# MINIMUM OFF-ROUTE ALTITUDES BASED ON DIGITAL ELEVATION MODELS

JEAN MARCEL KNAPP DOS SANTOS

## ABSTRACT

This article discusses a method that clears the pilot from manually calculating the Minimum Off-Route Altitudes of a flight route. The Minimum Off-Route Altitude can be calculated for each segment of a route based on a digital elevation model of the planet. The dataset is loaded through the byte-swapping method and is stored in the computer memory. Afterwards, a search area for elevation points is drawn, and, through triangulation equations, it is possible to calculate the highest elevation in the area nearby each segment of the route. It is possible to decrease the required time to plan a flight route, for each flight hour, up to 4 minutes, as well as to eliminate all calculation errors.

Keywords: Minimum off-route altitude, MORA, Automation, HGT, STRM, Air Mission.

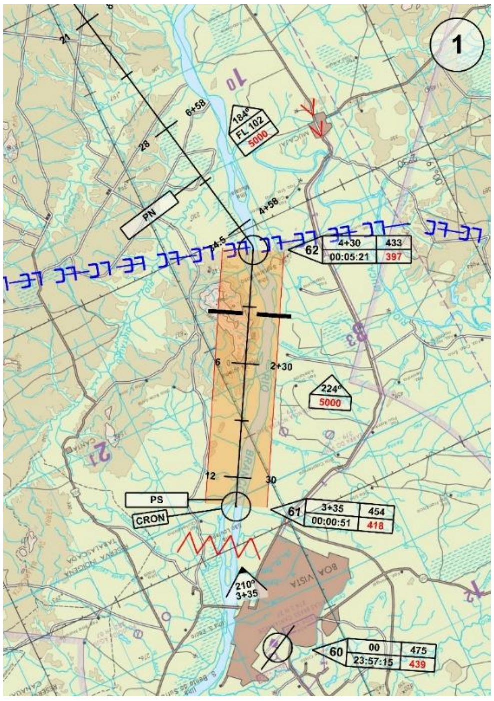
## INTRODUCTION

An aircraft commander or a flight leader has the responsibility of planning and executing all flight orders. Usually he has between four and twenty-four hours since the order is received until the departure to study the mission, plan the route, brief the crew, and even rest if necessary.

During the planning phase, the pilot makes a flight map which contains the route to be flown. This route contains a collection of control points, which must be flown over, as well as the information, between these points, of the minimum off-route altitude (MORA) which guarantees a safe flight in instrument conditions. This means that, if the pilot if flying at the MORA, it is guaranteed that he won't hit any terrain or obstacle, even though he is not visual with them.

This altitude is calculated based on the visual analysis of the printed visual navigation charts, by searching for high elevation points in a radius of 10NM of each route segment. It's added 1.000ft on plain fields or 2.000ft over mountains to the highest point found to establish a safety margin.

Figure 1 – Attack Mission planning example.



Source: 1º Esquadrão do 3º Grupo de Aviação of the Brazilian Air Force.

This paper discusses a method which clears the pilot of manually calculating the minimum off-route altitude, allowing a computer to do the job based on the Earth elevation models. To evaluate the efficacy of this method, five flight routes of one hour of flight each were planned, each with six segments of ten minutes, flown at 210kt. The Minimum Off-Route Altitudes were calculated either by highly trained Brazilian Fighter Pilots or by a computer software. The time required for each calculation was compared, as well as the accuracy.

## CURRENT OUTDATED METHOD

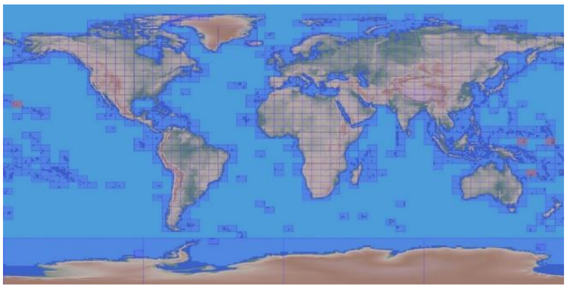
The current process of calculating MORAs is straightforward but involves some manual labour. After tracing the flight route, the pilot must analyse each segment. Using a visual chart, the pilot traces two parallel lines, each 10NM of distance from the route segment. The pilot, then, look for all the elevations marked in the area formed between the two lines, and chooses the highest one for reference. With that reference, he adds a fixed safety margin to calculate the MORA.

