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Evaluating and Comparing Airspace Structure Visualisation and Perception on Digital Aeronautical Charts

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Abstract.
Given the challenge of visualising 3D space on a 2D map, maps used for in-flight navigation by pilots should be designed especially carefully. This paper studies, based on existing aeronautical charts, the visualisation, interaction, and interpretation of airspace structures with aviation infrastructure and the base map.

We first developed a three-tiered evaluation grid for a cartographic analysis of existing aeronautical charts. Subsequently, we evaluated four countries' maps based on our evaluation grid. To validate our analysis, we conducted a user study with 27 pilots, the users of aeronautical charts.

The results of our cartographic analysis show that aeronautical charts produced by different countries all fulfil the need of pilots being able to orient themselves. According to our evaluation, the Swiss aeronautical chart scored slightly more favourably than the other evaluated charts for effective map-reading. These findings were confirmed in the results of the user study.

The major contribution of this work is the evaluation grid for the cartographic analysis. With its different layers, adaptable main- and sub-topics, it can be used to compare and improve the design not only of aeronautical charts, but for a broad spectrum of thematic maps.

Keywords. cartographic analysis, aviation map, airspace structure, evaluation grid, user study

1 Introduction

Modern digital devices (e.g., tablets) enable new possibilities when it comes to cartographic visualisations. Not only can traditional (2D or 2.5D) maps and charts be shown in a static manner, but interactive 3D visualisations are equally possible. While the transition from paper maps to digital charts is well underway, the step to 3D visualisations has yet to come. Given the current state of using tablets to visualise static aeronautical charts in a manner similar to using paper charts, we wanted to study the efficiency of the visualised charts on digital devices.

Aircraft (unlike, e.g., cars) operate in all three dimensions. The 3D space is split up into different structures ("volumes" in space), with varying geographical and vertical extent. Thus, the challenge of mapping 3D space to a 2D map is omnipresent. Figure 1 shows the general airspace structure of Switzerland, with the 3D complexity being apparent in this cross-sectional view.

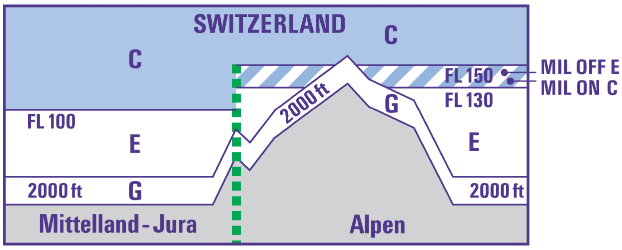


Figure 1. A cross-section of the airspace structure in Switzerland. (Federal Office of Topography, 2021)

While recommendations by the International Civil Aviation Organisation (ICAO) exist with proposed standards on how to visualise airspace structures, these proposals are not uniformly applied globally, with each country having considerable leeway in the design of their national aeronautical charts. We want to discover if a specific design facilitates effective map-reading in the cockpit, first from a cartographic point of view, and subsequently verify our results with a user study.

This led to the two following research questions:

1. Which cartographic design choices make for an effective aeronautical chart?

2. How do users of aeronautical charts rank differently designed charts in terms of design and for effective map-reading?

Answers to the first research question were developed by following long-standing cartographic principles, such as an analysis of graphic variables. We designed an evaluation grid for a such comparison. The levels in our evaluation grid are generally applicable to any thematic map, and the main topics in the different layers can, with evident, minor modifications, readily be applied to a broad range of topics.

To answer the second question, we designed a user study and invited pilots, users of aeronautical charts, to participate. The user study first enquired on how the pilots orient themselves using aeronautical charts, secondly on discovering if a specific chart design permits more effective map-reading, and finally, on the perception of the design of airspace structure visualisations.

We compared the aeronautical charts for flying according to visual flight rules (VFR) of four countries: Switzerland, Austria, the United States, and Australia. The former two are designed based on the ICAO recommendations, while the latter two do not. This becomes evident after analysing the respective designs of the chart elemants, and could be inferred by the chart title. To aid this comparison, the recommendations of ICAO for the design of aeronautical charts were included in the cartographic evaluation grid.

This paper continues with an brief historical overview of the development of aeronautical charts, and introduces the analysed charts. Subsequently, we present the methodology and results of our cartographic analysis. In section 4 we present the results of a survey conducted with 27 expert users, all licensed pilots. Finally, in section 5 and section 6, we discuss our findings and present an outlook to possible future work.

2 Background and Related Work

2.1 Historical Development of Aviation Cartography

The earliest aviators, at the beginning of the 20th century, were soon aware that the requirements for aerial navigation differed from those of map users on the ground (Lees, 1921). Lees emphasised the importance of revising the representation of certain map elements. In particular, he discussed the representation of roads and railways, the latter of which are more important in aviation, and should thus be coloured in red. He stated that the labelling of cities and towns is not as important as the outline of the settlement. Furthermore, he discussed the problem of information overload, as well as the matter of map generalisation. These are all issues that one still finds challenging in the design of aeronautical charts today.

Despite these insights, the first aeronautical charts were often produced with monochrome printing of additional aeronautical information over existing topographic maps (Taylor, 1985). It was not until the end of the Second World War that a more widespread standardisation in aviation was achieved by the newly founded ICAO. With the first publication of the ICAO document entitled *Aeronautical Charts* in 1948, design standards and regulations for aeronautical charts were introduced by this body (Meine, 1966). The 11th and current version of Aeronautical Charts (International Civil Aviation Organization, 2009) provides suggestions for various chart products (e.g., Enroute Chart, Area Chart, Instrument Approach Chart, etc.). Specifications are given on the function of the chart, availability, scale, projection, cultural and topographic representation and aeronautical information.

Taylor and Hopkin (1975) identified five general principles for the representation of symbols in order to increase readability, namely high contrast, exaggerated physical dimensions, simple symbol forms with high association value, low confusability, and reduced information content and clutter. The essence of these principles still apply to aeronautical charts today. Both Taylor and Hopkin (1975) and Taylor (1985) showed the then current state of research and development of aeronautical charts. Important findings and conclusions include considerations on map aesthetics, colour coding and the presentation of charts on the first displays in the cockpit.

