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DOI
10.1016/j.ifacol.2019.12.166

Publication date
2019

Document Version
Final published version

Published in
IFAC-PapersOnLine

Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 52-19 (2019) 151–156

Evaluation of a 3D Solution Space-based ATC Workload Metric

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Abstract: Air Traffic Control (ATC) workload is a limiting factor for air traffic growth, creating a need for objective ATC workload metrics. Previous research has shown that the solution space diagram can be a basis for a workload prediction metric. The current solution space metric however, does not incorporate altitude. In this paper, a 3D solution space metric is described and evaluated. An experiment has been conducted to test the relation of the 3D solution space metric with workload and compare it to other workload metrics; the aircraft count, and a quasi-3D metric: the 2D layered solution space and the Instantaneous Self Assessment-based method. Weak correlations with workload were found for all tested metrics and no significant differences were found between them. Although no significant differences were found, the 2D layered metric showed better results than the 3D solution space-based metric, indicating that air traffic controllers might think in 2D layers over fixed altitude ranges rather than considering the complete 3D physical solution space.

Keywords: Air Traffic Control, mental workload, supervisory control, decision making

1. INTRODUCTION

Air Traffic Control (ATC) workload will remain to be one of the main limiting factors for air traffic growth (Abdul Rahman et al., 2015). To accommodate the high workload demanded of the air traffic controllers, many investments are already made into the development of new procedures and sector designs, of which effects on workload need to be determined (Boag et al., 2006), sparking a need for ATC workload predictions (Gaillard, 1993).

Research has shown that workload originates from two main parts (Hilburn and Jorna, 2001): (i) the taskload, that is, the part of the work demand imposed on the controller purely by the task, and (ii) individual operator factors such as expertise, training, strategy and resource management. To predict the average experienced workload, objective metrics for workload assessment focus on the taskload (Athènes et al., 2002; Hilburn, 2004; Crutchfield and Rosenberg, 2007; Abdul Rahman et al., 2011).

The simplest metric for controller workload is the aircraft count, or, the Static Density (Hilburn, 2004). Although this metric quickly yields acceptable results, its main limitation is that it cannot take into account other important air traffic parameters. Some of these are the interaction between aircraft and flight characteristics (Djokic et al., 2010; Mogford et al., 1995), and it has been shown that the aircraft count has a non-linear relationship with workload (Lee, 2005).

More complex metrics that aim to take the dynamic interaction between aircraft into account include the Dynamic Density (Kopardekar and Magyarits, 2002) and the Traffic Load Index (Athènes et al., 2002). The downside of these metrics is that they have to be tuned from subjective ratings for specific situations in a specific sector to give reliable results (Athènes et al., 2002; Hilburn, 2004).

To start closing this gap and find a solution to estimate workload objectively, the solution space metric (Hermes et al., 2009; D'Engelbronner et al., 2015) has been developed. This metric combines sector geometric and aircraft kinematic aspects and uses the intersection of the velocity obstacle and the aircraft flight envelope to define a so-called "solution space".

So far, this method has shown promising results in 2D test cases (Abdul Rahman et al., 2015; Mercado-Velasco et al., 2010). This paper describes the work to extend this metric to 3D. First, the existing 2D analytical model of the solution space, as described by (Mercado-Velasco et al., 2015), was extended to 3D. Next, to validate the 3D solution space-based metric and to compare its performance with existing metrics, an experiment was performed with a 3D ATC simulator based on the Amsterdam Advanced Air Traffic Control (AAA) system, simplified by excluding wind and radio communication. Subjective workload measurements from this experiment are compared to the predictions from the 3D solution space metrics.

Furthermore, the new higher fidelity set-up gives the opportunity to test the contribution to the experienced workload of aircraft that have been given a transfer of control. Finally, it can be investigated whether air traffic controllers think in layers, or in actual 3D space by comparing a 'quasi-3D' layered solution space with the new developed 3D metric.