The visual charts usually already contain the MORA for each 3600NM². Due to the reduced amount of time the pilots have to plan the mission, sometimes they ignore the method cited above and use this MORA instead. This often results in a MORA higher than what should be, and this can abort a mission when the flight route can’t be executed in the MORA chosen by the pilot, but it could be executed with the MORA calculated by the correct method, if they had the time or patience to do it. Having the MORA calculated using elevation models can remove this problem, by reducing the manual labour and accelerating the overall required time to plan it.

## ELEVATION MODEL ANALYSIS

The elevation model used is the DEM3 of the SRTM, an international project leaded by the United States National Geospatial-Intelligence Agency and the United States National Aeronautics and Space Administration.

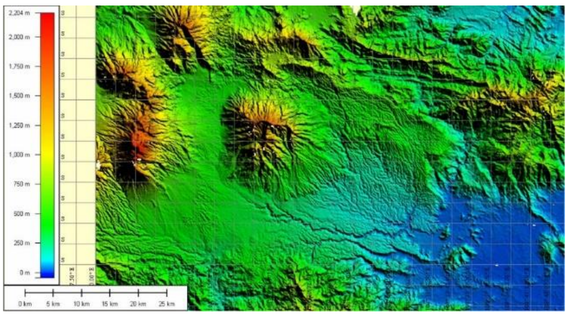
Figure 2 – Coverage map of DEM3.



Source: http://www.viewfinderpanoramas.org.

The DEM3 model is stored on *.hgt* files. The files are named according to the latitude and longitude they represent. For example, the file N33W177 contains the data between latitudes 33N e 34N and between the longitudes 177W e 188W (1).

Figure 3 – Colorized *.hgt* file.

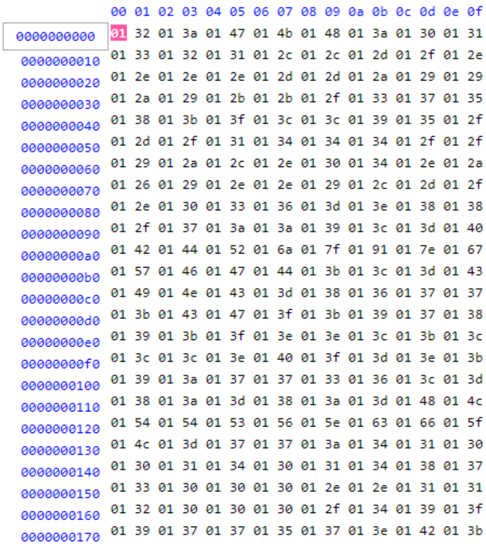


Source: https://fagustin.files.wordpress.com.

Each DEM3 table contains 1201 rows and 1201 columns. Each cell contains the elevation of a square with an edge of 300ft. The extra row and column represent the right and bottom borders of the area, which is repeated in adjacent files.

The data is stored in the. *hgt* files through signed integer bytes. The bytes are in Motorola big-endian order, which means the most important byte of a couple comes first. Current computers use the little-endian format for reading bytes, which the most important byte comes last. To correctly read the file, it`s necessary to perform a byte-swapping operation, converting the bytes to an integer by reading them backwards.

