Optimization to IAMSAR search theory and implementation on Search & Rescue planning decision support software

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Abstract: - The activity connected to Search and Rescue (SAR) operation at sea is a rather complex, demanding activity, with consequent use of resources, very long times and high costs.
The search theory applied to sea SAR operations covered in the IMO IAMSAR Manual Volume II and implemented on artificial intelligence software significantly reduces the complexity and difficulty of the search related SAR planning phase, providing the tools necessary for optimal planning, which allow you to optimize the search effort, maximize the result of the successes obtained, reduce the time for locating the survivors, which are reflected in the increase in the number of lives saved, and, moreover, in the reduction costs in terms of use of SAR resources and above all on the risk and stress of SAR crews who are generally exposed for very long times to a hostile environment.
This work illustrates an innovative mathematical model that integrates the IAMSAR theory in order to further improve the optimization of the search effort and it is performed on open source software that allows to considerably reducing the costs of the hardware and software technology with an increase in the efficiency of the SAR system.

Key-Words: - Theory of Search, Search & Rescue Planning, decision support software, IAMSAR software

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1 Introduction

This research project introduces improvements to the POS maximization mathematical model dealt with in the IAMSAR Volume II Manual of the IMO and implemented on the software called SARSS (Search and Rescue Support System) totally Open Source.

The improvements that have been introduced concern the mathematical models inherent in computing the *Probability of Containment* of the search object (POC) "search in the right place" and the *Probability of Detection* (POD) of the search object "the search object must be detectable" and consequently the mathematical model of the optimal Probability of Success (POS_{opt}) which is the product of the two probabilities POC and POD computed in the maximum value of the function *Probability of Success* (POS):

$$POS = POCxPOD \quad (1)$$

In particular, the POC model concerns the correction of the geometry of the search area for point datum with divergent points that allows an increase in the value of the POC and consequently an increase in the POS, while the new model of the POD is adaptable to the weather and sea conditions, improving the accuracy of the POD and consequently the accuracy of the POS with further optimization *Search Effort* (Z), that's the area effectively swept by a search facility computed as the product of search speed (V), search endurance (T), and sweep width (W):

$$Z = V \times T \times W \quad (2)$$

The product (V×T) is the available autonomy of the facility in operation area.

The type of software that implements the search theory of the IMO IAMSAR Volume II Manual [1] supplemented by advanced algorithm uses open source resources, i.e. it uses the Google Earth software as a Geographic Information System for the execution of the cartographic outputs and the Meteo Information System (MIS) software application for the automatic acquisition of meteorological data directly from the website www.windy.com, with considerable cost savings in hardware and software resources as well as the high costs of maintaining and updating the systems.

The new Mathematical model in argument with the simulation tests through the SARSS software are described below.

2 Methodology of research

Search theory applied to SAR with advanced mathematical models for POC, POD and POS is described below. Let us first introduce some concepts and definitions:

- *Relative effort* (Z_r) is the amount of available search effort (Z) divided by the effort factor (f_Z). $f_Z=E^2$ for point datum and $f_Z= E\times L$, with L is the length of the datum line.
- *Optimal search factor* (f_s) is a value which, when multiplied by E, produces the optimal search radius $Ro=E\times f_s$; the width of the optimal search square (point datums) or rectangle (leeway divergence and line datums) is always twice the optimal search radius ($2\times R_o$).
- *Coverage factor* (C) is the ratio of the search effort (Z) to the area searched (A).

2.1 POC for divergent point datums

When a SAR event is known or suspected to have occurred in the vicinity of n. 2 (two) specific locations or positions, a point datum is assumed as a reference for each of the positions and therefore in this case the datums are n. 2 (two) points. The simulator for locating the search object in the marine environment provides n. 2 positions for point datum, as better described below.

The simulator is able to estimate the position of the search object and the relative uncertainty, computing the effects of the drift on it. Since the effect of the leeway generated by the wind causes the motion of the search object in two different directions with an angle of divergence depending on the search object, we obtain as a result n. 2 (two) diverging positions (diverging datums), as shown in Fig. 1.