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Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2019.12.166

This paper starts with a more elaborated description of the 2D solution space in Section 2 to give a background on the proposed method. Section 3 explains the proposed 3D solution space metric and the mathematical concepts. An experiment is presented in Section 4, and results are given in Section 5. Section 6 presents the final conclusions and recommendations.

2. THE SOLUTION SPACE

Van Dam et al. (2008) created displays for airborne separation, essentially applying the velocity obstacle method (Fiorini and Shiller, 1998) to calculate permissible speeds and headings that would avoid other traffic. This results in the *solution space*, the range of speeds and headings that the aircraft can both fly (thus considering aircraft capabilities) and that ensure avoidance of other traffic. In case aircraft trajectories are straight, the solution space of each aircraft will be constrained by triangular-shaped zones, the Forbidden Beam Zones (FBZ), which represent the speed and headings that an aircraft cannot fly because of the vicinity of other aircraft.

Hermes et al. (2009) used the solution space as a metric for ATC task demand, in scenarios with known planned track changes. His method required calculation of velocity obstacles with planned trajectory changes, resulting in complex code. A simpler implementation, not considering planned track changes, was evaluated for use in a workload metric by Abdul Rahman (2014), see Figure 1. Mercado-Velasco et al. (2015) devised a method to make these calculations simpler and more robust, opened the way for fairly easy calculations for scenarios that can include aircraft intent, such as planned speed and heading changes. The method results in a set of projected circles in the velocity space of the observer, the combination of these circles forms a forbidden zone, with headings and speeds to be avoided, see Figure 2.

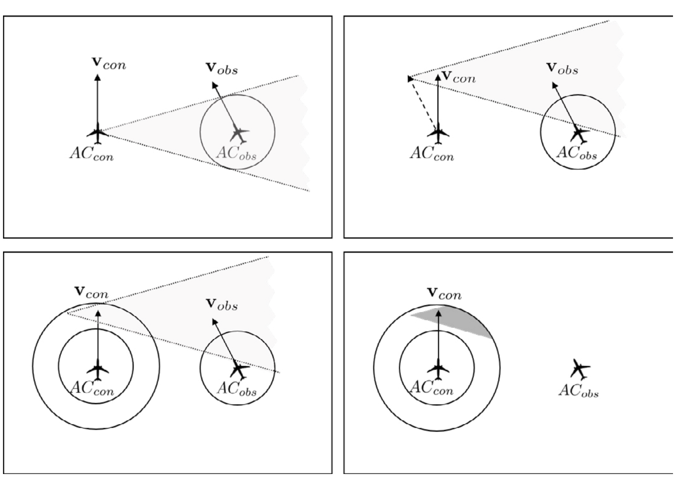

Fig. 1. Construction of the 2D solution space, where AC_{con} and AC_{obs} represent, respectively, the controlled and observed aircraft and $\mathbf{v}_{con}$ and $\mathbf{v}_{obs}$ are the controlled and observed aircraft's velocities, adapted from (Abdul Rahman, 2014)

This "family of circles" can be described by the following equation, referred to as the parametric equation 1:

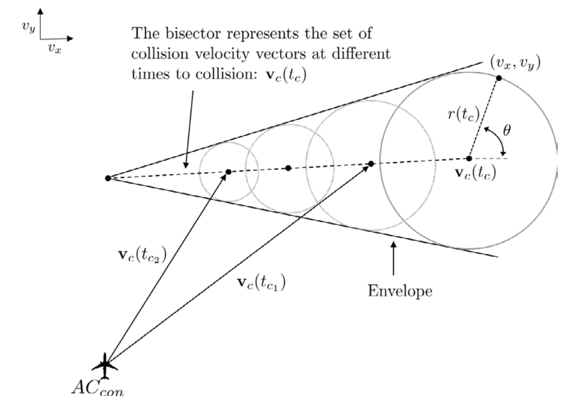

Fig. 2. Family of circles and its envelope, adapted from (Mercado-Velasco et al., 2015)

$$\begin{bmatrix} v_x \\ v_y \end{bmatrix} = \mathbf{v}_c(t_c) + r(t_c) \begin{bmatrix} \cos(\theta) \\ \sin(\theta) \end{bmatrix}$$
$$\forall \quad \theta \in [-\pi, \pi]; \quad t_c \in [t_0, \infty\rangle, \tag{1}$$

where the velocity coordinates of the family of circles are described by (v_x, v_y) and $r(t_c)$ is the radius of the corresponding circle at time to collision t_c. All points within the envelope of this circular velocity set will result in loss of separation. Subtraction of the envelope equation from the performance envelope of the controlled aircraft yields the solution space.