Figure 4 – Extract of file N00W056.hgt



| | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 0a | 0b | 0c | 0d | 0e | 0f |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0000000000 | 01 | 32 | 01 | 3a | 01 | 47 | 01 | 4b | 01 | 48 | 01 | 3a | 01 | 30 | 01 | 31 |
| 0000000010 | 01 | 33 | 01 | 32 | 01 | 31 | 01 | 2c | 01 | 2c | 01 | 2d | 01 | 2f | 01 | 2e |
| 0000000020 | 01 | 2e | 01 | 2e | 01 | 2e | 01 | 2d | 01 | 2d | 01 | 2a | 01 | 29 | 01 | 29 |
| 0000000030 | 01 | 2a | 01 | 29 | 01 | 2b | 01 | 2b | 01 | 2f | 01 | 33 | 01 | 37 | 01 | 35 |
| 0000000040 | 01 | 38 | 01 | 3b | 01 | 3f | 01 | 3c | 01 | 3c | 01 | 39 | 01 | 35 | 01 | 2f |
| 0000000050 | 01 | 2d | 01 | 2f | 01 | 31 | 01 | 34 | 01 | 34 | 01 | 34 | 01 | 2f | 01 | 2f |
| 0000000060 | 01 | 29 | 01 | 2a | 01 | 2c | 01 | 2e | 01 | 30 | 01 | 34 | 01 | 2e | 01 | 2a |
| 0000000070 | 01 | 26 | 01 | 29 | 01 | 2e | 01 | 2e | 01 | 29 | 01 | 2c | 01 | 2d | 01 | 2f |
| 0000000080 | 01 | 2e | 01 | 30 | 01 | 33 | 01 | 36 | 01 | 3d | 01 | 3e | 01 | 38 | 01 | 38 |
| 0000000090 | 01 | 2f | 01 | 37 | 01 | 3a | 01 | 3a | 01 | 39 | 01 | 3c | 01 | 3d | 01 | 40 |
| 00000000a0 | 01 | 42 | 01 | 44 | 01 | 52 | 01 | 6a | 01 | 7f | 01 | 91 | 01 | 7e | 01 | 67 |
| 00000000b0 | 01 | 57 | 01 | 46 | 01 | 47 | 01 | 44 | 01 | 3b | 01 | 3c | 01 | 3d | 01 | 43 |
| 00000000c0 | 01 | 49 | 01 | 4e | 01 | 43 | 01 | 3d | 01 | 38 | 01 | 36 | 01 | 37 | 01 | 37 |
| 00000000d0 | 01 | 3b | 01 | 43 | 01 | 47 | 01 | 3f | 01 | 3b | 01 | 39 | 01 | 37 | 01 | 38 |
| 00000000e0 | 01 | 39 | 01 | 3b | 01 | 3f | 01 | 3e | 01 | 3e | 01 | 3c | 01 | 3b | 01 | 3c |
| 00000000f0 | 01 | 3c | 01 | 3c | 01 | 3e | 01 | 40 | 01 | 3f | 01 | 3d | 01 | 3e | 01 | 3b |
| 0000000100 | 01 | 39 | 01 | 3a | 01 | 37 | 01 | 37 | 01 | 33 | 01 | 36 | 01 | 3c | 01 | 3d |
| 0000000110 | 01 | 38 | 01 | 3a | 01 | 3d | 01 | 38 | 01 | 3a | 01 | 3d | 01 | 48 | 01 | 4c |
| 0000000120 | 01 | 54 | 01 | 54 | 01 | 53 | 01 | 56 | 01 | 5e | 01 | 63 | 01 | 66 | 01 | 5f |
| 0000000130 | 01 | 4c | 01 | 3d | 01 | 37 | 01 | 37 | 01 | 3a | 01 | 34 | 01 | 31 | 01 | 30 |
| 0000000140 | 01 | 30 | 01 | 31 | 01 | 34 | 01 | 30 | 01 | 31 | 01 | 34 | 01 | 38 | 01 | 37 |
| 0000000150 | 01 | 33 | 01 | 30 | 01 | 30 | 01 | 30 | 01 | 2e | 01 | 2e | 01 | 31 | 01 | 31 |
| 0000000160 | 01 | 32 | 01 | 30 | 01 | 30 | 01 | 30 | 01 | 2f | 01 | 34 | 01 | 39 | 01 | 3f |
| 0000000170 | 01 | 39 | 01 | 37 | 01 | 37 | 01 | 35 | 01 | 37 | 01 | 3e | 01 | 42 | 01 | 3b |