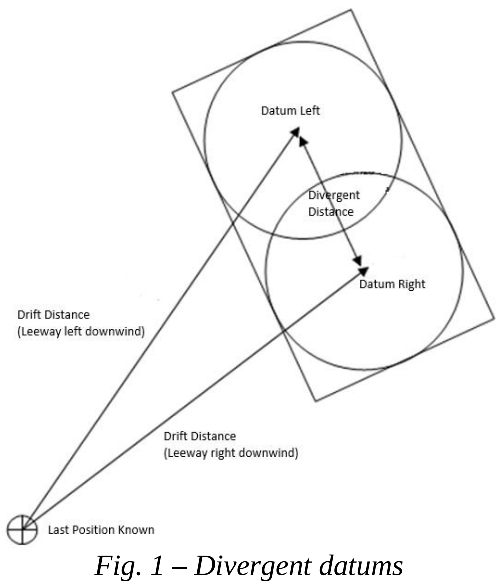

Fig. 1 – Divergent datums

Fig. 2 shows the probability density distribution function for divergent datums as a function of the *Divergence Distance D*.

Note that for *D=0* we obtain the probability density distribution function for point datum, which is a circular standard normal function, while for increasing divergence distances *D*, the function has a slightly higher trend than the curve with *D=0*. With the increase of the POC as a function of the increase in the divergence distance *D*, there is a slight improvement in the POS compared to the single point datum with zero divergence distance (*D=0*), as treated in the IAMSAR manual [1].

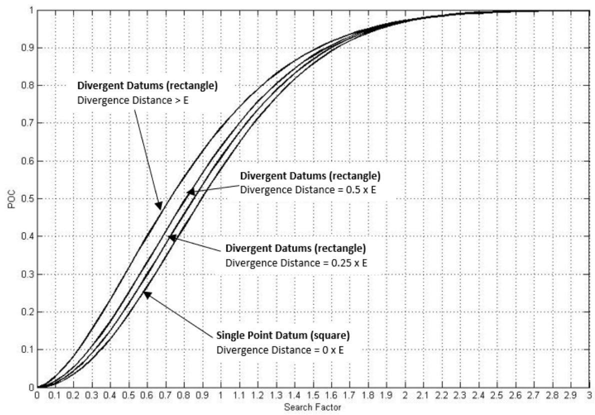

Fig. 2– Probability density function for divergent datums obtained with the Matlab simulator.

The POC model depicted in Fig. 2 is taken from Figure H-22 of the “U.S. COAST GUARD ADDENDUM" [2] and by applying the criterion of maximum true similarity, the POC model was developed as a function of the *split rate d* with $d = \frac{D}{E}$, that is d is the ratio of the *Divergence Distance D* to the *Total Position Error E*:

$$POC = 1 - e^{-\alpha R^x} \tag{3}$$

that’s basic model for standard circular distribution, with $\alpha = 0.8654\ and\ x = 2$ for standard circular distribution with *d=0,* while, with $\alpha = 0.8654 + 0.3d$ and $x = 2 - 0.39d$ for standard circular distribution with *d>0.*
Therefore, the basic model was used to calculate the POC:

$$POC = 1 - e^{-(0.8654+\beta d)R^{2-\gamma d}} \tag{4}$$

that’s (3) written as (4) in which the constants $\beta = 0.3\ e\ \gamma = 0.39$ have been calibrated using the maximum likelihood criterion and normalizing with respect to the radius *R*, thus obtaining the

POC model as a function of the *Search Factor* f_s and the *split rate d* shown below:

$$POC = 1 - e^{-(0.8654+0.3d)f_s{}^{2-0.39d}} \quad (5)$$

In the POC model represented in Fig. 2, with respect to the standard curve for d=0, however, the search factor f_s is the same for all the curves as *d* varies, therefore the size of the area considered in the POC is always the same for each curve as d varies, what changes is the shape of the area, i.e. square for d=0 and rectangular for *d>0*. The shape of the rectangular area as a function of d with respect to the classic square one, ensures that there is an increase in the POC, this is because the area is modulated in such a way as to contain a greater probability density within the rectangle containing the two diverging datums, as better represented in Fig. 3 and Fig. 4.

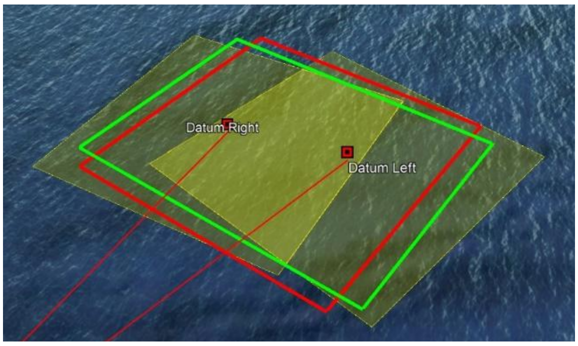

Fig. 3 - Comparison between areas with unitary search factor fs=1 of the single punctual datum POC (square) and the divergent datum POC (rectangle) with d=1.15 and E=4.66 NM