For workload prediction, the size of the intersection area of the FBZ and the flight envelope has to be considered (Hermes et al., 2009; D'Engelbronner et al., 2015). Abdul Rahman (2014) showed that controllers considers six attributes: flight level, flight path, longitudinal separation, relative velocity, direction of flight after reporting points and lateral separation. The 2D solution space metric as described, takes into account five of these parameters; extending it to 3D would include all six.

In 3D, the protected zone is defined as a cylinder to include an additional vertical separation constraint of 1000ft (ICAO, 2007). A first approach to translate the 2D solution space to 3D by using a cylindrical protected zone was reported in (Zhou, 2011). Results were promising, but due to a small sample size and other limitations, no conclusions could be drawn about the 3D solution space as a predictor for workload.

3. TOWARDS A 3D SOLUTION SPACE METRIC

The design of the new 3D solution space-based metric is based on the 2D solution space metric as analytically defined by (Mercado-Velasco et al., 2015).

3.1 3D FBZ Cylindrical Protected Zone

For an aircraft in 3D space, the protected zone is defined as a disk, with a 5 NM radius and 2000ft height, ensuring 1000 ft vertical separation, illustrated in Figure 3.

For the 2D case, Mercado-Velasco et al. (2015) were able to construct an envelope equation for the family of mappings of the protected zone as a velocity obstacle into the velocity space. For the 3D case, this principle will

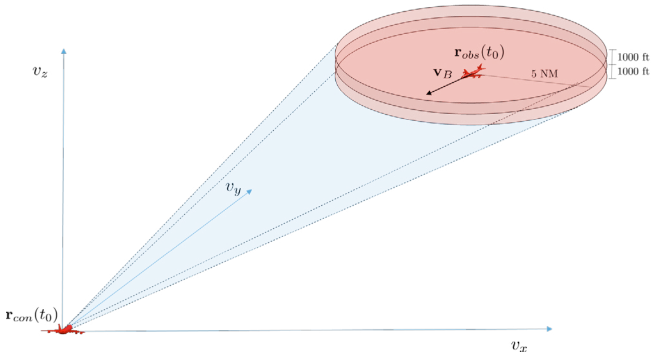

Fig. 3. Observed aircraft with cylindrical protected zone in relation to the controlled aircraft

be re-used, but the mapping in the vertical dimension will be determined by iteration. A family of zero-height circular protected zones for the observed aircraft is now considered, varying in height from 1000ft below to 1000ft above the aircraft, with their center at $r_{obs,z}$, see Figure 3. For each of these zones, the mapping to 3D velocity space is created, analogous to the procedure in (Mercado-Velasco et al., 2015). The mapping of protected zones to the velocity space is again determined by the radius $r_{obs,z}(t_c)$ of the mapped circles, now dependent on the height of the protected zone, and by the velocity vector to the center, $\mathbf{v}_c(t_c)$, which now also includes a 3rd, vertical, component.

3.2 3D performance envelope

The solution space approach uses the intersection of the performance envelope and the FBZ for workload calculations. The performance envelope is determined by multiple factors, namely the stall speed, idle thrust, maximum thrust, fastest climb, steepest climb and maximum speed, see Figure 4. However, air traffic controllers will not use the full performance envelope to give commands to aircraft. Therefore, in the solution space calculation, the envelope is simplified to a rectangle reflecting speed and – altitude dependent – climb and descent limits, as added to Figure 4.