Since 1985, research on visualising spatial information in the cockpit has focused on the digital display of said information. Andre et al. (1991) studied the effects of dimension, perspective and colour of displays on situation awareness, with especially colour providing clear benefits, and dimensionality being a double-edged sword. In the later 90s, Derefeldt et al. (1998) performed a similar study, coming to the conclusion that coloured displays are clearly advantageous over monochrome for moving map cockpit displays. A more recent overview of the state of the art cockpit displays is given in Curtis et al. (2010).

2.2 Guidelines for Cartographic Analysis of Maps

The foundation of our cartographic analysis is Bertin's canonical 1967 reference on the Semiology of Graphics (Bertin, 2010, Translation). Recent textbooks, such as (Kraak and Ormeling, 2010, Chapter 5) and (Slocum et al., 2022, Chapter 13), emphasise the same considerations for map design.

Bertin's visual variables (size, value, texture, colour, orientation and shape) were reviewed by Kraak (2017) and White (2017). Both of them compiled tables on the suitability of the visual variables for different measurements. These considerations equally played a role in the design of our cartographic analysis.

2.3 Studied Aviation Charts

Despite the efforts for standardisation of aeronautical charts by ICAO, not all countries' aeronautical charts follow the proposed standards. Even among the countries that follow the ICAO guidelines, there is leeway in the specific design of individual elements on the charts.

Hence, two charts were chosen that follow the ICAO proposals and two that do not. This enables comparisons between ICAO-conform charts, between non-conform charts, and between conform and non-conform charts. Snippets of all studied charts are available in Appendix A.

The *Aeronautical Chart ICAO Switzerland* (Federal Office of Topography, 2022) is the official chart for visual flight in Switzerland. It has been designed in accordance with the ICAO regulations. The chart is available as a foldable paper map at a scale of 1 to 500 000 or as a digital map. It covers the entire area of Switzerland. The digital version is available free of charge (for non-commercial purposes) as a geo-referenced raster file (TIF) on the Swisstopo website.

The official aeronautical chart of Austria – called *Aeronautical Chart ICAO - 1 : 500 000* (Austro Control, 2022a) – is designed under ICAO regulations. It is available as a foldable paper map at a scale of 1 to 500 000 and as a digital document. Here, too, one chart covers the entire country. The digital version is downloadable free of charge (for non-commercial purposes) in raster format as a non-geo-referenced PDF.

In the United States, the *VFR Raster Charts* (Federal Aviation Administration, 2022b) are a series of charts published by the Federal Aviation Administration (FAA). This series of over 50 charts forms the official basis for navigation under visual flight rules in the USA. These are available in a geo-referenced raster format (GEO-TIFF) or as PDF on the FAA website free of charge (for non-commercial purposes). The scale of the available paper maps is 1 to 500 000. The series covers the area of the entire United States.

The *Visual Navigation Charts* (VNC) (Airservices Australia, 2022) are a series of charts for flying in Australia. The series consists of 15 charts, which do not cover the entire continent, but only the densely populated coastal areas. Paper maps are available at a scale of 1 to 500 000. The digital version can be downloaded as a PDF. This digital chart differs from the other charts studied in that it is available as a vector file. A unique feature of the Australian VNC series is that not all maps have the same geographical orientation.

Map legends are available on the map sheets for the American (Federal Aviation Administration, 2022a) and Australian (Airservices Australia, 2022) aeronautical charts, and as map supplements for the Swiss (Federal Office of Topography, 2021) and Austrian (Austro Control, 2022b) charts.

In summary, all studied charts, except for the VNC series from Australia, are only available in raster format. During the cartographic analysis it became apparent that the resolution of the Swiss and Austrian charts is particularly poor. Although the American chart is also a raster file, it is available at a higher resolution, which leads to better legibility in a zoomed-in view.

3 Cartographic Analysis with an Evaluation Grid

3.1 Methodology

Only limited literature exists studying aeronautical charts used for visual flight rules from a cartographic design principles point of view. Hansman and Mykityshyn (1990) analysed existing issues for instrument flight rules. In the VFR field, the most similar work our literature search found is the thesis by Marx (2015), which attempted a redesign of VFR charts based on the users' perception. We have not found, in the aviation domain specifically, literature presenting both an analysis based on cartographic principles, a user study, and combining the findings of the two. Given the perceived gap of existing research, we started the development of an evaluation grid based on long-standing cartographic principles (see subsection 2.2) for aeronautical charts. Our evaluation grid is available as supplementary material (see Data and Software Availability).

The evaluation grid contains three levels of analysis, each level consisting of several main topics with associated sub-topics. Each sub-topic has one or more assessment criteria. The units of measurement for each criteria enable the charts to be compared in a meaningful way.

The three levels and main topics of each level can be seen in Table 1. The schematic structure of the evaluation grid can be found in Figure 2.

The first level of analysis *describes* the elements present on the chart. In each of the three main topics (airspace structures, aviation infrastructures and base map), the use of graphic variables is examined.

On the second level of analysis, the *interaction* of different map layers is examined. Here, airspace structure objects are compared with aviation infrastructure objects and with the base map objects. An important aspect in cartography are the emphasised objects and how information clutter is handled.

The third level deals with chart *interpretation*. It examines whether the choice of visualised objects and their representation is justified for the use case of VFR flying. This level is about analysing how certain design elements are used to represent facts and information. Using the results from the two previous levels, this level examines issues such as purpose, effectiveness and the (visualised and perceived) importance of individual elements for the charts.

When applying the evaluation grid, each of the four charts was examined and rated per level and criterion (see Figure 3). After rating one criterion on all charts, the results were compared and a favoured chart was selected. The order of charts when evaluating for the different criteria was randomised.