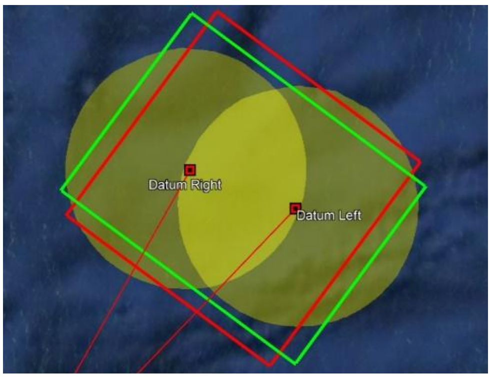

Fig. 4 – Comparison between areas with unitary search factor fs=1 of the single punctual datum POC (square) and the divergent datum POC (rectangle) with d=1.15 and E=4.66.

The example of Fig. 3 shows a simulation for a pleasure craft, which in the case under examination has a split rate d=1.15 for a search factor f_s=1. The red area represents the area squared for d=0, while the green outlined area represents the area for diverging datum d=1.15 quantified with the diverging POC curve for d>1.

The square area for d=0 and the rectangular area for d>1 have the same dimensions, with the difference that the divergent POC for d>1 is slightly larger than the POC for d=0, as it contains a higher probability density amount. Note that in figures 3 and 4, the probability density indicated with the yellow area is more contained within the green (rectangular) rather than the red (square) outlined area. The squares centered on datum left and datum right are oriented in the direction of drift left and drift right, respectively.

The rectangle and the square must have the same size and therefore, if the square has the following dimensions:

$$Side = 2 \cdot f_s \cdot E$$
$$Area = 4 \cdot f_s{}^2 \cdot E^2$$

For the rectangle with the same size we have:

$$Base = 2 \cdot f_s \cdot E \cdot \sqrt{\frac{f_s \cdot E + \Delta x}{f_s \cdot E + \Delta y}} \quad (6)$$

$$Height = 2 \cdot f_s \cdot E \cdot \sqrt{\frac{f_s \cdot E + \Delta y}{f_s \cdot E + \Delta x}} \quad (7)$$

where Δx e Δy represent the deviation of the left and right datums respect to the central datum (midpoint between left and right datum) along latitude and longitude respectively.

2.2 Intermediate POD and Search Condition Adaptative Model

The POD model is a function of the *Coverage Factor C* variable, i.e. the ratio between the effectively swept area or *Search Effort Z* and the Search Area A.

However, the POD model can be further improved, creating a universal one that is also good as an intermediate model between the Ideal and the Normal one. According to the IAMSAR manual Vol. II paragraph 4.6.14 [1] the Ideal model is used when the ratio between the *corrected sweep width* W and the maximum *uncorrected sweep width* (ideal sweep width), hereinafter referred to as δ, is greater than or equal to 0.5, while when δ is less than 0.5 the Normal model is used. Please note that the ideal sweep width or maximum uncorrected sweep width is the uncorrected sweep width when meteorological visibility is optimal (above 20 NM). The *sweep width W* is the width of the band explored by the SAR Unit during the search obtained from experimental data and reported in IAMSAR Volume II [1].

So for the ideal model according to the IAMSAR Vol. II manual we have:

$$\delta = \frac{corrected\ sweep\ with}{uncorrected\ sweep\ with}$$

$$if\ \delta > 0.5 \Rightarrow Ideal\ Model$$
$$if\ \delta \leq 0.5 \Rightarrow Normal\ Model$$

However, in the publication “U.S. COAST GUARD ADDENDUM” January 2013 edition [2], precisely in section H.5.6.2, unlike the IAMSAR Vol. II manual, takes into account the use of the ideal model when δ is greater than or equal to 0.9 and the use of the normal model when δ is less than 0.9, therefore we have the following correlation between δ and the two POD models:

$$if\ \delta \geq 0.9 \Rightarrow Ideal\ Model$$
$$if\ \delta < 0.9 \Rightarrow Normal\ Model$$

For this reason, an intermediate model can be developed as δ varies between the normal POD and the ideal POD:

$$if\ \delta \geq 0.9 \Rightarrow Ideal\ Model$$
$$if\ 0.5 < \delta < 0.9 \Rightarrow Intermidiate\ Model$$
$$if\ \delta \leq 0.5 \Rightarrow Normal\ Model$$

The intermediate model must be a POD whose curve varies between the curve of the ideal POD and the curve of the normal POD, with the variation of the parameter δ which is linked to the meteorological conditions.