Source: http://dds.cr.usgs.gov/srtm/

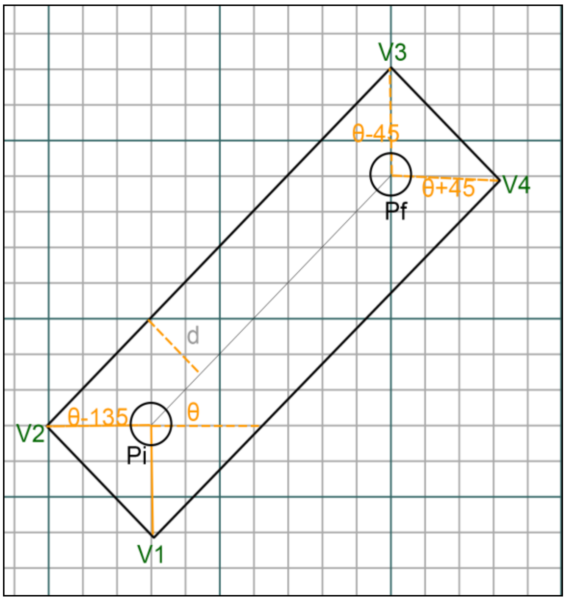
With the resolution of 1201, an.*hgt* file contains 1.442.401 entries of elevation data. Considering each entry contains 2 bytes, each file contains approximately 2.75MB. Considering a complete mapping of the surface of the Earth, there should be about 64.800 *.hgt* files, totaling 174GB of data loaded on memory. However, considering the mapping was only realized on firm land, which represents 29% of the total surface, loading the entire data should require about 50GB of memory.

To process each file, it would take 8.884.802 cycles of the processor, or, using technical terms, $O(2.884.802)$. If the storage was done in an HDD with a reading speed of 150MB/s, it would take about 6 minutes to read the entire dataset. To convert the entire data to readable integers, with a processing speed of 2.9GHz, it would take about 19 seconds.

## INITIAL CALCULATION

Considering a flight path with straight levelled segments, each segmentis represented by two points: a starting point ($P_i$) and an ending point ($P_f$). According to the default rules to calculate the MORA, it must consider the elevation in an area delimited by all the points with a distance less or equal to 10NM to the route. To perform the calculations, the area can be represented by a quadrilateral of vertices $V_1$, $V_2$, $V_3$ e $V_4$,with edges forming right angles, with the size of the smallest edges of 20NM and with the size of the largest edges equal to the route length. The route segment should be centred in this quadrilateral.

Figure 5 – Search area quadrilateral of the highest elevation per segment



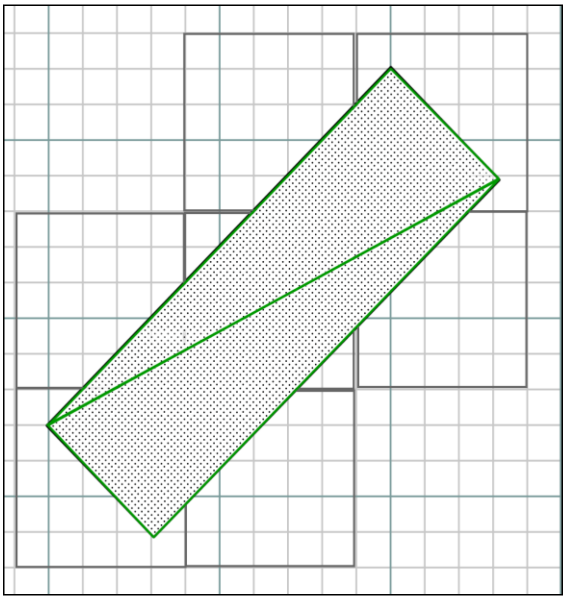

Source: The author (2018).

Having $\theta$ as the angle between $P_i$ e $P_f$, the vertices $V_1$, $V_2$, $V_3$ e $V_4$ are found through sins and cosines of the angles$\theta - 45°$,$\theta + 45°$,$\theta + 135°$, and $\theta - 135°$, respectively, with a length of $20\sqrt{2}NM$.

To avoid processing extra *.hgt* files, boundaries of latitudes and longitudes are calculated, using the minimum *.hgt* files possible to process the quadrilateral set above. These boundaries are represented by a new quadrilateral, aligned with the axis $\overline{NS}$ e $\overline{WE}$.

To read the *.hgt* files, a buffer size must be chosen. The buffer size is the number of bytes that will be read each time. There isn't an ideal value for every machine, requiring an initial test in each system to verify the ideal size. To get the elevation of each coordinate, two bytes are read each time. After reading, the bytes are inverted and then converted to an integer and stored into a table.

