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Dias

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# Development and validation of a new efficient SRTM DEM-based horizon model combined with optimization and error prediction methods

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## Abstract

Several post-processing methods have been developed over the last years in order to take into consideration topography within satellite-based solar radiation maps using digital elevation models (DEM). If the main part of these procedures is to estimate the obstructed horizon around each DEM point of a given region so as to consider terrain-based shading effects, the size of the area can also limit this implementation. That is why we have developed a new efficient horizon model based on the DEM retrieved during the Shuttle Radar Topography Mission (SRTM). In order to be usable at any world location with the same expected accuracy, this model is only derived from mathematical statements without any kind of empirical approximation. Validation against *in situ* horizons and comparison with some other models have finally shown this one presents both better accuracy (RMSE of  $1.555^\circ$  against  $1.712^\circ$  or more) and lower computation time (at least 4 times faster). Furthermore, in the case of very large areas, we propose an optimization procedure allowing the user to knowingly alter the modeling error in order to reduce processing time. Finally, using *in situ* data, we have also developed a method for predicting the repercussion of the original SRTM DEM error on the final horizon precision.

**Keywords:** horizon model; SRTM DEM; solar radiation maps; error prediction

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## Nomenclature

$a$	ellipsoid semi-major axis (m)
$B$	number of bootstrap samples
$ds_m$	meridian line element (m)
$ds_p$	parallel line element (m)
$\hat{E}$	empirical population randomly drawn from population $E$
$E$	population of horizon modeling errors

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$e$	ellipsoid eccentricity
$\hat{F}$	empirical population randomly drawn from a population $F$
$F$	population of observations
$f$	ellipsoid flattening
$f(S)$	arbitrary function of the DEM slope $S$
$H$	orthometric height (m)
$h$	ellipsoidal height (m)
$L$	isometric latitude (rad)
$\vec{n}$	ellipsoid normal
$N$	length of the ellipsoid normal (m)
$n$	number of observations
$P$	horizontal plane
$p$	arbitrary DEM pixel
$r$	normally distributed random variable centered on 0
$R_{DEM}^x$	DEM metric resolution along $x$ axis (m)
$R_{DEM}^y$	DEM metric resolution along $y$ axis (m)
$S$	slope of a DEM point
$s_\varepsilon$	standard deviation of the empirical population $\hat{E}$
$T_L$	Linke turbidity factor
$\alpha$	angular elevation (rad)
$\beta$	strictly positive constant
$\gamma$	azimuth (rad)
$\Delta_{WGS84-EGM96}$	geoid undulation with respect to the ellipsoid (m)
$\Delta\lambda$	longitude width of the DEM tile used in horizon computation (rad)
$\Delta\varphi$	latitude height of the DEM tile used in horizon computation (rad)
$\bar{\varepsilon}$	mean of the empirical population $\hat{E}$
$\varepsilon$	horizon modeling error
$\hat{\Theta}$	estimator of a given population

$\hat{\theta}$	parameter of a sample drawn from a given population
$\theta$	parameter of a given population
$\lambda$	geographic longitude (rad)
$\mu$	mean of a given population
$\nu$	significance level
$\rho$	radius of curvature in the north-south direction (m)
$\sigma$	standard deviation of a given population
$\sigma^2$	variance of a given population
$\varphi$	geographic latitude (rad)

## 1. Introduction

At the present time, the international energy situation is composed of two related main issues: global warming and depletion of fossil resources (Ben Ahmed et al., 2011; Hegerl et al., 2007). Since the advent of the sustainable development concept at the end of the 1980s, many political decisions have been implemented around the world in order to reduce the environmental impact of human development (Liébard and De Herde, 2005). Thereby, the use of renewable resources, which emit very few Green House Gases (GHG) and are almost unlimited energies (Ben Ahmed et al., 2011), is one of the first objectives of the Kyoto Protocol established in 1997 (United Nations, 1998). Among many other kinds of renewable energies, direct solar energy is currently used through different conversion technologies mainly to produce heat or electricity (Arvizu et al., 2011), such as photovoltaics (Luque and Hegedus, 2003), flat solar thermal collectors (Mosallat et al., 2013), concentrated solar power (Viebahn et al., 2010), solar cooking (Wentzel and Pouris, 2007) or solar air conditioning (Bermejo et al., 2010).

In order to predict reliability of these systems for supplying energy to rural or urban populations, it is necessary to accurately assess both the significance and distribution of the resource, i.e. to map the solar potential. The consistent solar mapping from ground measurements requires the distance between measuring sensors to be very low (Muselli et al., 1998; Perez et al., 1997), which almost never happens (Paulescu et al., 2013). Therefore, many models have been developed over the past years in order to retrieve solar radiation reaching the ground from satellite observations, like the *Heliosat* model (Beyer et al., 1996; Rigollier, 2004), or the ones developed by Brisson et al. (1999), Zelenka et al. (1999), Perez et al. (2002) or Janjai et al. (2005). Nevertheless, if the accuracy of these models is now well established (Paulescu et al., 2013), all of them only estimate ground solar irradiance from the extraterrestrial radiation and a physical characterization of the atmospheric transmittance, and leave out, because of their inherent spatial resolution, interaction of the radiation with the local topography.

Some models, part of Geographic Information Systems (GIS) like ArcGIS or GRASS, already take into account local terrain effects in the computation of solar radiation (Ruiz-Arias et al., 2009). However, these models are mainly based on

22 simplified atmospheric parameterizations (Ruiz-Arias et al., 2010, 2009), which still limits their consistency for developing  
23 regional solar map databases. As a result, in order to take benefit from the precision of the satellite-derived computation of  
24 the atmospheric transmittance, some post-processing procedures integrating topographic effects into satellite-based radiation  
25 maps have been proposed (Bosch et al., 2010; Haurant et al., 2012; Pillot et al., 2013; Ruiz-Arias et al., 2010). Finally,  
26 comparing estimates with ground data in mountainous areas, studies of Ruiz-Arias et al. (2010), Bosch et al. (2010) and  
27 Haurant et al. (2012) have shown this method improves geographic information and accuracy of the final solar radiation maps.