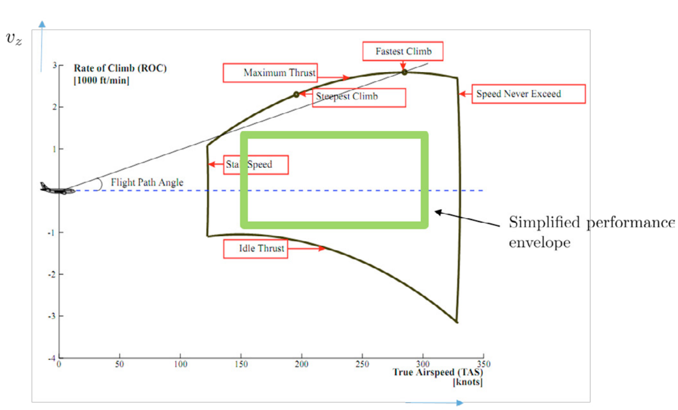

Fig. 4. Simplified performance envelope (green rectangle) shown on the true performance envelope of the Cessna Citation I in a trimmed flight condition at 16405 feet altitude, adapted from (Heylen et al., 2008)

3.3 Intersection FBZ and performance envelope

The 3D aircraft flight envelope is constructed by partly rotating a rectangle around the v_z-axis. Another view to this is imagining the flight envelope as a 'book' consisting of a finite number of pages, see Figure 5.

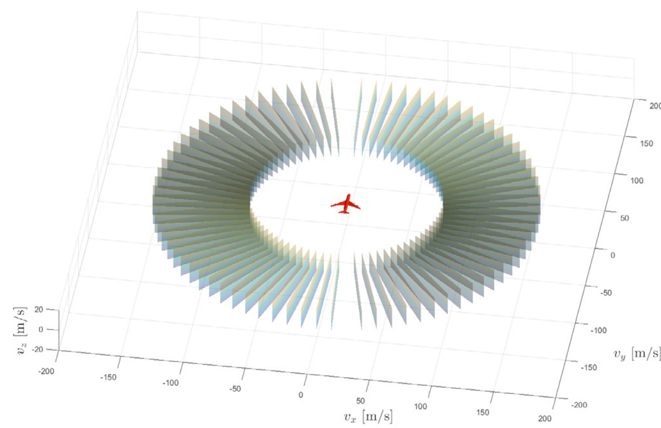

Fig. 5. Vertical cutting planes of the performance envelope forming a 'book'

3.4 Grid approach

To simplify combining the occupied areas from multiple aircraft, a combined grid approach, with grids covering the simplified performance envelope, is used. This is visualized in Figure 6. For each grid point, it is determined whether it is inside an intersection of the performance envelope cutting plane and the protected zone projected by one of the aircraft in the vicinity.

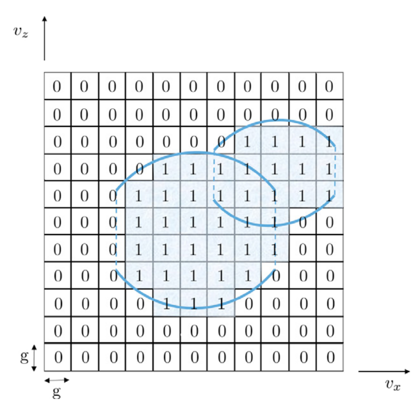

Fig. 6. Using a grid to approach the total solution space on a single vertical cutting plane

4. EXPERIMENT

4.1 Compared metrics

We performed an experiment to test the 3D Solution Space metric; a number of metrics were calculated:

- Aircraft count; the number of aircraft in the sector.
- A 2D layered solution space (Lodder et al., 2011), extending the 2D solution space by calculating the SSD for all aircraft that either (1) fly at the same

level as the considered aircraft, (2) are climbing or descending and have an instruction to cross the level of the considered aircraft, or (3) if the considered aircraft has a climb or descent instruction, cross any of the levels in that instruction.
- The newly developed 3D solution space

The 2D and 3D SSD metrics were evaluated in three variants, one giving the maximum of the blocked SSD areas calculated for all aircraft in the sector, a second giving the mean blocked SSD area, and a third one giving the sum of all blocked SSD areas. Compared to the second variant, the third will thus be more sensitive to the total number of aircraft in the sector.

