	0	0	-30	0
Pitch angle Θ (deg.)	0	0	0	10
Drift angle ν (deg.)	0	-12	0	0

Experimental Task

Participants were briefed at the beginning of the experiment on their task. This task is illustrated in Fig. 5. As soon as they recognized a new signal being shown on the FLARM display, participants were instructed to

a) look at the display, and then

b) look at the OTW view where they believed the traffic to be located, and then

c) select the cell on the touch screen monitor where they looked first.

Because *no* traffic was shown in the OTW view, participants were only able to answer where they suspected traffic to be located. This suspicion is based on the signal shown on the FLARM display and on the participants' understanding of the CAS.

Developing a theory of mental models

A sequential model of how participants fulfilled their task was developed. It is an extension of the sequential task model proposed by Schochlow [16, pp. 7–10], who in turn relies on the works of Donders [17] and Sternberg [18,19]. The experimental task implicitly required participants to form a personal coordinate system in which to interpret the polar coordinates shown on the FLARM display.

Successfully and correctly identifying the direction of traffic in the glider-fixed OTW view solely relying on FLARM display indications requires several steps. First, the participant must be aware that FLARM relies on the FLARM coordinate system. Hence, the participant's personal coordinate system must correspond with the FLARM coordinate system. Then, the relative orientation between the personal coordinate system and the glider-fixed coordinate system must be determined. Finally, a transformation of the signal shown on the FLARM display into the glider-fixed coordinates must be performed. Only then can the indicated traffic's position in the OTW view be properly estimated using the indications on the FLARM display.

We can see that the orientation of the personal coordinate system is a key characteristic of the participant's MM. Whenever it does not correspond with the orientation of the FLARM coordinate system, systematic errors are expected to occur. In the following section we will postulate multiple possible MMs, each of

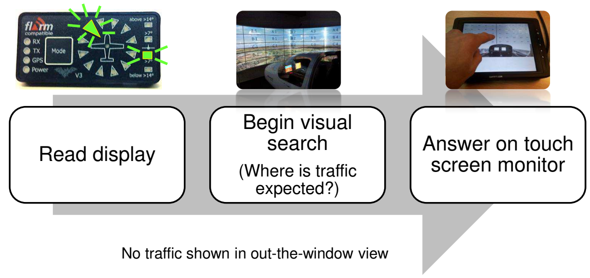


Fig. 5: Flow diagram of the participants' task.

which has an underlying coordinate system which may or may not correspond to the FLARM coordinate system.

Postulating different mental models

From this sequential task model it is evident that a transformation between the personal reference system and the glider-fixed coordinate system must be performed by the participants. In the case that the personal reference system is identical to the FLARM coordinate system this transformation can be described as a series of three angular rotations.

1. rotation around the FLARM system's $\vec{z}$-axis through the drift angle ν
2. rotation around the $\vec{y}'$-axis of the newly created first intermediate coordinate system through the pitch angle Θ
3. rotation around the $\vec{x}''$-axis of the newly created second intermediate coordinate system through the bank angle Φ

Glider pilots are confronted with the concepts of pitch, bank and drift angles in their pre-solo flight training [20, chap. 1]. Also, after the experiments, some participants described the need to correct for changes in pitch angle while others mentioned corrections for bank angle or drift angle. Therefore, a total of eight MMs was postulated. Each MM differs in the rotations which it assumes to be performed (Table 2). This results in eight MMs, which all have different orientations of their EPs and reference directions (RDs) ("zero-meridians"). Details of how the orientation of these postulated MMs differ with changes in flight condition are provided in Table 3.

Table 2: Characteristics of the postulated mental models: Rotations performed by each of the defined MMs. The check marks indicate that the corresponding rotations are assumed to be performed within the appropriate mental model.

	MM							
rotation through angle	MM 1	MM 2	MM 3	MM 4	MM 5	MM 6	MM 7	MM 8
Φ	✓	✓	✓	✓				
Θ	✓	✓			✓	✓		
ν	✓		✓		✓		✓	

Table 3: **Characteristics of the postulated mental models: Orientation of mental model coordinate systems as a function of MM and flight condition factor level**

	The MM coordinate systems coincide with the following coordinate systems...			
	Flight condition factor level			
MM	Straight and level flight	Horizontal flight with crosswind from left	Left-hand turning flight	Climbing flight
MM 1	FLARM & glider-fixed	FLARM	FLARM	FLARM
MM 2	FLARM & glider-fixed	glider-fixed	FLARM	FLARM
MM 3	FLARM & glider-fixed	FLARM	FLARM	glider-fixed
MM 4	FLARM & glider-fixed	glider-fixed	FLARM	glider-fixed
MM 5	FLARM & glider-fixed	FLARM	glider-fixed	FLARM
MM 6	FLARM & glider-fixed	glider-fixed	glider-fixed	FLARM
MM 7	FLARM & glider-fixed	FLARM	glider-fixed	glider-fixed
MM 8	FLARM & glider-fixed	glider-fixed	glider-fixed	glider-fixed