The factors that affect the corrected sweep width are the type of object being searched, the state of the sea, the meteorological visibility, the speed of the SAR unit and the degree of fatigue of its crews. Therefore the new POD model to be developed must be adaptable to the weather conditions, the basis of which is given below:

$$POD = \left(1 - e^{-AC^B}\right)^{\Gamma} \quad (8)$$

In the following model we have:

$$for\ \delta \geq 0.9 \Rightarrow Ideal\ Model$$
$$with\ A = 0.9776, B = 2\ and\ \quad = 0.5$$

$$for\ \delta < 0.5 \Rightarrow Normal\ Model$$
$$with\ A = 1, B = 1\ and\ \quad = 1$$

In addition, the following condition must be satisfied:

$$\frac{d}{df_s} POS(Z_r, f_s) = 0$$

From solving this equation and, considering that:
$if\ B = 2\ then\ \quad = 0.5\ and\ if\ \ B = 1\ then\ \quad = 1$ so it follows that $\quad = \frac{1}{B}$, therefore the basic POD model (8) becomes:

$$POD = \left(1 - e^{-AC^B}\right)^{\frac{1}{B}} \quad (9)$$

Then we need to determine the constants A and B for values of $0.5 < \delta < 0.9$ which take the following expression:

$$a + b\delta$$

Therefore we need to determine the constants *a* and *b* for each term *A* and *B*.

$$for\ A\ we\ have: \begin{cases} a + b\delta = 0.9776\ with\ \delta = 0.9 \\ a + b\delta = 1\ \ with\ \delta = 0.5 \end{cases}$$

$$solving\ the\ system \begin{cases} a + 0.9b = 0.9776 \\ a + 0.5b = 1 \end{cases}$$

$$we\ have\ a = 1.028\ e\ b = -0.056$$

Therefore we have:

$$\mathrm{A} = \ 1.028 - 0.056\delta$$

$$for\ B\ we\ have: \begin{cases} a + b\delta = 2\ \ with\ \delta = 0.9 \\ a + b\delta = 1\ \ with\ \delta = 0.5 \end{cases}$$

$$solving\ the\ system \begin{cases} a + 0.9b = 2 \\ a + 0.5b = 1 \end{cases}$$

$$we\ have = -0.25\ e\ b = 2.5$$

Therefore we have:

$$B = \ -0.25 + 2.5\delta$$

Now that the values of A and B have been determined as a function of the parameter δ we have:

$$POD = \left(1 - e^{-(1.028 - 0.056\cdot\delta)C^{(-0.25+2.5\cdot\delta)}}\right)^{\frac{1}{-0.25+2.5\cdot\delta}} \quad (10)$$

The new POD model varies as the parameter δ varies, i.e. the ratio between the ideal sweep width and the uncorrected sweep width and therefore adaptable to meteorological conditions: as the meteorological conditions worsen, the POD curve will approach that of the normal POD (δ ≤ 0.5) while in case of more favourable meteorological conditions the POD curve will tend towards the ideal POD (δ ≥ 0.9).

The model obtained is the following:

$$POD = \begin{cases} \sqrt{1-e^{-0.9776C^2}} & if\ \delta \geq 0.9 \\ \left(1-e^{-(1.028-0.056\delta)C^{(-0.25+2.5\delta)}}\right)^{\frac{1}{-0.25+2.5\delta}} & if\ 0.5 \leq \delta < 0.9 \\ 1-e^{-C} & if\ \delta \leq 0.5 \end{cases} \quad (11)$$

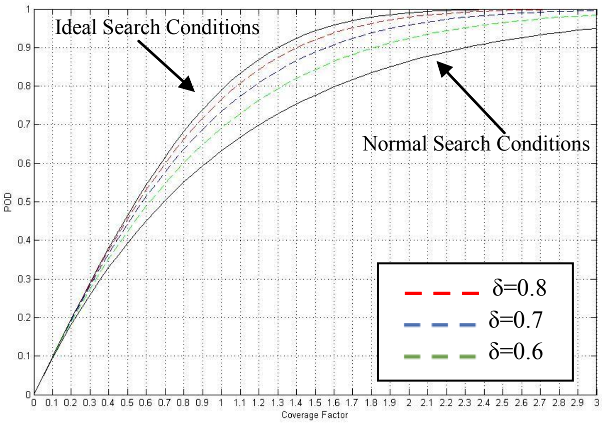

Fig. 5 – Weather-adaptive POD model (8) represented by Matlab with $A = 1.028 - 0.056\delta$ *and* $B = -0.25 + 2.5\delta$