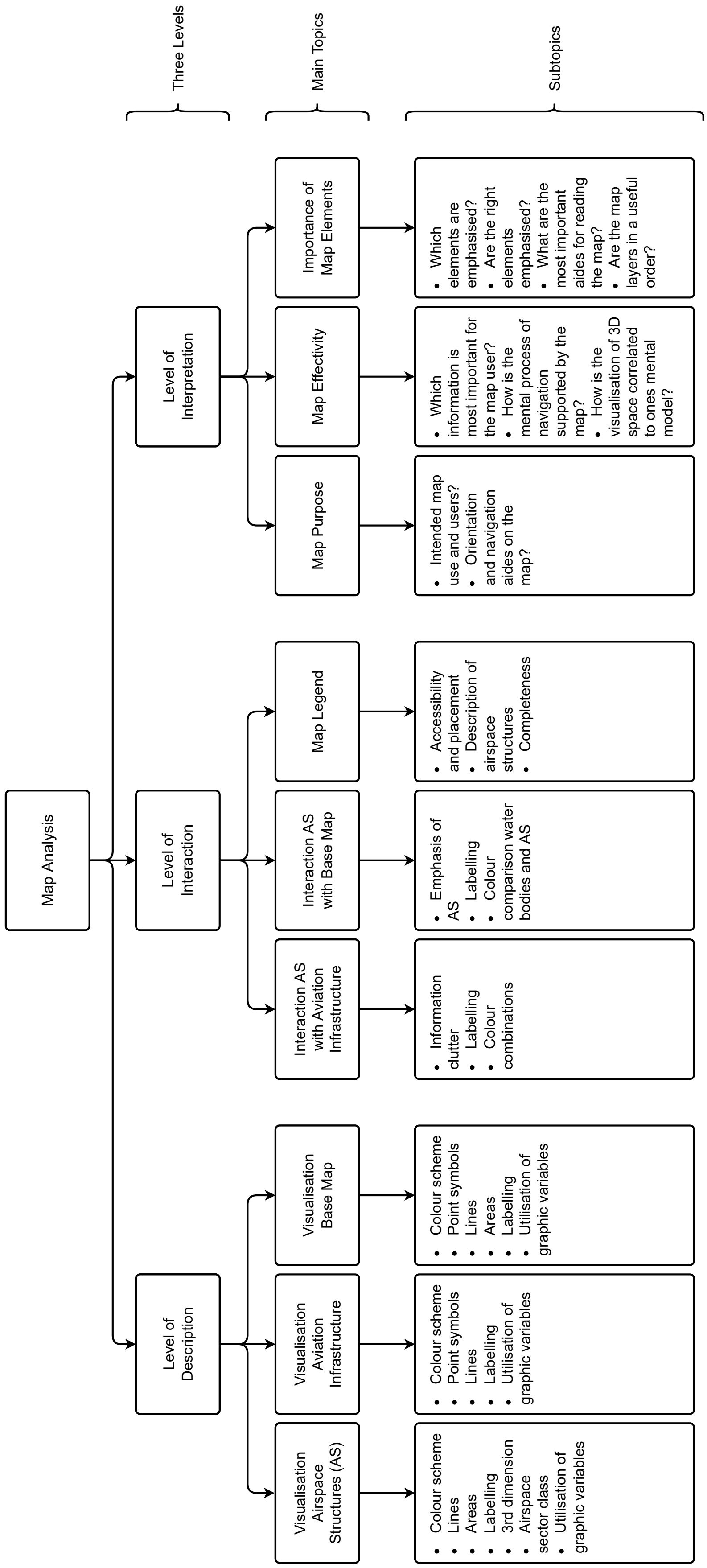


Figure 2. Structure of the evaluation grid.

Table 1. The three levels and main topics of the our evaluation grid for cartographic analysis of aeronautical charts.

Levels	Main Topics
Level of Description	Visualisation Airspace Structures Visualisation Aviation Infrastructure Visualisation Base Map
Level of Interaction	Interaction Airspace Structures with Aviation Infrastructure Interaction Airspace Structures with Base Map
Level of Interpretation	Map Purpose Map Effectiveness Importance of Map Elements

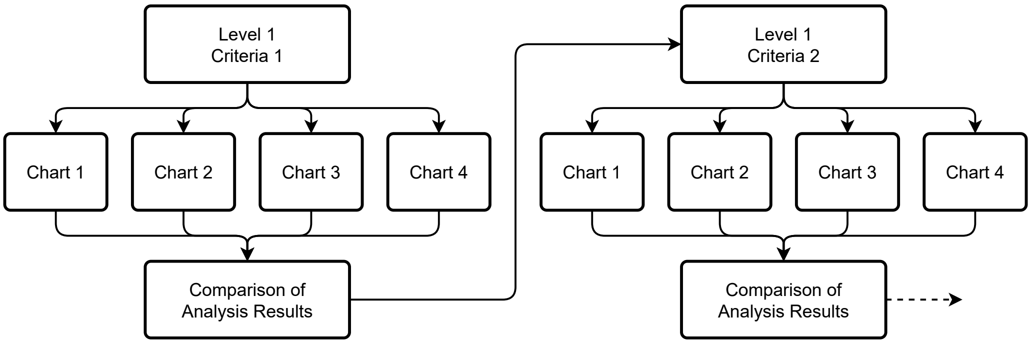


Figure 3. Flowchart depicting the cartographic analysis workflow.

3.2 Results

3.2.1 Level of Description

Colour differentiation makes it easier to efficiently identify objects of different categories, such as airspace structures, as stated by Derefeldt et al. (1998). The Australian chart uses five, the Swiss and American charts use three, and the Austrian chart uses only two colours to visualise airspace structures.

There is considerable difference in the saturation of the symbolisation of airspace structures. Specifically, the American and Austrian charts are similar with a weaker saturation, whereas the Swiss and Australian charts work with a stronger saturation of symbols.

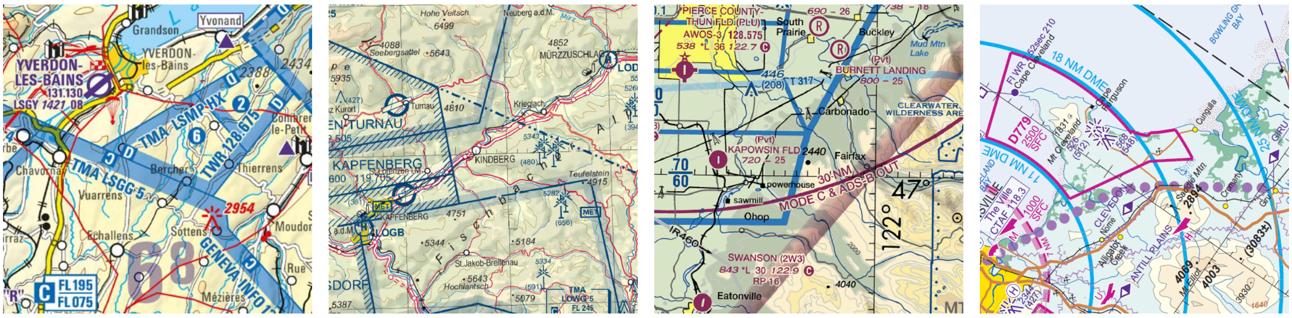
The two charts following ICAO recommendations use a two-part symbolisation for the lines along airspace boundaries, whereas a one-part symbolisation was chosen for the American and Australian charts. The two-part symbolisation consists of a wide semi-transparent line together with a thinner non-transparent line. This has the advantage of creating a clear boundary (with the thinner and non-transparent part of the line) without obscuring too much of the underlying content of the chart. Another advantage of the two-part symbolisation is the possibility to create an inner and outer boundary of the area of the airspace. Different styles used to visualise lines (the boundaries of airspace structures in our case) can be found in Figure 4.