4.2 Experiment set-up

A desktop ATC simulator was developed, modeled after the AAA system used in the Netherlands. Figure 7 displays the ATC simulator's main screen, showing one aircraft as an example and an ISA rating pop-up workload bar on the left. Traffic could be controlled by using a separate command window, Figure 8, operated either using the touchscreen function or by using the mouse. To control the traffic, the participant had to select the aircraft by clicking it with the mouse, afterwards commands could be given with the command window.

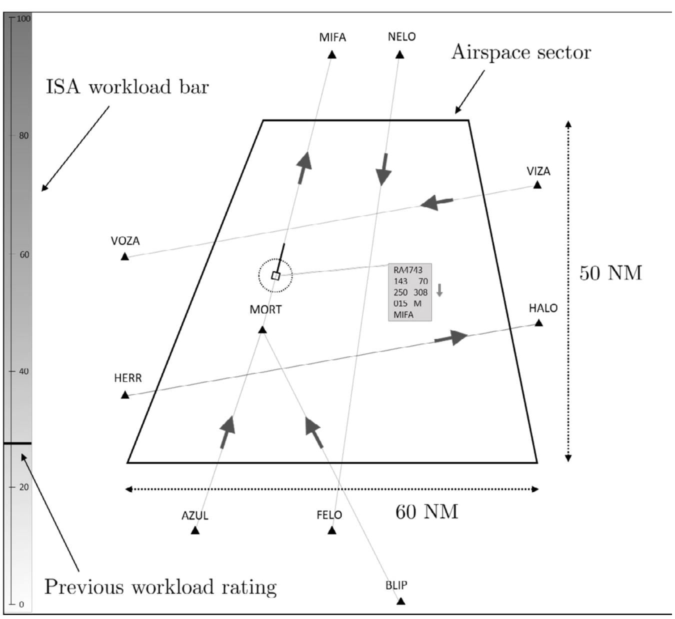

Fig. 7. Plan view display screen, showing the way points, routes, the ISA workload bar on the left and one aircraft visible in the center

Participants rated their subjective workload at 30 s intervals using an Instantaneous Self Assessment (ISA) scale (Tattersall and Foord, 1996) ranging from 0 to 100. Prior to the four measurement runs (20 min each), participants received a briefing and performed 8 training runs to get acquainted to the simulator. The simulations were run at double speed, simulations did not include wind.

Aircraft types were limited to three categories: light, medium and heavy. Separation violations were shown by coloring the aircraft symbol orange for a caution that loss of separation will occur within 120 seconds, and red for a warning for loss of separation within 60 seconds.

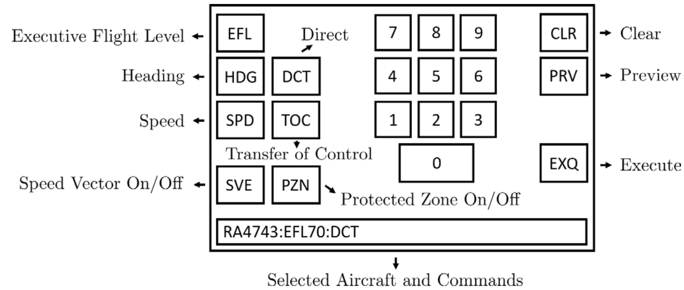

Fig. 8. The command window used to control aircraft

4.3 Participants and Instructions

Ten subjects (all male) participated, divided into two expertise level groups. Four participants were retired Air Traffic Controllers and six had either completed a multiple day extensive ATC-course and/or had worked as a researcher in the ATC field.