28 In order to evaluate terrain effects, this process requires the use of a numerical topographic map of the study region, i.e.  
29 a digital elevation model (DEM). First and main step of the procedure consists in retrieving the local horizon for every pixel  
30 of the DEM, in order to estimate diffuse and direct shading effects caused by the terrain onto the radiation (Dozier and Frew,  
31 1990; Quaschnig and Hanitsch, 1998). Thus, the higher the DEM resolution, the better the estimate accuracy, but also the  
32 longer the global computation, which is a very important parameter to take into consideration when the area of interest gets  
33 large, such as a small country (Pillot, 2014; Pillot et al., 2013). As a result, the authors think the corresponding horizon model  
34 has to present both accuracy and fast computing features, with in addition the possibility of evaluating model-based as well as  
35 DEM-based errors made on horizon estimates.

36 Consequently, we have developed a new efficient horizon numerical model using the Matlab programming language. In  
37 order to be fully implementable with exactly the same accuracy at any world location, it is exclusively based on theoretical  
38 assumptions without any empirical approximations. We have also added to this model a characteristic viewing distance com-  
39 putation allowing processing optimization, i.e. reduction of the model's running time by knowingly altering model precision.  
40 We have then compared resulting estimates with *in situ* data, collected during an original topographic measurement campaign,  
41 and with estimates from some other models in order to assess how relevant this new model was. At last, from the ground data  
42 comparison, we propose a first approximation method for predicting the DEM-based error achieved on horizon estimates.

43 This article is divided into 3 main parts: the first focuses on the characteristics of the DEM used in this work; the second  
44 depicts the model theoretical basis as well as the related horizon viewing distance and the proposed processing optimization  
45 method; the final part presents both the comparison and the DEM-based error prediction studies.

## 46 **2. DEM features**

47 Horizon modeling directly depends on which kind of DEM is employed and on which specific Earth's mathematical  
48 representation it is defined from. We therefore present here characteristics of the main DEM used at present time, retrieved  
49 from the global Shuttle Radar Topography Mission (SRTM), as well as the coordinate reference system in which elevation  
50 data are represented.

### 51 *2.1. The Shuttle Radar Topography Mission (SRTM): an interferometric measurement of the Earth's topography*

52 A lot of developed countries own large national cartographic databases which were used before 2000 to produce DEM.  
53 However, these DEM presented some limitations such as, on the one hand, country-specific resolution, scale and geographic  
54 projection, and, on the other hand, a low coverage of the global land because of some regions without any good-quality

55 topographic maps (Farr et al., 2007). Therefore, the National Aeronautics and Space Administration (NASA) in collaboration  
56 with the National Geospatial-Intelligence Agency (NGA) prepared and achieved the SRTM, in order to propose a new global  
57 and consistent high-quality representation of the Earth’s topographic surface.

58 The SRTM lasted 10 days in February 2000 and consisted in radar scanning, from the space shuttle *Endeavour*, of 80 %  
59 of the world emerged lands located between 60°N and 57°S (Farr et al., 2007; Rabus et al., 2003). The use of an interfero-  
60 metric synthetic aperture radar (InSAR), operating in the C band (wavelength = 5.6 cm), has permitted the assessment of land  
61 topography by measuring phase difference between radar pulses reflected by the surface and received at the same time by 2  
62 distinct antennas (Farr et al., 2007; Jarvis et al., 2004). Earth’s DEM surface computed from SRTM data is a regular altitude  
63 mesh at 1” resolution (SRTM-1 DEM, about 30 m near the equator), presenting an absolute vertical error lower than 9 m (90 %  
64 confidence interval).

65 First SRTM datasets were released in 2003 by the NASA, with the SRTM-1 DEM mesh available only for the United  
66 States<sup>1</sup>. Indeed, the rest of the world is covered by the DEM at 3” resolution (SRTM-3 DEM, about 90 m near the equator),  
67 computed by averaging  $3 \times 3$  pixels of the original SRTM-1 DEM product. Furthermore, a significant proportion of elevation  
68 data is still missing in the original DEM, corresponding to a total area of 796217 km<sup>2</sup> (Jarvis et al., 2008) and mainly resulting  
69 from the low contrast within the final image (sharp slopes) or from smooth areas (smooth water or sand) which reflect too little  
70 energy to the radar (Farr et al., 2007). Several methods have been developed to fill in these voids, mainly based on interpolation  
71 algorithms and on the use of elevation data from other sources. These schemes have been integrated into a global diffusion  
72 tool developed by the Consortium for Spatial Information (CGIAR-CSI), available via the organization website (Jarvis et al.,  
73 2008). This tool gives access to SRTM-3 DEM  $5^\circ \times 5^\circ$  tiles we have used in this work.

## 74 2.2. SRTM DEM coordinate reference systems

75 A DEM is a numerical mesh of the Earth’s topographic surface where geographic coordinates of each pixel depend on the  
76 mathematical shape used to represent it. The Earth’s shape is not a perfect sphere because of the flattening at the poles and  
77 the heterogeneous gravity field at the surface. Therefore, 2 coordinate systems have been used by the SRTM to produce and  
78 reference elevation data: the WGS84 ellipsoid of revolution for horizontal position (geographic, or geodetic, longitude and  
79 latitude) and the EGM96 geoid for vertical elevation (orthometric height).

### 80 2.2.1. Geographic coordinates: the WGS84 ellipsoid

81 The World Geodetic System 1984 (WGS84) is a geocentric, right-handed and orthogonal Earth coordinate system, where  
82 origin  $O$  is the globe’s center of mass,  $z$  axis is the axis passing through the poles and  $x$  axis is the intersection between the  
83 reference meridian (Greenwich) and the plane normal to the  $z$  axis and passing through  $O$  (NGA, 2000). The WGS84 ellipsoid  
84 of center  $O$  is a mathematical approximation of the Earth’s shape retrieved by revolution, around its semi-minor axis  $b$ , of an  
85 ellipse of semi-major axis  $a$  and flattening  $f = \frac{a-b}{a}$ :

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<sup>1</sup>At the time this study was driven, worldwide SRTM-1 DEM was not available yet. It has been meanwhile released and is now available from the NASA/USGS website (<https://lta.cr.usgs.gov/SRTM1Arc>).

$$\begin{aligned}
a &= 6378137.0 \text{ m} \\
f &= 1/298.257223563
\end{aligned}
\tag{1}$$