2.3 Development of a new optimal planning model for punctual or divergent single datums

So for the POS_{opt} we have by substituting the value of Z_r in the POS:

$$POS_{opt} = \left(1 - e^{-\alpha f_s{}^2}\right)^{\frac{B+1}{B}} \quad (12)$$

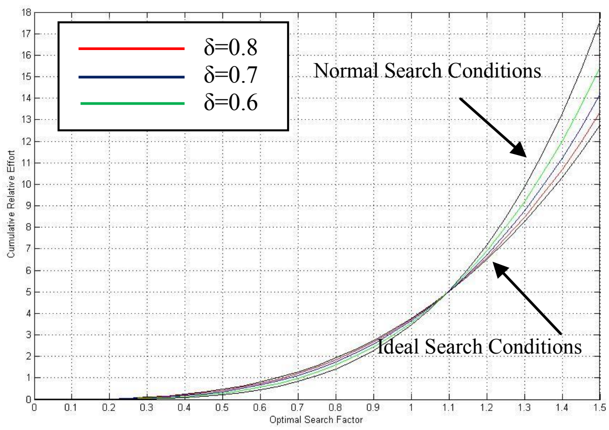

Fig. 6 – Optimum search factor for single or divergent point datum with varying meteorological conditions obtained by Matlab

$$Z_r = 4\left(\frac{\alpha}{A}\right)^{\frac{1}{B}} f_s{}^{2\cdot\frac{B+1}{B}} \quad (13)$$

The model for punctual datum in intermediate search conditions is represented in the Fig. 6, 7 and 8, with $A = 1.028 - 0.056\delta, B = -0.25 + 2.5\delta$ *and* $\alpha = 0.8654$.

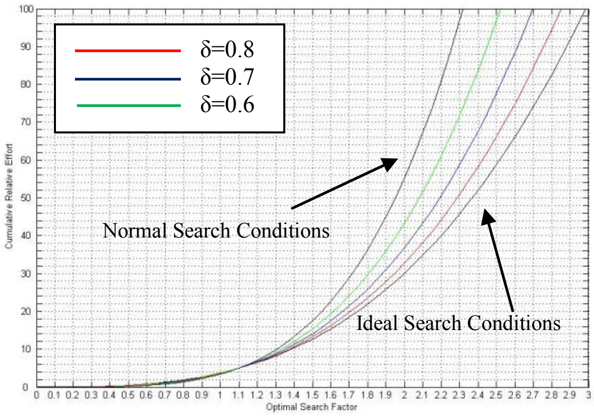

Fig. 7 – Optimal search factor for single or divergent point datum as meteorological conditions vary, obtained by Matlab

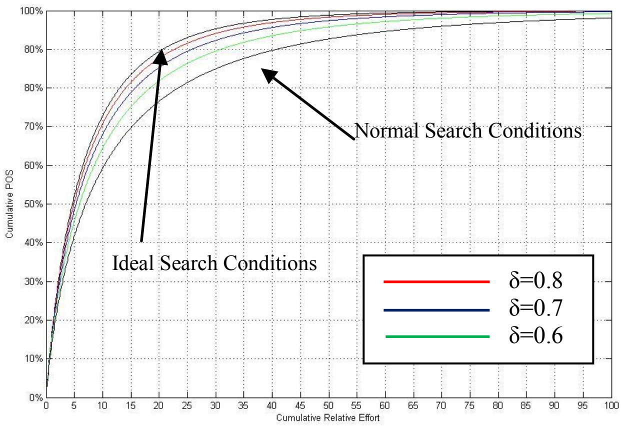

Fig. 8 – Probability of success POS for single or divergent point datum with changes in meteorological conditions obtained with Matlab

$$POS_{opt} = \left(1 - e^{-\alpha f_s{}^2}\right)^{\frac{B+1}{B}} \quad (14)$$

2.4 Development of a new optimal planning model for linear datum

So for the POS_{opt} we have by substituting the value of Z_r nella POS:

$$POS_{opt} = \left(1 - e^{-\alpha \cdot f_s{}^2}\right)^{\frac{B+2}{2B}} \quad (15)$$

The model for linear datum in intermediate search conditions is represented in the Fig. 9, 10 and 11, with $A = 1.028 - 0.056\delta, B = -0.25 + 2.5\delta$ *and* $\alpha = 0.8654$.