Treatment of Data

Before identifying the MMs, the data from previous work by the authors and their colleagues [8] were examined for outliers. Implausible answers as well as univariate and multivariate outliers were removed from the data. This left between 91 and 100 answers per participant for further examination. At this stage a significance level $\alpha = .05$ was defined for the ensuing statistical analysis

Identifying the best-fitting mental model

Now that the MMs were defined and the data were available, the best-fitting MMs of each participant could be identified. For this, the following procedure was developed. It is also illustrated in Fig. 6.

1. Select the first FLARM signal shown to the first participant. Also select the corresponding flight condition factor level and the participant's answered direction.

2. Determine the orientation of the coordinate systems of each of the eight postulated MMs for the selected flight condition factor level. For each MM, the orientation of the EP and RD are calculated from the recorded data.

3. For each of the eight MMs, predict where the participant will look in response to the FLARM signal shown.

4. Compare this prediction to the participant's answer. For each of the eight MMs, calculate the spherical angle $\Delta\gamma^{MM}$ between the MM's predicted response direction and the participant's answer. This difference is the MM's prediction error for the answer of the participant.

5. Repeat steps 1 through 4 for all other signals and factor levels of the flight condition experienced by the participant. Determine an average prediction error $\Delta\bar{\gamma}^{MM}$ for each MM based on the prediction errors of all signals shown to the participant.

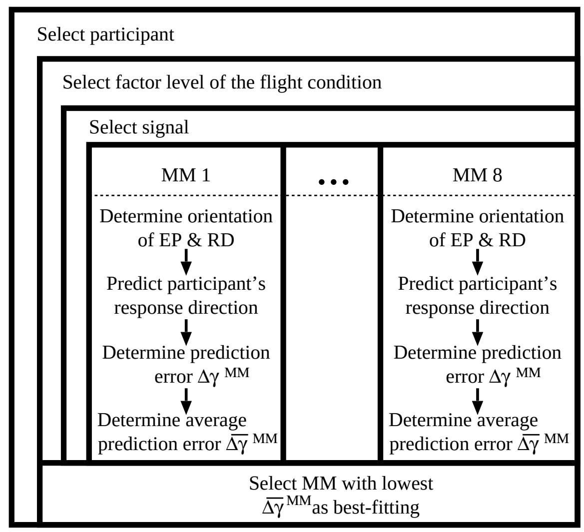


Fig. 6: Method for identifying mental models from the data available.

6. Select the MM with the lowest average prediction error $\Delta\bar{\gamma}^{MM}$ as being the best-fitting MM of the participant.

7. Repeat steps 1 through 6 for all remaining participants.

Predicting participants' response directions

The method presented in the previous section requires predictions about a participant's response to be made. These predictions were based on the discrete elevation and relative bearing stimuli of the FLARM display's LEDs. For each combination of the stimulus, participant and postulated MM, a predicted answer direction was identified. This predicted answer direction was the direction which minimized the square-sum of errors between the participant's response directions and the predicted answer directions, using the Levenberg-Marquardt algorithm [21, section 6.3].

Results

Before the results from the presented MM identification method were analyzed, the method was validated. The validation procedure is detailed in the appendix. No systematic errors in the identification method were found and the identification method behaved plausibly. It was therefore considered to be valid.

Through the presented method, one of the eight postulated MMs was identified as being best-fitting for each participant. The frequency with which each MM was selected as being best-fitting is shown in Table 4.

A χ^2 test was performed on these results to determine whether there were non-random differences in the frequency with which the different MMs were determined to be best-fitting. The results were statistically significant with the test value $\chi^2(7, N = 43) = 82.953$, statistical significance $p < .001$. By far the most frequently identified MM is MM 8. This MM uses a fully glider-fixed coordinate system. It was identified in more than half (25 of 43) of the participants. A MM corresponding to the actual FLARM coordinate system (MM 1) was only found in two of fourty-three participants. The remaining 16 participants used coordinate systems which where rotated around some, but not all three, Euler angles relative to the pilot's own glider.

Discussion

The results show that the different MMs, which are used by pilots, are distributed non-randomly. Some MMs are more common than others. Most frequently glider pilots use a glider-fixed coordinate system when interpreting the FLARM display's indications. This is attributed to the display's design features [6]. The available in-cockpit clues suggest this glider-fixed reference, whereas the FLARM manual [4] clearly states that the characteristic FLARM coordinate system is the basis of the display's indications. Therefore, the FLARM coordinate system can be considered the "correct" coordinate system. Whenever pilots use the FLARM coordinate system this will minimize the initial offset between their suspected and actual traffic positions.