86 The ellipsoid is fully defined by these 2 parameters, from which we can also express the first eccentricity  $e$  (Bosser, 2012;  
87 Burkholder, 2008):

$$e^2 = \frac{a^2 - b^2}{a^2} = 2f - f^2 \tag{2}$$

88 Let now  $M$  be a point of the Cartesian coordinate system  $(x, y, z)$  and  $M^*$  the orthogonal projection of  $M$  onto the ellipsoid  
89 such as  $\overrightarrow{M^*M} = h \cdot \vec{n}$ , with  $\vec{n}$  the normal to the ellipsoid in  $M^*$  (Bosser, 2012). In the geographic coordinate system,  $M$  is  
90 defined by its latitude  $\varphi$ , angle between  $\vec{n}$  and the equatorial plane, its longitude  $\lambda$ , angle between the reference meridian and  
91 the meridian passing through  $M^*$ , and its ellipsoidal height  $h$  along the normal. In order to retrieve the coordinates of  $M$  in  
92 the Cartesian space from the geographic space, it is firstly possible to express the normal to the ellipsoid as in the case of a  
93 sphere:

$$\vec{n} = \begin{pmatrix} \cos \lambda \cos \varphi \\ \sin \lambda \cos \varphi \\ \sin \varphi \end{pmatrix} \tag{3}$$

94 Then, we can calculate the Cartesian coordinates  $x, y, z$  of any point  $M$  onto the ellipsoid from its geographic coordinates  
95  $\varphi, \lambda, h$  (Bosser, 2012; Burkholder, 2008):

$$\begin{cases} x = (N + h) \cos \lambda \cos \varphi \\ y = (N + h) \sin \lambda \cos \varphi \\ z = (N(1 - e^2) + h) \sin \varphi \end{cases} \tag{4}$$

96 Where  $N$  is the length of the ellipsoid normal, i.e. the distance between  $z$  axis and  $M^*$  along the ellipsoid normal  $\vec{n}$   
97 (Burkholder, 2008):

$$N = \frac{a}{\sqrt{1 - e^2 \sin^2 \varphi}} \tag{5}$$

98 Figure 1 shows the WGS84 ellipsoid in the Cartesian coordinate system.  $A(\varphi_A, \lambda_A, h_A)$  and  $B(\varphi_B, \lambda_B, h_B)$ , with correspond-  
99 ing distances  $N_A$  and  $N_B$  from  $z$  axis, are 2 points of the Cartesian space such as  $\overrightarrow{A^*A} = h_A \cdot \vec{n}_A$  and  $\overrightarrow{B^*B} = h_B \cdot \vec{n}_B$ , and will be  
100 used later to explain horizon modeling.

### 101 2.2.2. Altitude baseline: the EGM96 geoid

102 A geoid is a mathematical model defining a specific equipotential surface of the Earth's gravity field around the mean sea  
103 level (NGA, 2000), and is used as a baseline to retrieve altitude of the topographic surface. The Earth Gravitational Model

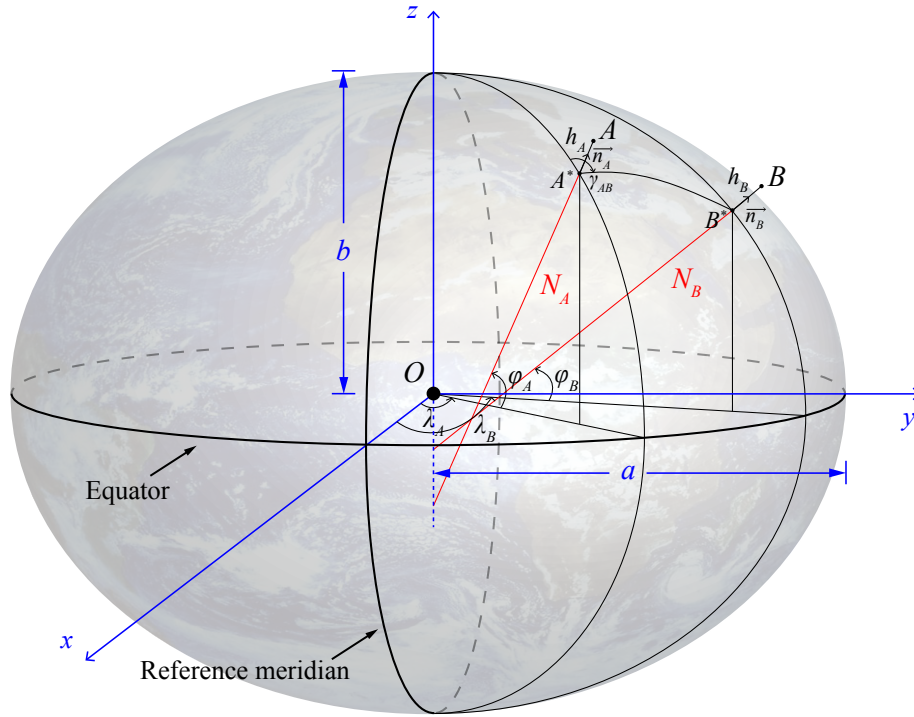


Figure 1: WGS84 ellipsoid of revolution used as the reference geographic coordinate system for the SRTM DEM.

104 1996 (EGM96) has been developed by the NASA and NGA in order to evaluate spatial variations of the gravity field, i.e.  
 105 to determine surfaces where it remains constant (Lemoine et al., 1998). Undulations of this geoid referring to the WGS84  
 106 ellipsoid, i.e. the distance between both the mathematical shapes in any point, can be determined using the model provided by  
 107 the NGA (NGA, 2014). It is thus possible, for any point of the DEM, to derive the geoid-based altitude or orthometric height  
 108  $H$  from the ellipsoidal height  $h$  considering the geoid undulation  $\Delta_{WGS84-EGM96}$  (Lemoine et al., 1998; NGA, 2000):

$$h = H + \Delta_{WGS84-EGM96} \quad (6)$$

109 The gap  $\Delta_{WGS84-EGM96}$  is positive or negative according to the geoid position above or under the ellipsoid, and remains  
 110 between approximately  $-107$  m and  $85$  m (NGA, 2000).