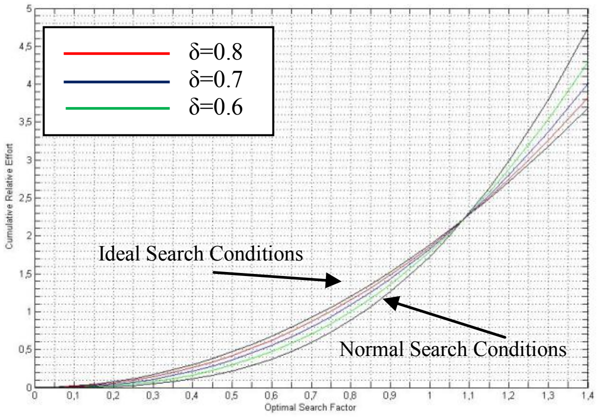

Fig. 9 - Optimum search factor for linear datum as meteorological conditions obtained by Matlab,

$$Z_r = 2\left(\frac{\alpha}{A}\right)^{\frac{1}{B}} f_s^{\frac{B+2}{B}} \qquad (16)$$

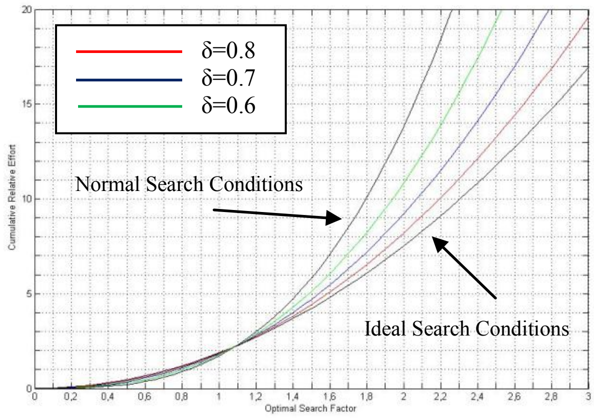

Fig. 10 - Optimum search factor for linear datum as meteorological conditions obtained by Matlab

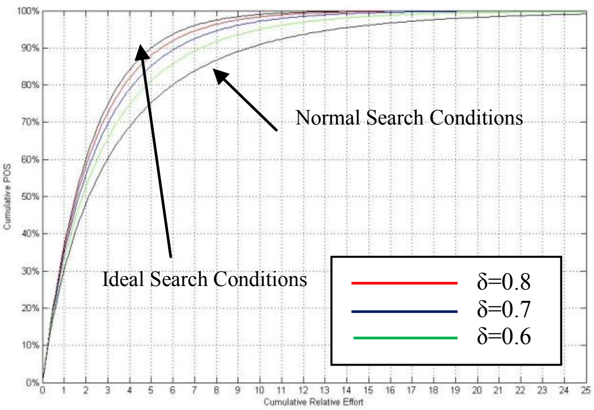

Fig. 11 – Probability of success POS for linear datum as weather conditions obtained by Matlab

$$POS_{opt} = \left(1 - e^{-\alpha \cdot f_s^{2}}\right)^{\frac{B+2}{2B}} \qquad (17)$$

3 Results, impact and benefits

SARSS software able to calculate search area both IAMSAR model and ADVANCED model.

We execute simulation with both of them the algorithms for a case of point datum search object computing the performance in terms of POS.

Let's take as simulation with data in table 1:

Search Object	5 meters length - sport fishing boat with centre console or small cabin
W	1.8 NM
E	6.67 NM
d	1.56
Autonomy SAR Unit	100 NM
Weather condition	5 NM visibility, sea 2/3
W corrected 2-sea	1.1 NM, ideal search condition (δ = 0.61)
W corrected 3-sea	0.9 NM, normal search condition (δ = 0.5)

Table 1 – Characteristics test boat search object

From the data results we have different values between the IAMSAR model and the Advanced one reported in table 2, 3 and 4 of which the following simulation are obtained:

	Iamsar	**Advanced**
f_s	0.87	0.87
C	0.82	0.82
POC	48.2%	60.7%
POD	69.4%	69.4%
POS	33.5%	42.2%

Table 2 - Performance comparison under ideal search conditions with table 1 date

	Iamsar	**Advanced**
f_s	0.88	0.88
C	0.66	0.66
POC	48.6%	61.0%
POD	48.6%	48.6%
POS	23.6%	29.6%

Table 3 - Performance comparison under normal search conditions with table 1 date

	Advanced Single Datum	**Advanced Divergent Datum**
f_s	0.90	0.90
C	0.77	0.77
POC	50.6%	62.8%
POD	58.7%	58.7%
POS	29.7%	36.9%