Airspace classes are distinguished with several different methods. On ICAO-compliant and Australian charts the classes are distinguished with an explicit labelling in the respective sector. In contrast, the American chart relies solely on colour coding of the airspace class boundaries, with the meaning of the colours explained in the legend.

Restricted areas are an important class of airspace structures. These areas must not be entered by most pilots. For this reason, they are marked with a unique symbolisation on all charts. While the Swiss, Austrian and Australian charts show the restricted areas in bright red to pink, on the American charts they are indistinguishable from the rest of the airspace structure in terms of colour. On the ICAO-compliant charts, the pattern on the inside of the line is offset by a fixed 45 degrees relative to the edge of the chart. Thus the angle between line and the hachure is variable. Keeping a constant angle makes the line look calmer. We see the opposite on the American and Australian charts, where the hachure is set perpendicularly to the line. This may lead to chaotic patterning. The different designs of restricted area borders are shown in Figure 5.

The representation of the vertical dimension is particularly crucial in 3D airspace. All examined charts resort to textual design elements for the third dimension, with distinct variations in the choice of displayed variables and visualisation style.

On the Australian chart, the arrangement does not appear compact, even disjoint, as the horizontal spacing of the labelling between the upper and lower boundaries is not al-



(a) Swiss example. (b) Austrian example. (c) United States example. (d) Australian example.

Figure 4. Chart snippets showing different line styles delimiting airspace sectors.

(a) Swiss example. (b) Austrian example. (c) United States example. (d) Australian example.

Figure 5. Chart snippets showing different styles of delimiting restricted areas.

ways identical. On the three remaining charts, information on the vertical dimension is compactly visualised and is thus easily identified as related, relevant information.

On the ICAO-compliant charts, vertical altitude information is framed. It is noticeable that altitude information is most clearly delineated on the Swiss chart, with it being framed and marked with a white background. While a frame is equally present on the Austrian chart, there is no background colour. On the non-ICAO-compliant charts, frame and background colour are omitted.

On the Austrian chart, all units are explicitly mentioned in addition to the numeric altitude. This necessitates a lot of text. On the Swiss chart this is solved such that altitudes measured in feet above sea level are shown in italics without unit, and flight levels have FL as unit abbreviation. If the altitude is in feet above ground, this is directly indicated with the unit "Above Ground Level", abbreviated AGL. On the American chart, no units are indicated, with all values implicitly being given in hundreds of feet.

In Figure 6, we present some examples on how the different countries present altitude information.

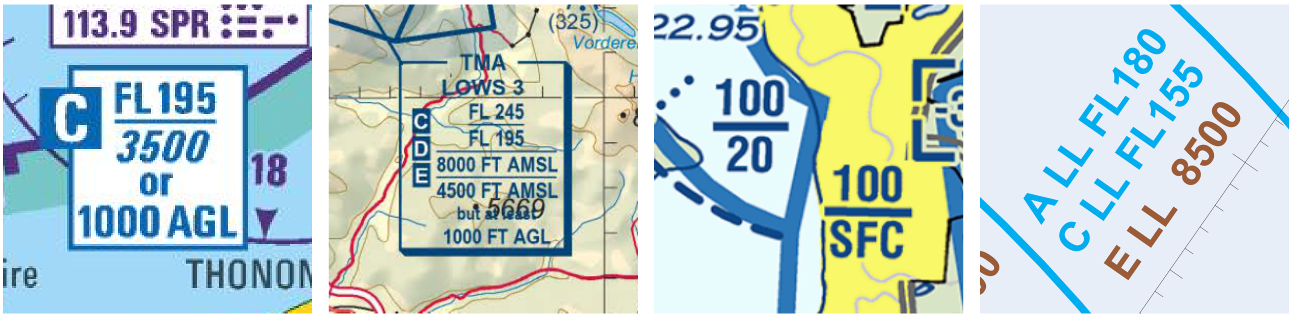
As we can see from above elaborations, different countries solve the existing challenges for visualisation the various information in different ways. While there are some similarities – e.g., restricted areas in warning colours and hachured – the differences are much more numerous.

3.2.2 Level of Interaction

The analysed charts show two basic approaches on how to visualise airspace structures and aviation infrastructures alongside each other. The American and Austrian charts selected the same colours for both object categories. This allows the entire thematic content to visually merge into one layer. The Australian and Swiss charts, on the other hand, choose different colours for the two object categories.

The Austrian chart is the only one of the four charts that shows the aviation infrastructure in a layer beneath the airspace structures. However, the very thin lines chosen for the airspace sectors do not heavily obscure its point symbols on the aviation infrastructure layer, such as aerodromes. The risk of obscuring aviation infrastructure is non-existent on the other charts, as this map layer is visualised above the airspace structure layer.

On all charts, labels use the same colour as the objects they are associated with. As a result, it is harder to connect the textual information to the respective object in the Austrian and American charts, with different shades of black, grey and dark blue being used for various kinds of objects. On the Swiss and Australian charts, information in text form is visually easy to assign to an object class. Careful placement of the labelling is therefore of great importance, especially on the two charts where the two thematic map layers do not differ in colour.



(a) Swiss example. (b) Austrian example. (c) United States example. (d) Australian example.

Figure 6. Chart snippets showing different ways of visualising altitude information.

Even with similar content, the base maps of the four charts are designed differently. A good base map provides sufficient topographic information for spatial orientation yet is kept as simple as possible keep the focus on the thematic content.