### 111 3. Horizon modeling

112 Obstruction induced by the Earth's topography modifies the local horizon and thus the solar radiation reaching the ground.  
 113 It is defined, in horizontal coordinates, by the azimuth  $\gamma$  and the angular elevation  $\alpha$ . Figure 2 depicts the horizon observed  
 114 from  $A(\varphi_A, \lambda_A, h_A)$  and including  $B(\varphi_B, \lambda_B, h_B)$ , defined in the horizontal plane  $P$  with respect to  $A$  by its azimuth  $\gamma_{AB}$  and its  
 115 elevation  $\alpha_{AB}$ . DEM-based horizon modeling consists therefore in computing elevation  $\alpha$  and azimuth  $\gamma$  of all the points of  
 116 the DEM around the observation point, and then retrieving the maximum  $\alpha$  for every azimuth between  $0$  and  $360^\circ$ .



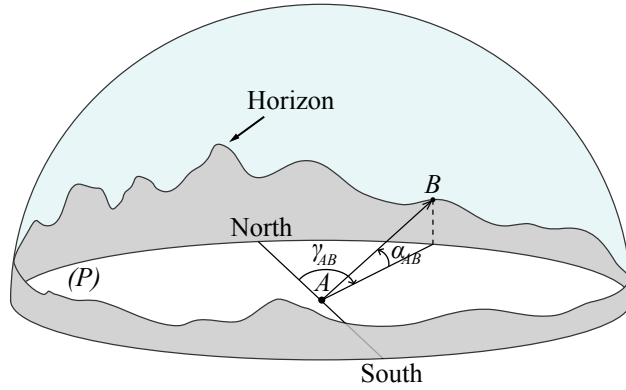


Figure 2: Obstructed horizon, induced by the terrain topography, represented in the horizontal coordinates  $(\gamma, \alpha)$  of the plane  $P$  centered on  $A$ .

### 117 3.1. Horizon theoretical model

118 Here we present the horizon model we have developed considering both the points  $A$  and  $B$  already described in Figure 1  
 119 and in Figure 2.

#### 120 3.1.1. Ellipsoidal height

121 Our theoretical model is based on both the reference systems previously described (WGS84 and EGM96). Every point of  
 122 a SRTM DEM is thus defined by its geographic coordinates and its orthometric height (Farr et al., 2007). Nevertheless, if the  
 123 angular elevation  $\alpha_{AB}$  depends on the height  $H_B$  as well as on the height  $H_A$ , they are not both computed with respect to the  
 124 same baseline because of the variations of the gravity field near the Earth's surface (geoid). Therefore, in order to accurately  
 125 evaluate  $\alpha_{AB}$  from the DEM, it is necessary to retrieve altitude of the 2 points with respect to a same regular surface such as  
 126 the WGS84 ellipsoid. As described before, it is possible to derive ellipsoidal heights  $h_A$  and  $h_B$  from relation (6):

$$\begin{aligned} h_A &= H_A + \Delta_{WGS84-EGM96}(A) \\ h_B &= H_B + \Delta_{WGS84-EGM96}(B) \end{aligned} \quad (7)$$

127  $\Delta_{WGS84-EGM96}(A)$  and  $\Delta_{WGS84-EGM96}(B)$  are geoid undulations with respect to the ellipsoid in  $A$  and  $B$  respectively, and  
 128 are depicted in Figure 3.

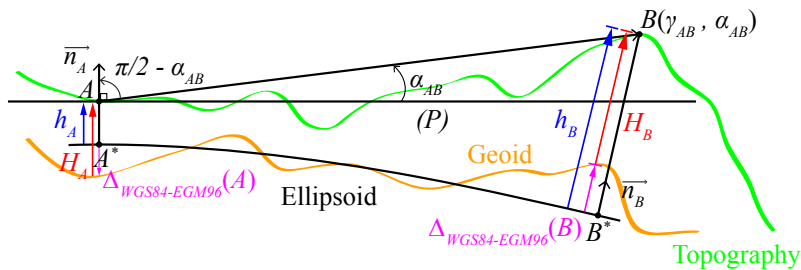


Figure 3: Sectional view of the ellipsoid surface in the  $AB$  direction.

129 **3.1.2. Angular elevation**

130 **Figure 3** is a sectional view of the ellipsoidal surface along the direction  $AB$  where belong the geoid, the terrain topography  
 131 and the horizontal plane  $P$  tangent to the ellipsoid in  $A$  (orthogonal to  $\vec{n}_A$ ). The fastest method to calculate the angular elevation  
 132  $\alpha_{AB}$ , i.e. the angle between the vector  $\vec{AB}$  and the plane  $P$ , is probably to use the scalar product. Indeed,  $\alpha_{AB}$  can be computed  
 133 coupling the scalar product between the normal  $\vec{n}_A$  and the vector  $\vec{AB}$  to the angle between them:

$$\vec{n}_A \cdot \vec{AB} = \|\vec{n}_A\| \cdot \|\vec{AB}\| \cdot \cos\left(\frac{\pi}{2} - \alpha_{AB}\right) \quad (8)$$

134 Obstruction only exists if the angular elevation is positive; so, using the sine, we finally have:

$$\alpha_{AB} = \max\left(\arcsin\left(\frac{\vec{n}_A \cdot \vec{AB}}{\|\vec{AB}\|}\right), 0\right) \quad (9)$$

135 In the Cartesian coordinate system,  $\vec{n}_A$  is derived from the relation (3). Then, equation (4) computes the coordinates  
 136  $(x_A, y_A, z_A)$  and  $(x_B, y_B, z_B)$  of  $A$  and  $B$ , which can be used to express the vector  $\vec{AB}$  and its norm:

$$\vec{AB} = \begin{pmatrix} x_B - x_A \\ y_B - y_A \\ z_B - z_A \end{pmatrix} \quad \text{and} \quad \|\vec{AB}\| = \sqrt{(x_B - x_A)^2 + (y_B - y_A)^2 + (z_B - z_A)^2} \quad (10)$$

137 **3.1.3. Azimuth**

138 In horizontal coordinates, azimuth  $\gamma$  is the rotation angle between the reference north direction and the direction of interest.  
 139 Azimuth  $\gamma_{AB}$  of the point  $B$  with respect to the observation point  $A$  is represented on the ellipsoid of **Figure 1** as well as on the  
 140 horizontal plane of **Figure 2**. It is possible to retrieve the azimuth  $\gamma$  using the meridian and parallel line elements  $ds_m$  and  $ds_p$   
 141 depicted in **Figure 4**, such as (Bossler, 2012):

$$\tan \gamma = \frac{ds_p}{ds_m} \quad (11)$$

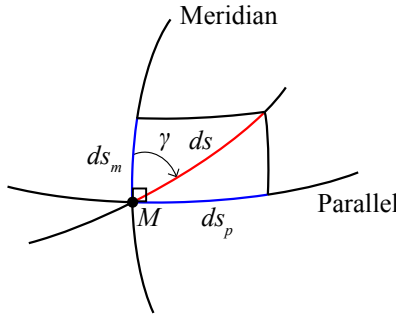


Figure 4: Azimuth  $\gamma$  of a line drawn on the ellipsoid and calculated from meridian ( $ds_m$ ) and parallel ( $ds_p$ ) line elements (Bossler, 2012).