Figure 6 – Search points of the highest elevation.



Source: The author (2018).

To get the highest elevation of each segment, the search quadrilateral is split into two triangles, and each point in the boundaries area is analysed recursively, checking if it belongs to one of the two triangles set above, and if its elevation is higher than the previous registered point. If it is true, then this point gets registered as the highest point, as well as its elevation. The same is done for the lowest elevations.

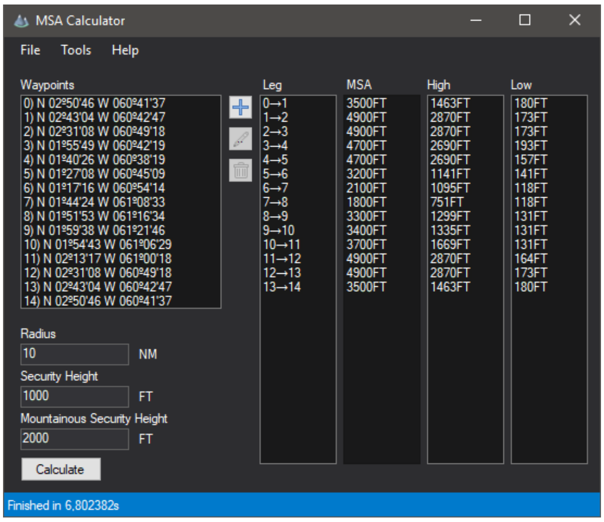
## FINAL CALCULATIONS

With the data of the highest and lowest elevation of each segment, the difference is analysed. If the difference is greater than 1.000ft, the terrain is considered mountainous, and 2.000ft are added to the highest elevation of the segment to get the MORA. If the difference is lesser than 1.000ft, 1.000ft is added to the highest elevation to get the MORA.

## RESULTS

To test the system, a program was developed to calculate the MORAs of routes of 1h of flight, with 6 segments of 10 minutes each.

Figure 7–MORA Calculator progrma




Source: The author (2018).

The accuracy check was done comparing the results of the program with the MORAs calculated by fighter pilots of the Brazilian Air Force, which were based on visual charts.

Table 1 – Comparison between the calculations made by the pilots and the software.

| Planning | Manual Calculation | Automatic Calculation | Accuracy | Manual Efficacy |
|---|---|---|---|---|
| 1 | 02min 55s | 05s | 33% | 03% |
| 2 | 04min 05s | 05s | 66% | 02% |
| 3 | 02min 52s | 05s | 33% | 03% |
| 4 | 03min 27s | 05s | 66% | 02% |
| 5 | 02min 28s | 04s | 33% | 03% |
| **Average** | **03min 09s** | **05s** | **50%** | **03%** |

Source: The author (2018).

The table above is a comparison between the calculations done by the pilots and the program. The fighter pilots took about 3min and 9 seconds to calculate the MORAs of each assigned route, while the program took approximately 5 seconds to do the same job, which is 37 times faster than the pilots. Also, 50% of the routes planned by the pilots had MORA miscalculations, while the program had zero errors, which either they missed higher elevations in the route, which would result in a higher MORA, or chose elevations which weren`t in the 10NM radius, which would make the MORA unnecessarily higher.

The values found by the computer program were later checked and all the elevation peaks found were consistent with the visual charts.

## CONCLUSION

Each MORA could be calculated based on the available elevation models of Earth, reading the SRTM files through byte-swapping and searching for the highest elevation points of each section of the route.

For mission planning of routes of about 1h of flight, the planning time was reduced in approximately 3 minutes.

Considering the planning phase has other steps not mentioned here, and with the current processing technology of data, it’s probable that other steps can be cut down, like the selection of control points, split plans, radar detours and so on. The automation of these processes will one day dismiss pilots from planning their flight navigation, requiring only the insertion of the mission data so the computer can perform all the calculations.

## REFERENCES

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3. **USGS.** Quick start. *Earth Resources Observation and Science Center.* [Online] https://dds.cr.usgs.gov/srtm/version2_1/Documentation/Quickstart.pdf.