3.2.3 Level of Interpretation

The purpose of all studied charts is the visualisation of information helping pilots to orient and navigate in visual flight. When analysing the charts, we noticed varying weight given to different information on the studied charts. Features used for orientation (roads, railways, waterways, etc.) are less prominent on the two non-ICAO-compliant charts and tend to be lost in the overall effect of the chart, while these object classes are very present on ICAO-compliant charts.

Aspects such as layer hierarchy or colour choice are important for assessing the importance of elements of a map. On the two ICAO-compliant charts, it is noticeable that objects warning pilots are coloured in red, such as restricted areas. On the Swiss chart, obstacles and military airfields are coloured red. Interestingly, however, on both ICAO-compliant charts restricted areas are not shown as the top layer. On American charts, the visual importance of restricted areas is clearly lower than on the other three charts.

Chart effectiveness was evaluated in six dimensions, namely airspace structures, aviation infrastructure, the base map, interaction between airspace structures and infrastructure and the base map, respectively, and finally, the hierarchy of layers. The results of this analysis are shown in Figure 7. On average, Switzerland has the highest ratings for chart effectiveness, judged by our rating within our evaluation grid.

The focus of each chart, such as airspace structures for Switzerland, or the base map in the case of Austria, can also clearly be seen, by the comparatively high rankings in the respective category.

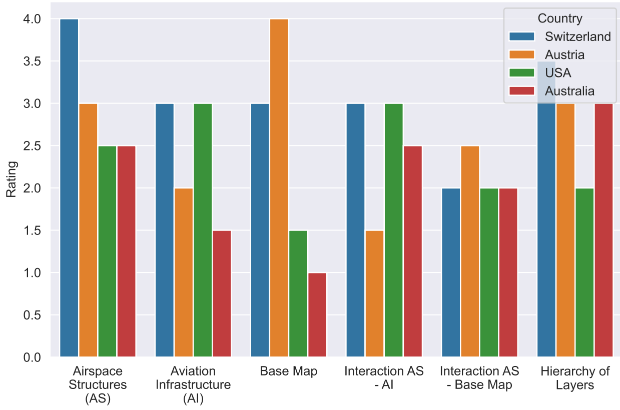


Figure 7. Chart visualisation effectiveness. (0: Visualisation degrades chart effectiveness; 4: Visualisation improves chart effectiveness)

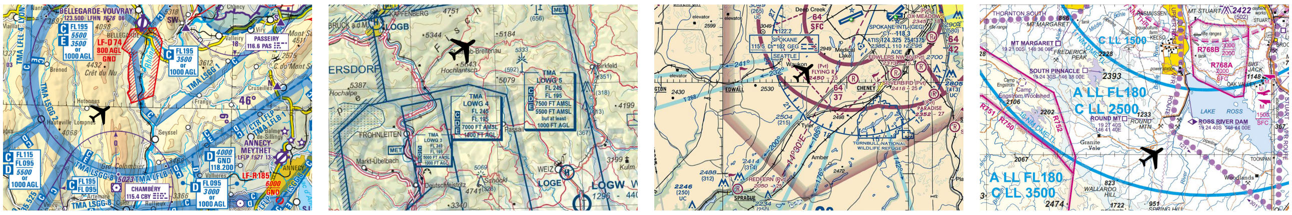
4 User Study

4.1 Methodology

A user study with 27 participants was conducted to answer research question two, how the users of aeronautical charts perceive different chart designs and if a specific chart design can be read more effectively than others. Study participants were recruited through word-of-mouth. The survey was conducted anonymously via an online form, without remuneration. The time required for the participants to complete the survey was around 20 minutes. The set-up enabled to participants to complete the study at a time and place, and with on a device of their choosing.

Before distributing the survey, the questionnaire was discussed with two certified pilots and adjusted where necessary. The full survey is available as supplementary material (see Data and Software Availability).

The first part of the survey was used to collect *demographic information*. This included information such as age, gender, licence type, number of flight hours accumulated, years of flight experience, experience flying in and using charts of the countries investigated, and on which medium (paper/digital) they used the VFR chart.



(a) Swiss example. (b) Austrian example. (c) United States example. (d) Australian example.

Figure 8. Stimuli for the third part of the study, the airspace class determination task.

In the second part, participants were asked questions on *how they orient themselves using aeronautical charts*. Here, we wanted to determine which elements of the chart are used to aid orientation and which of these are perceived as most important. Participants were asked to provide a ranking of water bodies, roads and railroads, settlement edges and names, prominent buildings, aviation infrastructure and obstacles, and mountains ranges and passes.

In the third part, participants were asked to *determine the airspace class* an aircraft was located in. An aircraft symbol was drawn on a section of the chart, which represented the current position. Information concerning altitude was given textually. See Figure 8 for examples. Based on the given chart snippet, participants had to determine in which airspace class the aircraft was located. One correct answer was expected from five given choices consisting of three airspace classes, that more information was required (e.g., knowing the chart legend), or none were correct. The survey was designed in a static manner: The map snippets were not interactive, no zooming or panning was possible.

The following factors were controlled for each snippet:

- Five to seven airspace sectors are evident across two to three airspace classes;
- The snippet contains a settlement area;
- The snippet is located in the vicinity of an international airport.

Post-task, each participant was asked whether the given visualisation enabled an efficient completion of the task, and how legible the information of the vertical extent of the airspace sectors was.

The fourth part of the survey was designed to discover *participants' preferences for the representation of the airspace structures*. Participants were asked where they prefer information about the vertical dimension of airspace structures – in the chart or in the legend. Later, given a choice of different visualisations for altitude information, participants selected their preferred visualisation. Subsequently, a question to rank the importance of colours and lines was posed.

Participants were then asked to establish two rankings, first only according to the favoured representation of airspace structures, the second considering the overall chart design.

To conclude the survey, two questions were asked on the countries in which the pilots had flying experience, and their perceived bias due to potentially having experience with some, but not all, of the charts presented in the survey.

4.2 Results

4.2.1 Demographics

Twenty of the 27 participants held a private pilots' licence, the remaining seven a higher-rated licence (e.g., flight instructor or commercial pilot). All participants regularly used aeronautical charts for VFR flights. The median flight experience was about 700 hours in 10 years of flying experience, with ten participants having less than five years of experience, and eight participants more than 25 years of experience. Two participants had more than 10 000 hours of flight experience.