142 Each line element depends on the considered geographic coordinate system  $(\lambda, \varphi)$ , which is not a symmetric parameteri-  
 143 zation, i.e. the same angular variation ( $d\lambda = d\varphi$ ) doesn't lead to the same travel onto the surface ( $ds_p \neq ds_m$ ). A symmetric  
 144 parameterization  $(\lambda, L)$  of the ellipsoid is thus defined as follows:

$$\frac{ds_p}{ds_m} = \frac{d\lambda}{dL} \quad (12)$$

145 Where  $L$  is the isometric latitude, undefined at the poles ( $\varphi = \pm\pi/2$ ), and which is retrieved from the geographic latitude  
 146  $\varphi$  by applying the *first fundamental quadratic form* to the ellipsoid of revolution (Bossler, 2012; Eisenhart, 1909):

$$L = \ln \left[ \tan \left( \frac{\pi}{4} + \frac{\varphi}{2} \right) \cdot \left( \frac{1 - e \sin \varphi}{1 + e \sin \varphi} \right)^{\frac{e}{2}} \right] \quad (13)$$

147 So, finally, the azimuth  $\gamma_{AB}$  is determined by integrating equation (12) along the loxodrome  $AB$ , i.e. the constant azimuth  
 148 line between  $A$  and  $B$ :

$$\gamma_{AB} = \arctan \left( \frac{\lambda_B - \lambda_A}{L_B - L_A} \right) \quad (14)$$

#### 149 3.1.4. Computing full horizon

150 We have just defined the angular elevation  $\alpha_{AB}$  and the azimuth  $\gamma_{AB}$  of a DEM point  $B$  with respect to an observation point  
 151  $A$ . In order to compute the full horizon, it is therefore necessary to apply the process to all the terrain which can be viewed  
 152 from this point. Once it is perfectly characterized in the horizontal coordinate system  $(\gamma, \alpha)$ , it is then possible to identify, for  
 153 a complete  $360^\circ$  azimuth rotation, every maximal angular elevation, and so to retrieve the horizon.

154 From relations (9) and (14), a DEM originally referenced in the geographic coordinate system  $(\lambda, \varphi, h)$  can be now repre-  
 155 sented in the new horizontal coordinate system  $(\gamma, \alpha)$ . Furthermore, InSAR technology collects *surface* altitude: the SRTM  
 156 DEM is therefore an elevation regular mesh at  $1''$  or  $3''$  resolution, composed of square pixels referenced by the geographic  
 157 coordinates of their geometric center (Farr et al., 2007; Jarvis et al., 2004).

158 As shown in Figure 5, the first step of the process consists in demarcating a new narrower DEM tile, characterized by  
 159 longitude width  $\Delta\lambda$  and latitude height  $\Delta\varphi$ , around a given observation point  $A(\lambda_A, \varphi_A, h_A)$ . The size of this new area will  
 160 determine the horizon computation time and will be defined in the next section. Once the local terrain mesh is perfectly  
 161 known, the angular elevation  $\alpha$  of each pixel is retrieved applying equation (9) to the geographic coordinates of its center  
 162  $M(\lambda, \varphi, h)$ .

163 As described in Figure 5, a loxodrome  $\gamma_{AF}$  drawn from  $A$  to any boundary point  $F$  passes through a finite number of  
 164 pixels  $[p_1, p_2, \dots, p_i]$  with angular elevation  $[\alpha_1, \alpha_2, \dots, \alpha_i]$ . Along this line, the point  $B$  presents the highest elevation  $\alpha_B$  and  
 165 thus belongs to the horizon observed from  $A$ . To detect the pixels belonging to the loxodrome, our model calculates for each  
 166 pixel of center  $M(\gamma, \alpha)$  azimuth of northwest, southwest and southeast corners  $\gamma_{NW}$ ,  $\gamma_{SW}$  and  $\gamma_{SE}$  using relation (14). Then,  
 167 the azimuth line passes through the pixel if  $\gamma_{AF}$  is between  $\gamma_{NW}$  and  $\gamma_{SW}$  along a meridian, and between  $\gamma_{SW}$  and  $\gamma_{SE}$  along  
 168 a parallel. Once elevation of all the pixels of the line is computed, the maximum is easily retrieved and corresponds to the  
 169 horizon elevation in the  $\gamma_{AF}$  azimuth direction.