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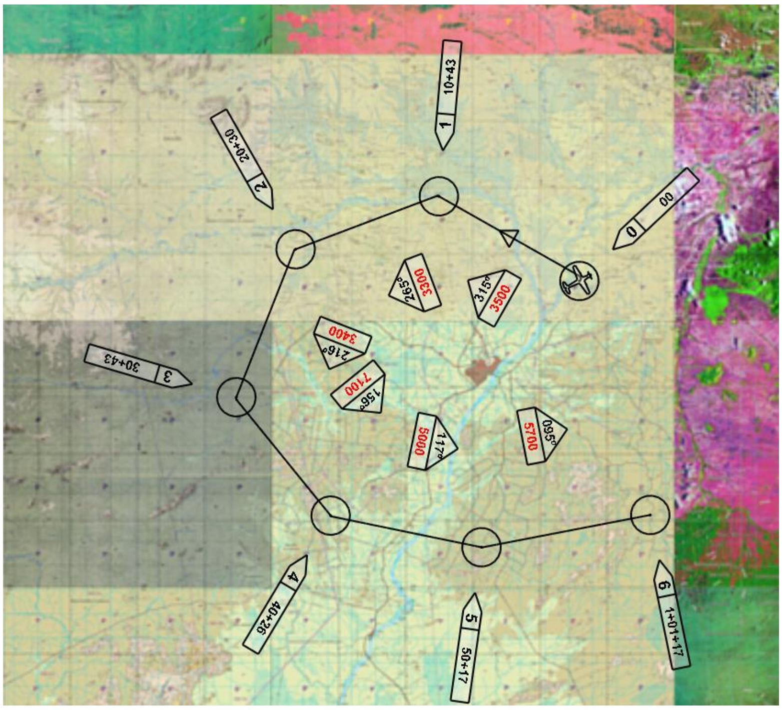
5. **Aeronáutica, Comando da.** *Doutrina Básica da Força Aérea Brasileira.* 2012.

# ATTACHMENT A – PLANNING 1

Figure 8 – Planning 1 done by a pilot.




Source: 1º Esquadrão do 3º Grupo de Aviação of the Brazilian Air Force

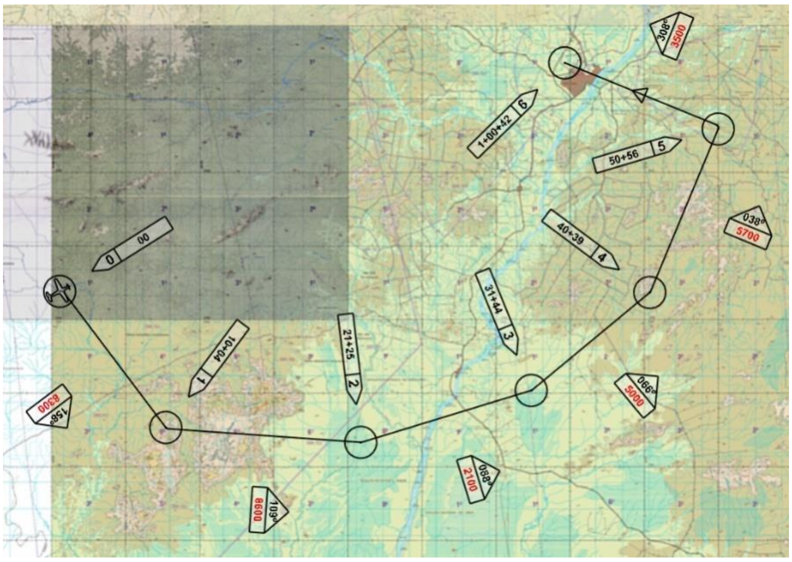
Table 2 – MORA calculation results of planning 1.

| **Coordinates** | **Manual MORA** | **Automatic MORA** | **Manual MORA Verification** |
|---|---|---|---|
| N0309 W06021 | 3500ft | 2000ft | 2000ft |
| N0328 W06053 | 3300ft | 3300ft | 3300ft |
| N0316 W06125 | 3400ft | 2200ft | 2200ft |
| N0342 W06138 | 7100ft | 6900ft | 6900ft |
| N0216 W06117 | 5000ft | 5900ft | 5900ft |
| N0209 W06043 | 5700ft | 5300ft | 5300ft |
| N0216 W06005 | - | - | - |
| **Processing time:** | **02min 55s** | **05s** | **-** |

Source: The author (2018).