Table 4 - Performance comparison under intermediate search conditions with table 1 date

Both in ideal and normal search conditions, the

Advanced model reports a higher POS value than that determined with the IAMSAR model, therefore the model Advanced performs better due to increased POC attributed to datum divergence distance. The table 4 shows the Advanced model with intermediate POD, both for single datum and divergent datum. Since δ = 0.61, according to the IAMSAR model we have ideal search conditions, while the advanced model shows intermediate search conditions between ideal and normal with a lower POD (intermediate) value than the IAMSAR and consequently a lower POS value, with different values of the factors C and fs, but still more accurate than the ideal POD which tends to overestimate the value. Furthermore, there is always an increase in the POC for divergent datums and the search area is made rectangular rather than square, without affecting the fs factor as the size of the search area remains constant, i.e. equal to $4 \cdot {f_s}^2 \cdot E^2$.

We now report a second simulation with the following data:

Search Object	person in water: placement/rescue equipment unknown
W	*0.3 NM*
E	*1.44 NM*
d	*0.62*
Autonomy SAR Unit	*120 NM*
Weather condition	3 NM visibility, sea 2/3
W corrected 2-sea	0.2 NM, ideal search condition (δ = 0.67)
W corrected 3-sea	0.1 NM, normal search condition (δ = 0.33)

Table 5 – Characteristics test PIW search object

	Iamsar	**Advanced**
f_s	1.46	1.46
C	1.37	1.37
POC	84.1%	86.9%
POD	91.7%	91.7%
POS	77.2%	79.8%

Table 6 - Performance comparison under ideal search conditions with table 5 date

	Iamsar	**Advanced**
f_s	1.14	1.14
C	1.12	1.12
POC	67.5%	73.3%
POD	67.5.6%	67.5%
POS	45.5%	49.5%

Table 7 - Performance comparison under ideal search conditions with table 5 date

	Advanced Single Datum	**Advanced Divergent Datum**
f_s	1.41	1.41
C	1.47	1.47
POC	82.2%	85.3%
POD	86.9%	86.9%
POS	71.3%	74.1%

Table 8 - Performance comparison under intermediate search conditions with table 5 date

In this case the POC variation is less significant than in the previous case as there is a lower split rate *d* and a higher search factor f_s. The POC with divergent datum converges to the POC with single datum as the search factor f_s increases and as the distance between the two data decreases. The variation of the coverage factor C is slightly more significant since in the case under examination C is found in the zone of maximum variation of the POD between the ideal search conditions and the normal search conditions (figure 5).

However, search effort Z_L and then reasonable relative effort must be employed to avoid excess effort. There is excess effort when a significant increase in Zr does not lead to an appreciable increase in POS, this is because the POS has a behavior that tends asymptotically to 1 (100%) when

Zr tends to infinity, i.e.:

$$\lim_{Z_r \to \infty} POS = 1$$

Fig. 12 and Fig. 13 show a comparison between the IAMSAR model and the ADVANCED model for two different types of research objects.

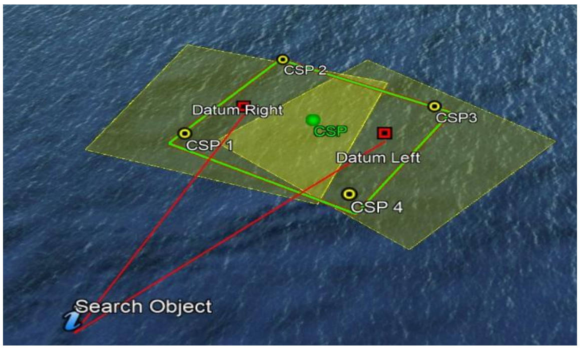

Fig. 12 – Iamsar model simulation for 5 mt sport fishing boat, with $d = 1.56, E = 6.67NM$, $POS = 33.5\%$, $f_s = 0.87$ *e* $C = 0.82$ *– Square area – Weather condition with sea force 2 and discrete visibility*

Fig. 13 – Advanced model simulation for 5 mt sport fishing boat, with $d = 1.56, E = 6.67NM, POS = 36.9\%,\ f_s = 0.90\ e\ C = 0.77$ *– Rectangle area – Weather condition with sea force 2 and discrete visibility*