Participants were instructed to separate the air traffic and hand them over at the adjacent sector at predefined flight levels. Traffic could be separated by giving speed, heading and/or altitude commands and had to be given a transfer of control (TOC) before leaving the sector. The task included the following, see also Figure 7:

- Inbound traffic coming from AZUL and BLIP and going to the northern waypoint MIFA, has to be merged and leave the sector between FL 70 - 100.
- Outbound traffic from NELO to FELO has to leave the sector at FL 200.
- Overflights towards HALO have to be handed over at FL210.
- Overflights towards VOZA leave the sector at the same flight level as they enter (FL140).
- Aircraft have to be given a transfer of control before they leave the sector.
- When aircraft are given a transfer of control they have to be separated (at least 1000 ft vertically and 5NM horizontally) from each other and should not be involved in any conflicts.

4.4 Scenarios and variables

The experiment consisted of four scenarios of 20 minutes each, further detailed in Table 1.

Table 1. Scenario characteristics

	A	B	C	D
Traffic	High	Low	High	Low
Traffic mix	yes	partly	yes	yes
Merges	+/-	-	+	+/-
Overtakes	+/-	-	+	+/-
Crossings	+/-	+/-	-	-
Deviating aircraft	-	-	-	+

4.5 Hypotheses

The goal of the experiment is to determine if the developed 3D solution space metric could be a good objective ATC

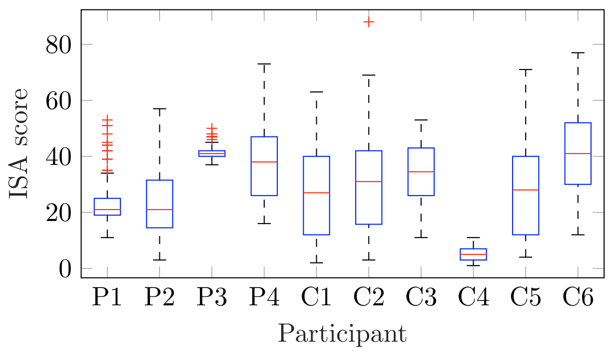

Fig. 9. ISA score distribution per participant

workload metric and is better in predicting ATC workload than existing metrics. Prior to the experiment the following main hypotheses were established.

- **H1A.** If the 3D solution space-based metric is related to ATC workload, the 3D solution space metric will show significant correlation with subjective ATC workload indications.
- **H1B.** If the 3D solution space-based metric is a better predictor for ATC workload than existing metrics (e.g., the aircraft count and 2D layered SSD), it will show better correlation with the subjective workload ratings than the aircraft count and 2D layered SSD.
- **H2.** If professional air traffic controllers think in flight levels and project the 3D space on a 2D plane, then for this group the 2D layered solution space metric will show significantly better correlation with the subjective workload ratings than the 3D solution space-based metric.

5. RESULTS

Every scenario started out with an empty sector and aircraft starting to fly in. To eliminate the effects of this start-up phase, the first 5 minutes of the experiment data were removed. The remaining 15 minutes of data were used for the analyses.

Data were first inspected for outliers. Multiple ISA outliers were found for participants P1 and P3, as shown in the boxplot in Figure 9. In both cases these outliers are consistent with consequently higher ratings at that time, hence these outliers fit in the behavioral pattern of the corresponding participant. For participant C2, one outlier was detected. At this moment in time, loss of separation occurred, so it seems plausible the workload was indeed very high. Because all outliers can be explained, none are rejected and all obtained ISA workload data were used for further analysis.

5.1 Scenarios

The scenarios were designed to feature different characteristics, see Table 1. To test if these characteristics also have an influence on the experienced workload, the scenarios are compared to each other for number of commands, instructions given per command and ISA z-score.

For the Number of Commands, significant differences were found between most scenarios, except A and C, and B and D. For instructions given per command no significant differences were found. For the ISA z-score, as illustrated in Figure 10, first a Shapiro-Wilk test has been used to validate that the z-score distributions per scenario had a normal distribution. An ANOVA was performed, with a post-hoc Bonferroni test, showing a significant difference ($F(3,24)=24.456$, $p<0.05$). With the conservative Bonferroni test, it could be determined that scenario A was significantly different compared to B and D, and scenario B was significantly different compared to C.