## ATTACHMENT B – PLANNING 2

Figure 9 - Planning 2 done by a pilot.




Source: 1º Esquadrão do 3º Grupo de Aviação of the Brazilian Air Force

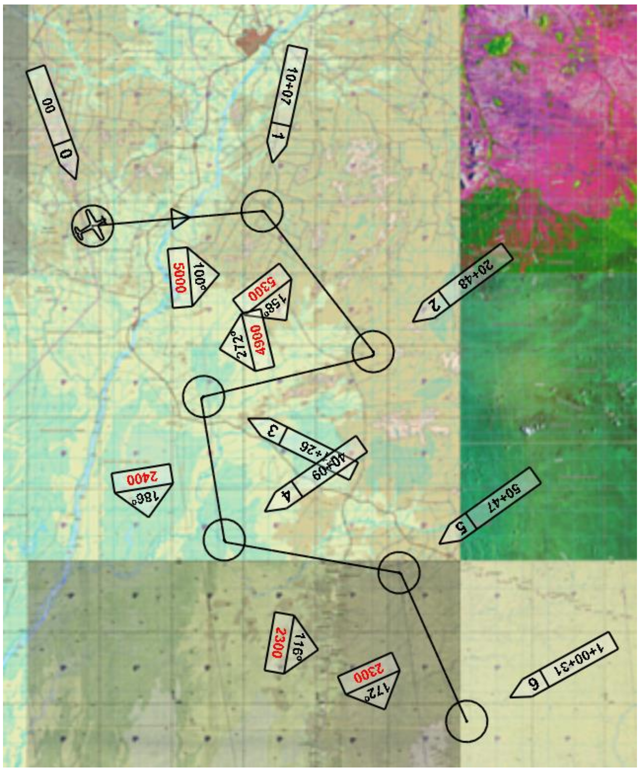
Table 3 - MORA calculation results of planning 2.

| **Coordinates** | **Manual MORA** | **Automatic MORA** | **Manual MORA Verification** |
|---|---|---|---|
| N0205 W06228 | 8300ft | 8200ft | 8200ft |
| N0138 W06207 | 8600ft | 8200ft | 8200ft |
| N0134 W06127 | 2100ft | 2100ft | 2100ft |
| N0145 W06052 | 5000ft | 5300ft | 5300ft |
| N0205 W06029 | 5700ft | 5600ft | 5600ft |
| N 0238 W06015 | 3500ft | 3500ft | 3500ft |
| N0252 W06046 | - | - | - |
| **Processing time:** | **04min 05s** | **05s** | **-** |

Source: The author (2018).

# ATTACHMENT C – PLANNING 3

Figure 10 - Planning 3 done by a pilot.




Source: 1º Esquadrão do 3º Grupo de Aviação of the Brazilian Air Force

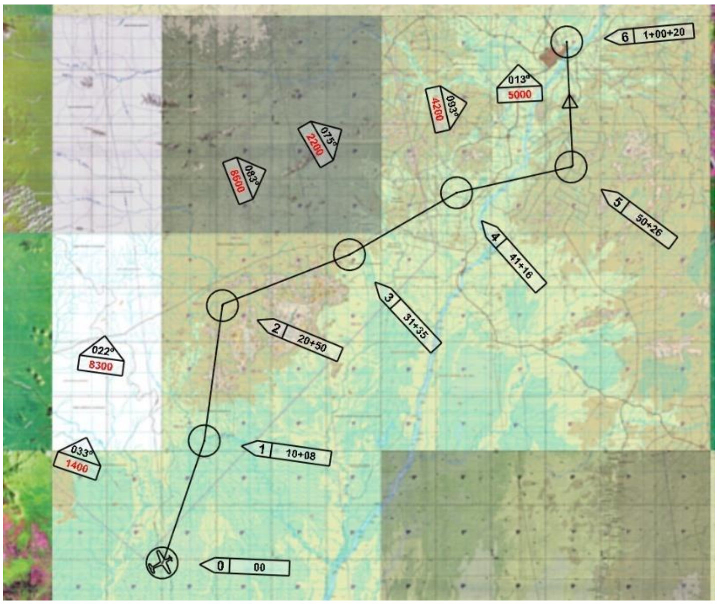
Table 4 - MORA calculation results of planning 3.