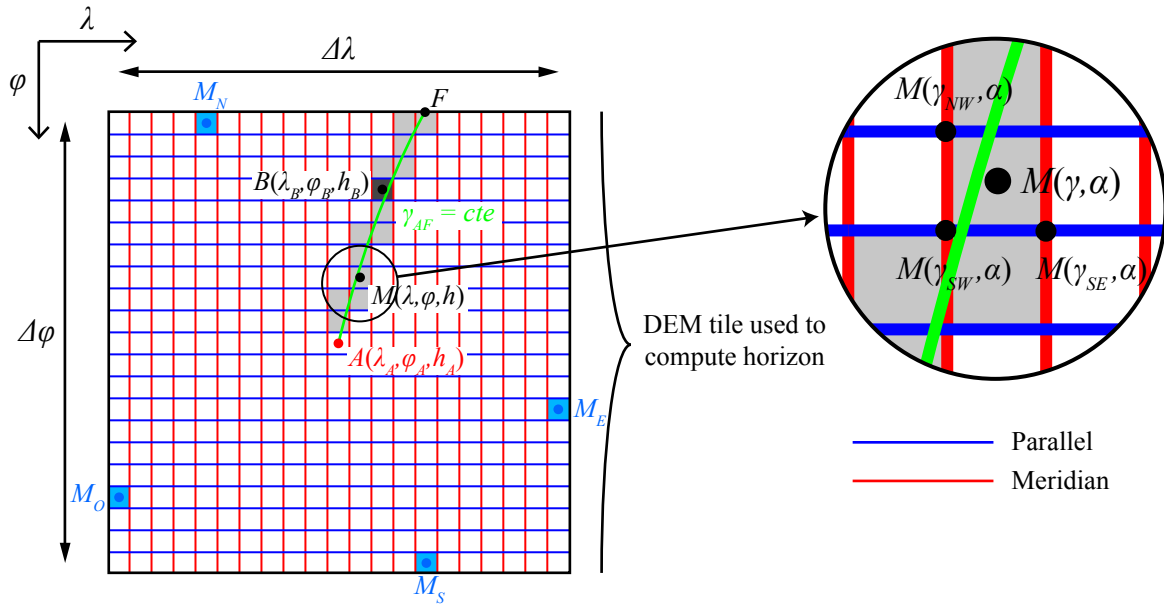


Figure 5: Methodology for computing the horizon around a given point  $A$ . Within a specific DEM tile of size  $(\Delta\lambda, \Delta\varphi)$  centered on  $A$ , and for each azimuth between  $0^\circ$  and  $360^\circ$ , it consists in retrieving the pixel with the highest elevation (here  $\alpha_B$ ) among all the pixels the given loxodrome passes through (here  $\gamma_{AF}$ ).

170 Finally, computing the full horizon consists in repeating this step for a set of azimuth lines  $[\gamma_{AF_1}, \gamma_{AF_2}, \dots, \gamma_{AF_i}]$ . Obvi-  
 171 ously, the selected number of lines directly influences horizon accuracy and computing time: in this study, we have considered  
 172 a horizon azimuth step of  $1^\circ$ .

### 173 3.2. Characteristic horizon viewing distance and model optimization

174 We present here an innovative way to reduce the size of the DEM tile required for accurately computing a single horizon,  
 175 as well as a related method allowing us to save computation time in the case of large geographic areas, by knowingly altering  
 176 the precision of multiple estimated horizons.

#### 177 3.2.1. Characteristic viewing distance

178 Most horizon numerical models, whether specialized as the Carnival French software or included in a GIS as the *r.horizon*  
 179 model (Hofierka et al., 2007) part of the *r.sun* add-on of the GRASS GIS software (Šúri and Hofierka, 2004), let the user  
 180 define the maximal distance used to compute the horizon around the observation point. However, the Earth's roundness  
 181 inherently limits the minimum altitude of any DEM point: beyond a given distance from the observation point, this point is  
 182 then necessarily located below the horizontal plane  $P$ . We can observe this statement in Figure 3 where, beyond a specific  
 183 angle between  $\vec{n}_A$  and  $\vec{n}_B$ , the angular elevation  $\alpha_{AB}$  turns negative.

184 Consequently, we have developed a *characteristic viewing distance* concept, i.e. the maximum distance beyond which any  
 185 DEM elevation data is no longer useful to compute a given horizon with the highest possible accuracy. In our model, the DEM

186 tile used to model the horizon has width  $\Delta\lambda$  and height  $\Delta\varphi$ , and is centered on an observation point defined in the geographic  
 187 coordinate system  $(\lambda, \varphi)$ . The aim was therefore to define a *characteristic viewing area* for the horizon computation, i.e. the  
 188 largest efficient DEM tile of width  $\Delta\lambda_{max}$  and height  $\Delta\varphi_{max}$  beyond which angular elevation of any DEM pixel is necessarily  
 189 negative or 0.

190 To do this, it is firstly possible to express relations allowing calculation of the angle  $\varphi - \varphi_A$  along a meridian (constant  
 191 longitude), and the angle  $\lambda - \lambda_A$  along a parallel (constant latitude), between any point  $M(\lambda, \varphi, h)$  of normal length  $N$  and the  
 192 observation point  $A(\lambda_A, \varphi_A, h_A)$  of normal length  $N_A$ , where  $h > h_A$ , such as  $\alpha_{AM} = 0$ . The angular elevation being equal to 0  
 193 when the normal  $\vec{n}_A$  is perpendicular to the vector  $\vec{AM}$ , it leads to the 2 following equations:

$$\left(\vec{n}_A \cdot \vec{AM}\right)_{\lambda=\lambda_A} = 0 \quad (15)$$

$$\left(\vec{n}_A \cdot \vec{AM}\right)_{\varphi=\varphi_A} = 0 \quad (16)$$

194 From the revolution symmetry of the ellipsoid results an explicit solution to the equation (16):

$$|\lambda - \lambda_A|_{\varphi=\varphi_A} = \delta\lambda(h)|_{\varphi} = \arccos\left(\frac{(N_A + h_A) \cos^2 \varphi_A - (h - h_A) \sin^2 \varphi_A}{(N_A + h) \cos^2 \varphi_A}\right) \quad (17)$$

195 Meanwhile, asymmetry of the meridian ellipse leads to an implicit formula for the angle  $\varphi - \varphi_A$ :

$$(N + h) \cos(\varphi - \varphi_A) + (N_A \sin \varphi_A - N \sin \varphi) e^2 \sin \varphi_A - (N_A + h_A) = 0 \quad (18)$$

196 While this equation can be numerically solved (iteration, dichotomy), it is however more interesting to use a local approx-  
 197 imation in order to obtain an explicit solution. This is done by regarding the meridian ellipse as a circle where the radius is the  
 198 radius of curvature in the north-south direction (Bosser, 2012; Burkholder, 2008). The middle term of the previous equation  
 199 disappears (eccentricity equal to 0) and the lengths of the ellipsoid normal  $N_A$  and  $N$  are replaced by the radius  $\rho$  of the local  
 200 spherical approximation calculated in  $A$ :

$$|\varphi - \varphi_A|_{\lambda=\lambda_A} = \delta\varphi(h)|_{\lambda} = \arccos\left(\frac{\rho + h_A}{\rho + h}\right) \quad (19)$$