Pilots may use deviating MMs — and therefore deviating coordinate systems — when interpreting the FLARM display. The reasons why pilots develop deviating mental models are not yet understood. It may be possible that, for the sake of simplicity, some pilots may consciously elect to use the glider-fixed coordinate system, and therefore consciously deviate from the "correct" FLARM coordinate system. Several participants described that their goal was to begin their visual search for traffic as quickly as possible. Contemplating the relative orientation of the FLARM coordinate system would be time-costly and result in less time being available for the visual search, they said. These specific pilots are aware of the technical limitations of FLARM and consciously elect to simplify their MMs in order to maximize eyes-out time. However, in the post-experiment interviews it became obvious that many glider pilots are *unaware* of the technical limitations of FLARM and the "correct" FLARM coordinate system. Apparently, most contemporary flight training and ground school curricula do not go into depth of how FLARM and other CASs function. Lacking expert guidance and feedback, student pilots are left to develop their own MMs of these systems.

The authors suspect that a well-designed ground school and flight training curriculum is able to convey the concept of the FLARM coordinate system to student pilots. According to the results of the appendix, this would decrease errors made by these pilots when initially estimating the traffic's position, based on FLARM indications. Lower errors would result in quicker visual acquisition of the traffic and therefore more time for evasive maneuvering, reducing the likelihood of collisions.

Table 4: Frequency of each best-fitting mental model

MM:	1	2	3	4	5	6	7	8
Frequency:	2	2	2	4	2	4	2	25

Practical Implications

Because many pilots rely on coordinate systems which differ from the "correct" FLARM coordinate system, several critical situations may arise in practical flight operations. Many pilots will begin their search for traffic with a systematic offset in their initial search direction. This may be particularly problematic whenever short reaction times are available to avoid collisions with other traffic. These systematic errors are expected to increase whenever large bank angles, pitch angles or drift angles exist. Flight operations where this is the case may be (i) thermaling in narrow thermals (high bank angles), or (ii) performing aerobatics (high pitch and bank angles), or (iii) soaring in mountain wave conditions with crosswinds (large drift angles), or (iv) ridge soaring with crosswinds (large drift angles). However, it is still uncertain how much time is lost due to these errors when searching for traffic in the OTW view. The experiment presented so far could not answer several important practical questions. These questions are "what is the effect of using a correct MM of FLARM on pilot workload?" and "does using a correct MM of FLARM actually decrease the time until visually identifying traffic?" These questions should be addressed in future work.

Conclusion

Analysis of the experimental data has shown that most glider pilots use a personal coordinate system which differs from the FLARM coordinate system used for showing traffic information on the FLARM display. This leads to systematic errors in their visual search behavior whenever the bank angle, pitch angle or drift angle deviate from zero. It is expected that higher errors result in longer times until traffic is visually identified and avoidance maneuvers can be initiated.

In order to reduce the errors made by pilots when interpreting the FLARM display — and accelerate the time until the traffic is visually acquired — several approaches are possible:

I.) "Make the pilots fit the box" by training them to use the "correct" FLARM coordinate system. While this should serve to decrease errors in the initial visual search direction it may do so at the cost of increased pilot workload.

II.) "Create a new box" by devising a new display format. Replicating a perspective OTW view of traffic on a display is expected to increase traffic awareness [22]. When properly designed, such a display should have the benefit of optimized usability. Also, it may allow for better local traffic awareness [23]. Heinbücher conceptualizes such a display format by gathering the preferences of glider pilots through expert interviews and an online survey [24]. It is an initial step in a user-centered design of such perspective CAS display for gliding applications [25].

In light of the new results, the previous recommendation issued by the authors and their colleagues to retrofit existing CASs with attitude sensors should be seen with caution [8]. They recommended converting the data shown on the FLARM display into glider-fixed coordinates using attitude sensors. While those pilots already using a glider-fixed personal coordinate system (MM 8) would clearly benefit, a notable part of the user population already performs some or all attitude corrections (MMs 1 through 7). These glider pilots already performing some attitude corrections would need to be identified and retrained on the new system architecture, making the recommendation impracticable.

As of now glider pilots should allow enough time in their task planning for adequate visual scans. Not all other glider traffic may be equipped with FLARM. Therefore not all traffic generates traffic information on the FLARM display and can only be detected visually. Even if traffic is shown on a FLARM display, the glider pilot should allow adequate time for visually detecting and avoiding the traffic shown. There will most likely be an initial offset in the direction where the glider pilot begins her or his search for the traffic in the OTW view and the direction where the traffic is actually located. Finding the traffic in the OTW view will not happen instantaneously and the pilot needs to allocate enough time for this task.