All participants were familiar with the VFR chart of Switzerland (Aeronautical Chart ICAO Switzerland). About half of the participants have already used the aeronautical chart of Austria and about one third of the participants have used the VFR chart series of the USA. None of the participants used the Australian visual flight charts.

Six pilots stated to only use paper maps, eight only digital charts or an app with integrated charts, and thirteen participants use both paper and digital maps. This is shown visually in Figure 9. Surprisingly, less than half of the participants use the medium on which they were trained on, but in general, have switched from paper to digital maps. However, the paper map is still used, e.g. as back-up.

4.2.2 Orientation with VFR Charts

This part of the survey asked the participants what features of the chart they use for orientation. Water bodies were used for orientation by all participants. Twenty-five of 27 participants use prominent mountain ranges and passes. Twenty-three and 21 pilots use roads and railways or prominent buildings, respectively, for orientation. An overview on how many participants use what chart features can be seen in Figure 10.

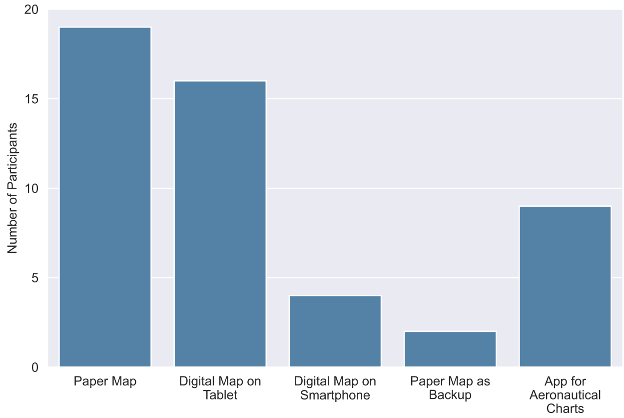


Figure 9. Used medium for viewing the aeronautical chart. (Multiple selection possible. $n = 27$)

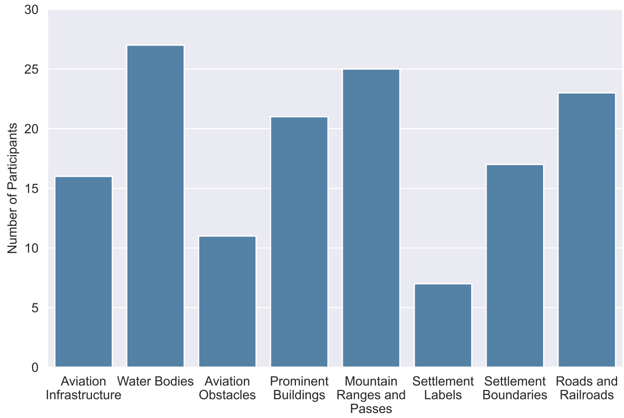


Figure 10. Features used for orientation. (Multiple selection possible. $n = 27$)

4.2.3 Airspace Class Determination Tasks

In this part of the survey, our aim was to test the effectiveness of the charts' representation of airspace structures, by asking the participants in what class or airspace an aircraft currently is. The stimuli are shown in Figure 8.

The two ICAO chart snippets have the same proportion (85%) of correct answers. The Australian chart snippet has 63% correct answers. 85% of participants gave the correct answer for the American chart snippet task, namely that this question is only solvable when given the chart legend. This clearly shows a disadvantage of the US chart, or any chart that requires external information to complete a task.

4.2.4 Visualisation of Airspace Structures

In the last part of the survey, the participants were asked about the visualisation of airspace structures. As highlighted in the cartographic analysis, aspects such as the labelling of the height limits, the symbolisation of the airspace structure boundaries or the indication of the airspace sector class are particularly important for the effectiveness of the chart.

Participants preferred the Swiss visualisation in all aspects (as described above). For instance, seeing altitude information in an emphasised manner, even if this leads to obscuring information from underlying layers, was favoured over other forms of depicting altitude information.

When asked which graphic variable would most improve the representation of airspace structures, participants perceived colour as the most helpful in differentiating airspace classes. After colour, stroke width, then hue were stated as suitable choices. Saturation is considered to be the least suitable.

When asked to rank the charts by the representation of airspace structures, and to rank the charts overall, the participants ranked the charts in the same order. The preferred order from most to least preferred was the Swiss, Austrian, US, and Australian VFR charts.

Participants self-identified a clear bias towards the Swiss VFR chart. Twenty-one of the 27 participants ranked their bias four or higher on a five-point scale towards the familiar Swiss chart. Of these 21, 17 answered in a follow-up question that this bias has an influence of four or higher (out of five) on their preferences.

5 Discussion

5.1 Cartographic Analysis

The following elements make an effective chart with regard to airspace information: The associativity of the symbolisation, the contrast between airspace structures (and their labelling) to the base map, clearly highlighted and legible vertical boundaries of the airspace structures and colour distinction between aviation infrastructure and airspace structures. The saturation of the relief must be as low as possible when designing a base map. Important elements for orientation in flight should be displayed legibly, in a different design than the airspace structures. The cartographic analysis has thus shown that for an effective reading of airspace information, interaction with other elements of the chart are equally of high importance. This is especially true for the mental translation of the airspace structures on the visual flight chart to their position in the outside world.

On the Swiss chart, the two-part line separating airspace classes successfully creates a clear boundary of the airspace sectors without obscuring too much of the information in the background. The Swiss chart highlights the vertical boundaries of the airspace structures well, with coloured boxes standing our from the background. However, the solid white background colour obscures underlying map layers. The positioning of the boxes is fortunately chosen in a manner that no relevant information is lost. The Swiss chart has a weakness in the contrast between restricted areas topographic shading at higher elevations.

The saturation of the relief on the Swiss chart appears too strong in the higher regions (dark orange colouring).

On the Austrian chart, the base map is very successful. It leaves enough contrast to the thematic content and yet offers the possibility to easily orient oneself on the chart. In our opinion, the major weakness of the Austrian chart is the interaction of airspace structures and aviation infrastructure, as well as their labels. The choice to colour the two object classes with the same colour has two major disadvantages. The assignment of the labelling is not as clear as it would be if different colours were used, and the same colour makes the two object classes merge. This can lead to illegibility of information. The Austrian chart's transition from green to dark orange for forest and terrain altitude, respectively, seems intuitive for orientation and height estimation. For us, the width of the railway lines is too thin.