201 Where  $\rho$  is given by the following relation (Bosser, 2012; Burkholder, 2008):

$$\rho = \frac{a(1 - e^2)}{(1 - e^2 \sin^2(\varphi_A))^{\frac{3}{2}}} \quad (20)$$

202 In that specific case,  $M$  can be any point located whether on the meridian or on the parallel passing through  $A$ . But we  
 203 can easily generalize these 2 relations to any boundary point of coordinates  $(\lambda_A \pm \delta\lambda(h)|_{\varphi}, \varphi_A \pm \delta\varphi(h)|_{\lambda}, h)$  since we will still  
 204 have  $\alpha_{AM} \leq 0$ . It is then possible to use this methodology to retrieve the size  $(\Delta\lambda_{max}, \Delta\varphi_{max})$  of the largest efficient DEM  
 205 tile used to build the horizon. Instances of boundary points in the 4 cardinal directions,  $M_N(\lambda_{M_N}, \varphi_{M_N}, h_{M_N})$  to the north,

206  $M_E(\lambda_{M_E}, \varphi_{M_E}, h_{M_E})$  to the east,  $M_S(\lambda_{M_S}, \varphi_{M_S}, h_{M_S})$  to the south and  $M_W(\lambda_{M_W}, \varphi_{M_W}, h_{M_W})$  to the west, are depicted in [Figure 5](#)  
 207 and are retrieved by iteration. To do this, we firstly initiate heights  $h_{M_N}$ ,  $h_{M_E}$ ,  $h_{M_S}$  and  $h_{M_W}$  with the maximum theoretical value  
 208 of the global DEM (Everest's altitude for instance). Then, we iteratively reduce the size of the optimal DEM tile, by looking  
 209 for the maximum height in each cardinal direction within the remaining area, as long as one of the following conditions is still  
 210 met:

$$\left\{ \begin{array}{ll} 0 \leq \varphi_{M_N} - \varphi_A \leq \delta\varphi(h_{M_N})|_{\lambda} & \& \lambda_{M_W} \leq \lambda_{M_N} \leq \lambda_{M_E} \\ 0 \leq \varphi_A - \varphi_{M_S} \leq \delta\varphi(h_{M_S})|_{\lambda} & \& \lambda_{M_W} \leq \lambda_{M_S} \leq \lambda_{M_E} \\ 0 \leq \lambda_A - \lambda_{M_W} \leq \delta\lambda(h_{M_W})|_{\varphi} & \& \varphi_{M_S} \leq \varphi_{M_W} \leq \varphi_{M_N} \\ 0 \leq \lambda_{M_E} - \lambda_A \leq \delta\lambda(h_{M_E})|_{\varphi} & \& \varphi_{M_S} \leq \varphi_{M_E} \leq \varphi_{M_N} \end{array} \right. \quad (21)$$

211 Finally, the width and height of the optimal DEM tile required to perfectly characterize the horizon are given by:

$$\Delta\varphi_{max} = \varphi_{M_N} - \varphi_{M_S} \quad (22)$$

$$\Delta\lambda_{max} = \lambda_{M_E} - \lambda_{M_W} \quad (23)$$

212 Obviously, in mapping applications, it is not really efficient to define a characteristic area for every single computed  
 213 horizon of a given region. But it is possible to define the optimal DEM of a specific region, i.e. the zone beyond which it is  
 214 no longer necessary to look for elevation data to compute any horizon of the region with the highest possible accuracy. In that  
 215 case, we no longer consider a single point but a geographic rectangle enclosing the boundaries of the study region; the optimal  
 216 DEM tile is then retrieved by using the previous method and by regarding  $h_A$  as the minimum height inside the region. This  
 217 tile encompasses the region enough for allowing the computation of all horizons with the highest possible accuracy.

### 218 3.2.2. Reducing model's running time

219 Depending on the size of the considered region, the desired accuracy and the purpose of the study, it may be interesting  
 220 to reduce the model's computation time in order to improve efficiency of the whole process. Moreover, now both the optimal  
 221 DEM and the maximum characteristic area of a given region are defined, it is possible to knowingly decrease accuracy of a  
 222 given horizon by comparing it with the theoretical ideal one. We therefore propose an efficient method allowing, in the case  
 223 of large geographic areas, computation time to be reduced and resulting horizon precision to be estimated.

224 In order to avoid an optimization as time-consuming as the area processing itself, it is relevant to use statistical inferences,  
 225 which consist in assessing the most significant properties of the global error distribution through a given territory by analyzing  
 226 smaller data sets sampled from it.

227 Regarding statistical inferences, estimating the parameter  $\theta$  of a population of observations  $F$  consists in determining the  
 228 estimator  $\hat{\Theta}$ , random variable equal to  $\hat{\theta}$  for each sample we randomly pull out from  $F$  ([Walpole et al., 2011](#)). However, in  
 229 order to accurately assess the standard error and the confidence intervals of the sampling distribution of  $\hat{\Theta}$ , the distribution

230 of the population  $F$  also requires to be perfectly known (Walpole et al., 2011). Here, it was therefore necessary to look for a  
 231 non-parametric method, i.e. fully independent of the distribution, remaining accurate in spite of the low sample size.

232 A well-suited method to that kind of problem is the *bootstrap* method (Efron and Tibshirani, 1993), which relies on the  
 233 *plug-in* statistical principle. This principle consists in determining the parameter  $\theta$  of any distribution  $F$ , such as  $\theta = t(F)$ ,  
 234 from the estimate  $\hat{\theta}$  of an empirical distribution  $\hat{F}$ , which is a sample composed of  $n$  observations randomly drawn from  $F$ ,  
 235 such as  $\hat{\theta} = t(\hat{F})$ . In addition, it is also necessary to apprehend the corresponding error, and here comes the main idea of  
 236 the bootstrap concept. It consists in re-sampling  $\hat{F}$ , i.e. in drawing with replacement  $B$   $n$ -sized random samples  $\hat{F}^{*(b)}$  in  $F$ ,  
 237 with  $b = 1, 2, \dots, B$ , called *bootstrap samples*. Then, the distribution of the  $B$  bootstrap sample estimates  $\hat{\theta}^{*(1)}, \hat{\theta}^{*(2)}, \dots, \hat{\theta}^{*(B)}$   
 238 around  $\hat{\theta}$ , such as  $\hat{\theta}^{*(b)} = t(\hat{F}^{*(b)})$ , is used to calculate the standard error and the confidence interval of the estimate  $\hat{\theta}$  (Efron  
 239 and Tibshirani, 1993; Singh and Xie, 2010).