| Coordinates | Manual MORA | Automatic MORA | Manual MORA Verification |
|---|---|---|---|
| N0210 W06117 | 5000ft | 4500ft | 4500ft |
| N0213 W06041 | 5300ft | 5300ft | 5300ft |
| N0144 W06018 | 4900ft | 5000ft | 5000ft |
| N0134 W06049 | 2400ft | 2100ft | 2100ft |
| N0104 W06049 | 2300ft | 3300ft | 3300ft |
| N0057 W06013 | 2300ft | 3300ft | 3300ft |
| N0026 W05959 | - | - | - |
| **Processing time:** | **02min 52s** | **05s** | **-** |

Source: The author (2018).

# ATTACHMENT D – PLANNING 4

Figure 11 - Planning 4 done by a pilot.




Source: 1º Esquadrão do 3º Grupo de Aviação of the Brazilian Air Force

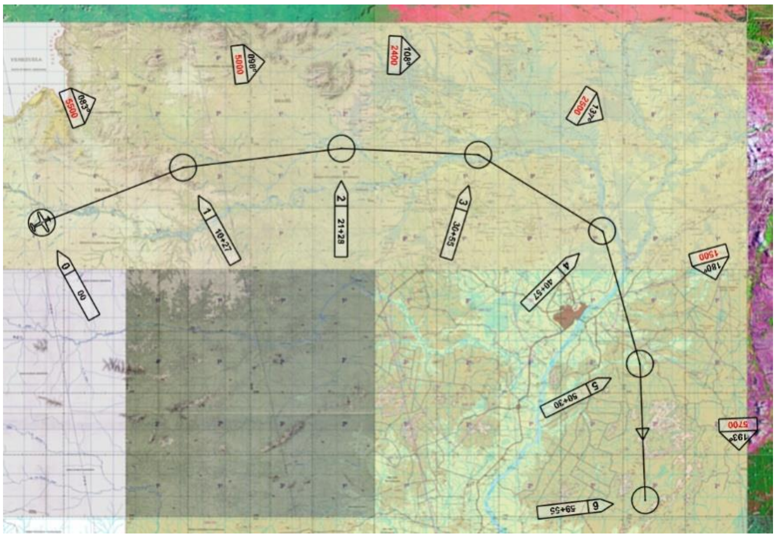
Table 5 - MORA calculation results of planning 4.

| Coordinates | Manual MORA | Automatic MORA | Manual MORA Verification |
|---|---|---|---|
| N0029 W06230 | 1400ft | 1600ft | 1600ft |
| N0103 W06218 | 8300ft | 8200ft | 8200ft |
| N0140 W06213 | 8600ft | 8500ft | 8500ft |
| N0154 W06138 | 2200ft | 4300ft | 4300ft |
| N0211 W06109 | 4200ft | 4500ft | 4500ft |
| N0218 W06038 | 5000ft | 4500ft | 4500ft |
| N0253 W06039 | - | - | - |
| **Processing time:** | **03min 27s** | **05s** | **-** |

Source: The author (2018).

# ATTACHMENT E – PLANNING 5

Figure 12 - Planning 5 done by a pilot.



Source: 1º Esquadrão do 3º Grupo de Aviação of the Brazilian Air Force

Table 6 - MORA calculation results of planning 5.

| **Coordinates** | **Manual MORA** | **Automatic MORA** | **Manual MORA Verification** |
|---|---|---|---|
| N0311 W06250 | 5500ft | 5600ft | 5600ft |
| N0325 W06216 | 5000ft | 5400ft | 5400ft |
| N0329 W06138 | 2400ft | 3300ft | 3300ft |
| N0328 W06105 | 2500ft | 3500ft | 3500ft |
| N0309 W06035 | 1500ft | 3500ft | 3500ft |
| N0237 W06026 | 5700ft | 5600ft | 5600ft |
| N0204 W06025 | - | - | - |
| **Processing time:** | **02min 28s** | **04s** | **-** |

Source: The author (2018).