On the American chart, the cropping of certain textual information, as well as certain objects, was successful. This ensures that a lot of information remains legible in a small space. It is noticeable that there are clear differences between this chart and the ICAO-compliant charts, with very different approaches having been chosen for the visualisation of elements. Whether these are better or worse than the approaches of the ICAO charts is debatable. In any case, our results feature many points of criticism regarding the visualisation of chart elements. For example, the choice of colours for the relief appears rather random. Choosing a green hue for the lowest altitude category with a clear border to the next higher category is misleading as it erroneously suggests forest cover. Especially for orientation in flight this can be confusing. The very saturated colours additionally reduce the contrast to the thematic content. Furthermore, the American chart uses a lot of text, which creates additional clutter and cognitive load on an already visually busy chart. Lastly, grey roads are difficult to separate from the relief (due to the lack of contrast) and therefore difficult to find.

On the Australian chart, the thematic content is strongly emphasised, compared with the base map. This may hinder orientation with features present on the base map, as it gets pushed into the visual background. The saturation of relief are hard to separate from bodies of water in low-lying topography. Likewise, the Australian chart lacks associativity in the point symbols for aviation infrastructure. Specifically, the lack of directions of runways on the airport symbols is a convenient, but missing, feature. While the vertical boundaries of airspace structures are present on the chart in a large font, it may happen that they are barely legible in certain areas because they are not exposed and the background has a similar colour as the airspace sector boundary label. The jagged lines of transmission cables help to distinguish the object class cables from the rest of the lines, but are not very intuitive. The different geographical orientations result in poorer readability of the charts, they also make it more difficult to use the charts together in the field.

5.2 User Study

Our survey revealed which elements of the chart are important to the pilots for orientation in visual flight. These answers are particularly important for estimating which elements should be given which importance on the chart. It turned out that, in addition to water bodies and road networks, prominent buildings are of particular importance for orientation in flight.

As the relief proved to be an important component for the effectiveness of reading the chart in the cartographic analysis, it would have been a further interesting question to ask about the importance of the relief's colouring.

The tasks to determine the airspace classes produced results on the effectiveness of the charts. The tasks on the two ICAO-compliant charts were solved with equal effectiveness by the participants. The two other charts did not perform as well. In the case of the American chart, this was mainly due to the unfamiliar unit of the altitude data and the non-explicit labelling of the airspace classes, and the Australian chart being unfamiliar to all participants. While on the Swiss and Austrian charts the majority stated that all the information for the task was available on the chart, on the other two charts the participants were not unanimous as to whether all the information was available or not. We conclude that the background knowledge when reading an aeronautical chart has a clear influence on how effectively it can be read.

For the representation of airspace structures, the two-part line symbolisation (thin solid + thick half-transparent) is preferred by the survey participants. Clearly highlighted and legible vertical boundaries of the airspace structures are important to pilots. This can be one of the reasons why the Swiss chart was favoured. Additionally, explicit labelling of the airspace class is clearly preferred.

While the survey results show a clear preference towards the Swiss visualisation of airspace structures but also visual flight charts in general, the validity of the results on the survey is weakened by the bias of the pilots. The Swiss chart is the most familiar to the participants, i.e., they are used to its visual design. This assumption was confirmed by the two questions on bias and somewhat weakens the validity of the survey results. In the aspect of the base map, the Austrian chart was seen as a favourite. Overall, the ICAO-compliant charts appear to be higher rated than the non-compliant charts.

5.3 Comparison of Cartographic Analysis and User Study

When combining the results from the cartographic analysis and the user study, they coincide well. Especially when looking at the presentation of the airspace structures in detail and their interaction with the rest of the chart content, they come to the same conclusions. Aspects that are important for the effectiveness of reading an aeronautical chart are well-highlighted airspace structures, easily legible labelling of altitudes, a simple base map that shows sufficient contrast with the thematic content, colour differentiation of different object classes and a layer hierarchy that is adapted to the purpose.

Map users do not always favour the cartographically most effective representation. Especially in aviation, people rely on a lot of information and get used to it. It may therefore be that having more information is preferred by pilots over a map that is considered cartographically useful. This favouring of wanting a very high realism in visualisations has been proven previously (Smallman and St. John, 2005; Andre and Wickens, 1995).

The trade-off between providing as much information as possible and a cartographically effective representation is very important. Given pilots' experience of maps with high information content, eliminating preference for "too much" information is a challenging outlook.

While the cartographic analysis uncovered which elements were considered important to aid orientation from a cartographic point of view, the survey showed the users' actual used.

5.4 Limitations

The evaluation grid for the cartographic analysis was based on the authors' knowledge of cartography and aviation. The design of the evaluation grid could potentially be improved by developing it in an iterative process with (aviation) subject matter experts. In our case, this may then however reduce the differentiation between the cartographic evaluation and the validation of the user study.

The study was based on static map images in an online form. We could not take into account possibilities of interaction (zooming, panning, etc.). Thus, we could not study if user preferences change depending on zoom level or other visualisation differences.

Both in the cartographic analysis and in the survey, the two ICAO charts turned out to be preferred for a large part of the criteria and questions. Nevertheless, the bias of the survey participants towards the Swiss chart must be kept in mind. While the validity of the survey may be weakened by the participants' bias, the results support the findings from the cartographic analysis.

6 Conclusion and Outlook

Although the cartographic analysis did not produce a clearly favoured chart, it was possible to show the strengths and weaknesses of the individual charts with regard to important aspects for the effectiveness of reading information on airspace structures on a VFR chart. Clear boundaries of airspace structures and easily legible labelling of altitude limits have been shown to be of high importance. However, not only the presentation of airspace structures alone is important, but also their combination with the rest of the content. For example, the base map should show enough contrast to the thematic content.

From the user study, the Aeronautical Chart ICAO Switzerland emerged as the clear favourite in all aspects surveyed. To overcome the limitations mentioned earlier, participant bias would not only have to be estimated, but eliminated. An interesting future research question is if participants in general prefer the representation of the chart they are used to.