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Appendix

Validation of identification method

In this paper a method for identifying MMs from experimental data is presented. However, before analyzing the results provided by this method, the method must first be validated. Therefore, the two following validation hypotheses were proposed beforehand.

> **Validation Hypothesis 1:** Each participant's answers are centered around the predicted answer directions of the best-fitting MM. No systematic prediction errors exist.

> **Validation Hypothesis 2:** The best-fitting MM influences the magnitude of the error between assumed and indicated traffic direction. Pilots relying on the glider-fixed polar coordinate system (MM 8) make larger errors than those relying on the FLARM polar coordinate system (MM 1).

These hypotheses are tested and discussed subsequently.

Treatment of data for validation

Outliers and implausible answers were removed from the data set before testing. For each combination of the participant's answer and MM, a prediction error was calculated. This prediction error is defined as being the difference between the participant's assumed direction and the direction where a MM predicted the participant's answer to be located. It was decomposed into the visual bearing direction and visual elevation direction ($\Delta\tau^{MM}$ and $\Delta\delta^{MM}$ respectively) of the OTW view. For each participant's answer, also the visual search error $\Delta\gamma$ between the traffic's actual direction and the participant's assumed direction was determined. Missing values were conservatively replaced with appropriate mean values where necessary.

Results of validation hypothesis testing

Testing of the first validation hypothesis was achieved by using each participant's prediction error distributions ($\Delta\tau^{MM}$ and $\Delta\delta^{MM}$) of the best-fitting MM. Each distribution was tested using a one-sample Student's t-test. These tests were performed around the zero-value of each distribution. Due to sample size no further test of normality, though assumed, was necessary [26, section 6.3]. In total, 86 t-tests were performed; one for each error direction of each participant. All of these t-tests remained insignificant. The lowest significance value p for all 86 t-tests was reached by $t(97) = 0.75$, $p = .46$.

The second validation hypothesis was tested using a repeated measures analysis of variance (ANOVA). The ANOVA's design relies on the visual search error $\Delta\gamma$ as the ANOVA's dependent variable. Independent variables are the signal number and flight condition (both within-subject) and the participants' best-fitting MM (between-subjects). Mauchly-Tests of the within-subject factors showed no deviation from the assumption of sphericity (Mauchly's $W = .00$, $\chi^2(299) = 300.06$, $p = .70$ for signal number; and Mauchly's $W = .79$, $\chi^2(5) = 8.14$, $p = .15$ for flight condition). The assumption of normality is violated in 52 of 100 cases (all Levene tests $0.42 \leq F(7,35) \leq 39.82$, $.00 \leq p < .89$). However, these violations do not affect the ANOVA's results substantially [27]. Variations of the visual search error $\Delta\gamma$ with the best-fitting MM are illustrated in Fig. 7.

A significant influence of the best-fitting MM on $\Delta\gamma$ exists; $F(7) = 2.32$, $p = 0.05$. The corresponding generalized η^2 [28] reveals a small effect size; $\eta^2_G = .02$. Visual search errors for participants using an glider-fixed coordinate system (MM 8) are 6.21° larger on average than the errors of participants using the FLARM coordinate system. According to a post-hoc least significant difference (LSD) test, this difference is statistically significant; $p < .01$.

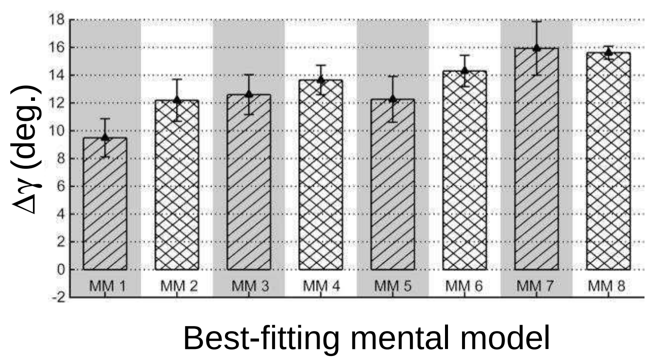

Fig. 7: ANOVA results: Means and 95% confidence intervals of visual search error $\Delta\gamma$ varying with best-fitting mental model.

Discussion of validation results

The MM identification method shows no sign of making systematic errors when predicting participants' answers. This is the result of testing the first validation hypothesis. Instead, all prediction errors scatter equally around the predicted answer direction.

Also, the identification method fulfills its task of explaining the magnitude of the pilots' visual search errors. As expected, error magnitude varies between the different MMs. The lowest visual search errors were made by pilots using the FLARM polar coordinate system while the largest errors were made by those using a glider-fixed coordinate system. The error magnitude of pilots using partially corrected coordinate systems (MMs 2 through 7) lays in-between these two extreme cases.

In summary, the identification method behaves as expected. Also, no systematic errors are evident. Thus, the MM identification method is assumed to provide valid results.