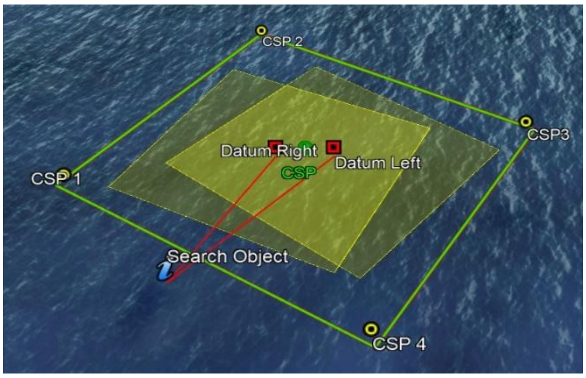

Fig. 14 – Iamsar model simulation for person in water under unknown conditions with $d = 0.62, E = 1.44NM,\ POS = 77.2\%,\ f_s = 1.46\ e\ C = 1.37$ *- Square area – Weather condition with sea force 2 and discrete visibility*

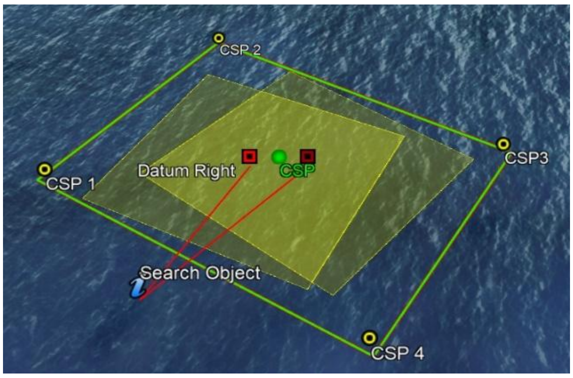

Fig. 15 – Advanced model for person in water under unknown conditions, with $d = 0.62, E = 1.44NM,\ POS = 74.1\%,\ f_s = 1.41\ e\ C = 1.47$ *- Rectangle area – Weather condition with sea force 2 and discrete visibility*

For the above, between the two models, we have the following considerations:

- For slightly divergent datums and high values of the search factor *fs* and therefore in high conditions of available search effort there is no appreciable variation in the optimization of the POS and calculation of the search area which is reflected in the determination of the search factors search f_s and coverage C;
- For divergent datums and low values of the search factor fs as well as a scarce search effort available, there is an appreciable increase in the POS as well as a POD value in the intermediate search conditions that is more realistic than the overestimated value of the POD model in conditions of search for ideals.

Therefore, for divergent datums, it is always advisable to determine a rectangular search area especially in conditions of non-optimal available search effort.

4 Brief description of the SARSS software

Software for the planning of search and rescue operations at sea designed for any Coast Guard in order to reduce the complexity and difficulties of the SAR planning phase, linked to the search activity, providing the necessary tools for optimal planning, optimization of the research effort, maximization of the result of the successes obtained, reduction of the time to locate survivors, increase in the number of lives saved.

SARSS automatically acquires meteorological information from the windy site and automatically updates the datum in real time.

The software control units, the graphic interfaces and the weather search function are developed in the Visual Basic programming language which makes it portable, interoperable for the WEB and compatible from Windows 7 onwards. All processing units such as the calculation of the datum, the search areas, the search schemes are developed in C/C++ which makes it faster in performing the calculations, being a lower level language that runs directly in the kernel. The graphical interfaces with Google Earth are developed in the KML language.

Software simulation examples are shown in fig. 16.

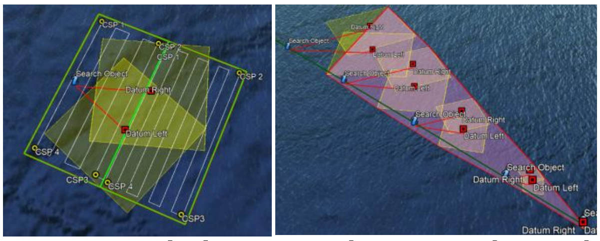

Fig. 16 - Calculation search areas with search pattern on the left and calculation of the line datum with error E on the right

5 Conclusions

In conclusion, the new mathematical model provides better performance than the IAMSAR model as well as being more accurate, especially in conditions of a low value of the available search effort, a condition which requires the maximum capacity of the optimal use of the scarce SAR resources available.

However, it has a considerable computational complexity such as to require implementation on a software platform compared to manual use such as the IAMSAR model which in itself also has a certain complexity such that the same IAMSAR Vol. II manual suggests the software solution. The SARSS software has the advantage of using open source resources such as Google Earth for the GIS and the windy.com site for the input of meteorological data with consequent reduction of costs.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The author contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

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