The combination of cartographic evaluation and user study did not, even with the charts all being intended for the same purpose, aerial navigation under visual flight rules, provide a clearly better chart for all surveyed aspects. Nevertheless, with the identified strengths and weaknesses, the design of aeronautical charts could be improved.

Many aspects of digital cartography (e.g., zoom, interaction) were not taken into account. More research could be done on the advantages and disadvantages of digital vs. paper maps. Further analysis on the integration of charts into flight navigation apps, and interactions therein, could be studied in future work. The implementation of 3D maps for VFR is also a possible future research direction.

Data and Software Availability

Our data can be found at https://polybox.ethz.ch/index.php/s/x0pLRq60DnoXTvJ. This includes our cartographic evaluation grid, the user survey, and survey results.

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Appendix A

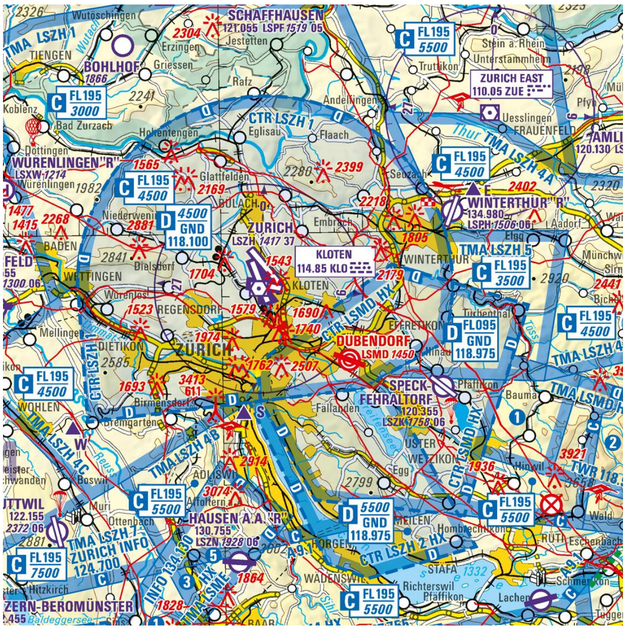

Figure A1. An extract of the Swiss aeronautical chart.

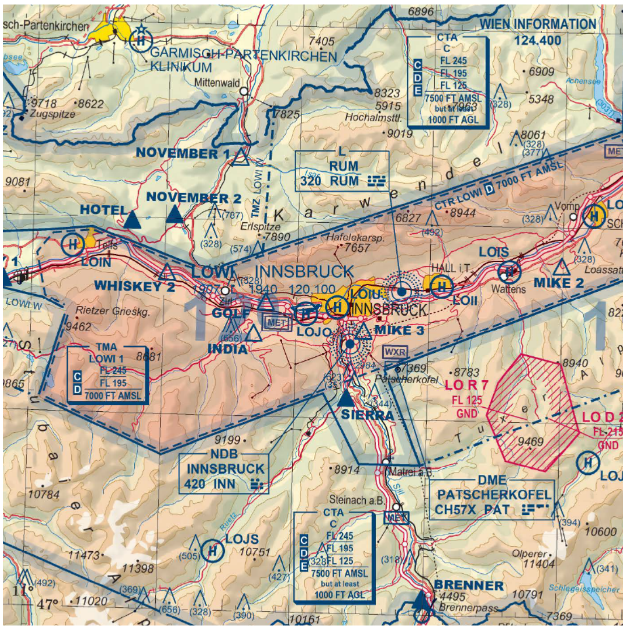

Figure A2. An extract of the Austrian aeronautical chart.

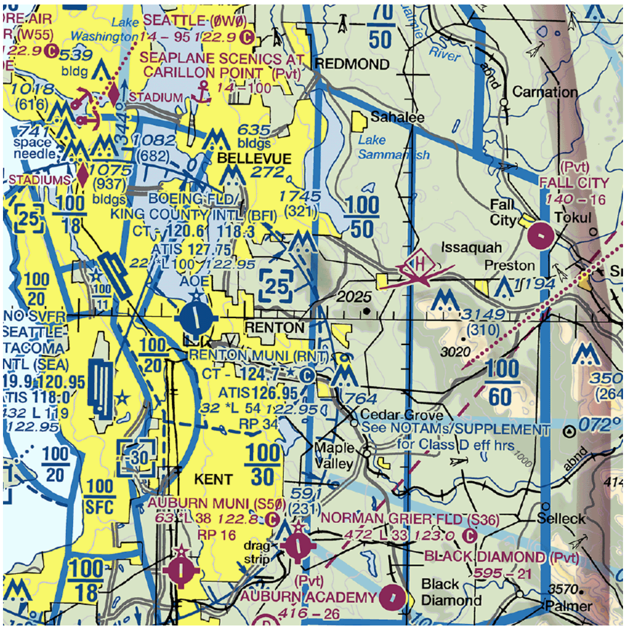

Figure A3. An extract of the US aeronautical chart series; Seattle sheet.

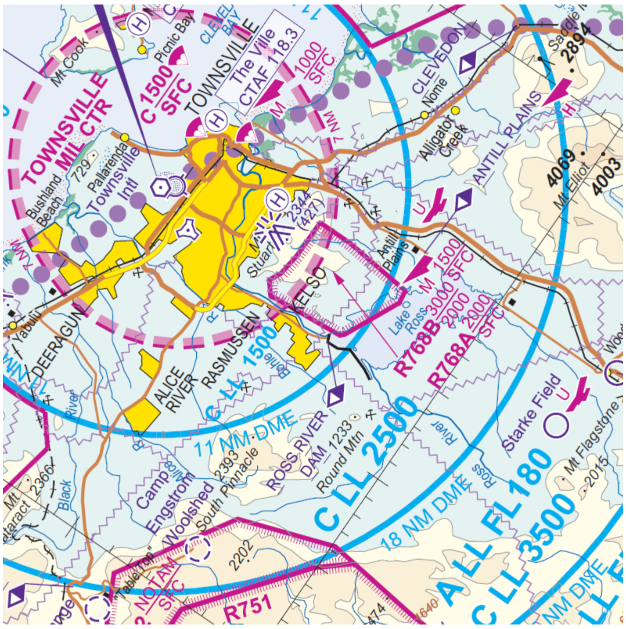

Figure A4. An extract of the Australian aeronautical chart series; Townsville sheet.