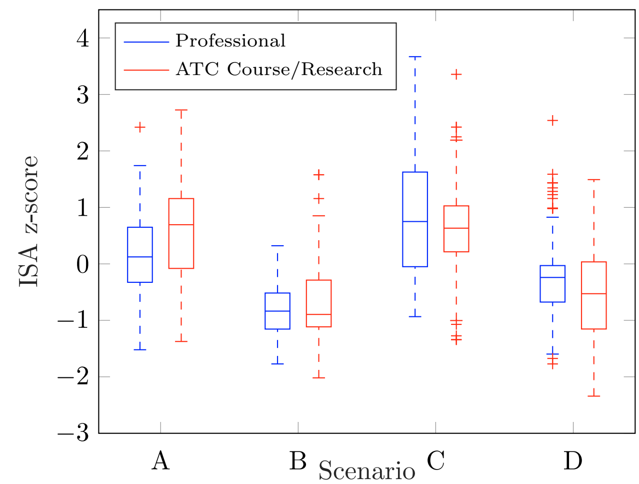

Fig. 10. ISA z-score per expertise group per scenario

For the different metrics the scenario differences were also analyzed. For normally-distributed metrics an ANOVA with post-hoc Bonferroni, and for non-normal distributed metrics a Friedman test with post-hoc Wilcoxon test, was done. Significant differences ($p<0.05$) were found between all scenarios, except scenarios A and C. It can be concluded that scenario differences are distinct enough to analyze the workload and metrics on a scenario level.

For all these analyses combined it can be concluded that scenarios A and C were indeed more difficult than scenarios B and D and hence, scenarios with higher traffic and more merges and overtakes lead to higher workload. Crossings and deviating aircraft did not have a significant influence in the difference in experienced difficulty level of the scenarios.

5.2 Correlation Analysis

Using the simulator data, the different metrics were calculated at 3-second intervals. Both the mean values of these metrics over the interval covered by an ISA rating, and the maximum values of these metrics over that interval were considered for correlation with the ISA z-scores.

The combined correlation, over all subjects and scenarios, is shown in Table 2. It can be seen that taking the sum of the layered 2D SSD yields the best correlations, with second-best the Aircraft Count, then followed by taking the sum of the 3D SSD metric; no significant differences were found on an individual level, however. Taking the mean or maximum value compared to the ISA z-score does not seem to have an effect. It should be noted that, due to limited availability of experienced controllers, the comparison between the two groups has limited power.

Table 2. Correlations metrics with ISA z-score

	Mean		Max	
	R	p	R	p
Aircraft Count	**0.3852**	**< 0.05**	**0.3987**	**< 0.05**
2D Layered SSD_{mean}	0.3091	< 0.05	0.3069	< 0.05
2D Layered SSD_{max}	0.3246	< 0.05	0.3172	< 0.05
2D Layered SSD_{sum}	**0.3888**	**< 0.05**	**0.3907**	**< 0.05**
3D SSD_{mean}	0.3105	< 0.05	0.2954	< 0.05
3D SSD_{max}	0.2788	< 0.05	0.2362	< 0.05
3D SSD_{sum}	**0.3778**	**< 0.05**	**0.3714**	**< 0.05**

6. CONCLUSIONS

In this paper we presented the development and evaluation of a 3D solution space-based metric for air traffic control workload. It can be concluded that the 2D solution space was successfully updated to a 3D model. Results from a human-in-the-loop experiment, however, did not give conclusive answers as to the correlation of the newly developed metric with workload.

For the 3D solution space, as well as the aircraft count and a "quasi-3D" layered solution space metric, only weak correlations were found with subjective workload ratings. Overall, the 2D layered solution space is deemed more promising, probably due to its alignment with current ATC practice but also because of its easier implementation, relative to the more complicated (but mathematically exact) 3D solution space.

It is recommended to devote more research to "quasi-3D" layered solution space metric, for scenarios mimicking current-day ATC practice.

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