240 Let  $\varepsilon$  be the error between an horizon estimate retrieved for a given viewing area  $(\Delta\varphi, \Delta\lambda)$  and the ideal theoretical horizon  
 241 corresponding to the optimal area  $(\Delta\varphi_{max}, \Delta\lambda_{max})$ . Let then  $E_k$  be the population of all the errors achieved on the calculation  
 242 of each  $k$ -horizon, i.e. computed using a specific  $k$ -area of size  $(\Delta\varphi_k, \Delta\lambda_k)$ , within a given region. In order to determine the  
 243 main components of the resulting error, i.e. both the mean  $\mu_{E_k}$  and the variance  $\sigma_{E_k}^2$  of the population  $E_k$ , a plug-in estimate  
 244 of  $n$  independent errors  $\hat{E}_k = \{\varepsilon_1, \varepsilon_2, \dots, \varepsilon_n\}_k$  is gathered by computing the errors of  $n$   $k$ -horizons corresponding to  $n$  random  
 245 DEM pixels.

246 First of all, in order to define the horizon viewing area of a given region of interest, it is relevant to consider a low number  
 247 of observations ( $n \leq 50$ ) and to repeat the previous step for different  $k$ -areas. Then, by using a box plot representing the error  
 248 against the computation time, it is possible to select the best compromise between them. As an example, Figure 6 shows the  
 249 box plot we have used to determine the most relevant area size for computing all horizons of the Republic of Djibouti (Pillot,  
 250 2014).

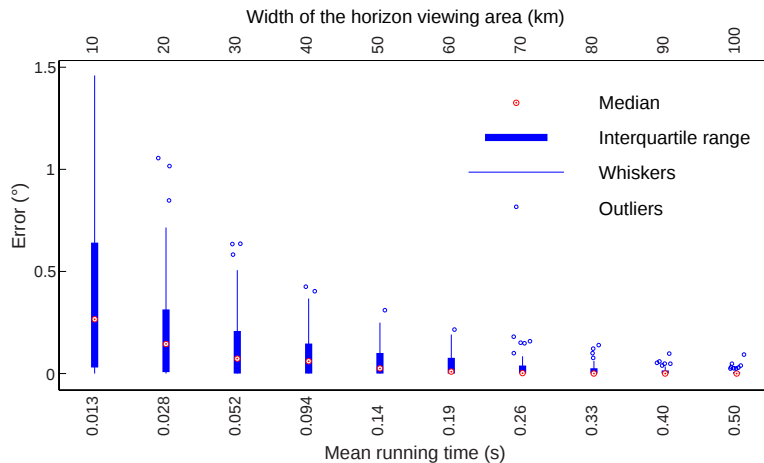


Figure 6: Example of the box plot used to optimize horizon calculation in the Republic of Djibouti, where model's error is plotted against mean running time for different  $k$ -areas (Pillot, 2014). In that example, the error determined with respect to the ideal horizon is the root mean square error.

251 Once the desired  $k$ -area is known, it is then possible to evaluate the likely error performed on any corresponding horizon  
 252 computed within the given region. In other words, it means estimating the mean  $\mu_E$  and the standard deviation  $\sigma_E$  of the  
 253 distribution  $E$  of the modeling error  $\varepsilon$ , which follows a probability law  $\varepsilon \sim (\mu_E, \sigma_E^2)$ . To perform this, a new empirical  
 254 random sample  $\hat{E} = \{\varepsilon_1, \varepsilon_2, \dots, \varepsilon_n\}$  composed of a larger set of observations (for instance  $n = 200$ ) is implemented. From this  
 255 empirical population,  $B = n^2$  bootstrap samples  $\hat{E}^{*(b)} = \{\varepsilon_1^*, \varepsilon_2^*, \dots, \varepsilon_n^*\}$ , where  $b = 1, 2, \dots, B$ , are drawn with replacement  
 256 (Singh and Xie, 2010). Thereafter, both the mean  $\bar{\varepsilon}^{*(b)}$  and the standard deviation  $s_{\varepsilon}^{*(b)}$  of each sample are calculated. Their  
 257 distribution allows assessing the accuracy of the mean  $\bar{\varepsilon}$  and the standard deviation  $s_{\varepsilon}$  of the empirical population, which infer  
 258 the parameters  $\mu_E$  and  $\sigma_E$  of the global population.

259 Finally, a simple method for estimating confidence intervals of the population parameters ( $\mu_E$  and  $\sigma_E$ ) is the percentile  
 260 method. However, asymmetry and bias of the standard deviation distribution (Walpole et al., 2011) make an approach such  
 261 as the bias-corrected and accelerated (BC<sub>a</sub>) procedure, developed by (Efron, 1987), better suited. The classical percentile  
 262 approach gives, for a significance level  $\nu$ , the  $(1 - 2\nu)$  % confidence interval of the given estimation  $\hat{\theta}$  as  $[\hat{\theta}^{*(\nu)}, \hat{\theta}^{*(1-\nu)}]$ , where  
 263  $\hat{\theta}^{*(\nu)}$  is the  $100\nu^{\text{th}}$  percentile of the distribution of the  $B$  bootstrap estimates  $\hat{\theta}^{*(1)}, \hat{\theta}^{*(2)}, \dots, \hat{\theta}^{*(B)}$ . In order to correct both the  
 264 bias and the asymmetry of the given estimator, the BC<sub>a</sub> method enhances this first approximation by using other interval  
 265 boundaries, as  $[\hat{\theta}^{*(\nu_1)}, \hat{\theta}^{*(\nu_2)}]$  where  $\nu_1$  and  $\nu_2$  are adjusted with respect to  $\nu$  and  $1 - \nu$  using the standard normal cumulative  
 266 distribution function (Efron, 1987; Efron and Tibshirani, 1993).

267 Accordingly, the resulting distribution  $E$  of the horizon modeling error  $\varepsilon$  will follow a probability law  $\varepsilon \sim (\mu_E, \sigma_E^2)$  such  
 268 as:

$$\begin{cases} \mu_E \in [\bar{\varepsilon}^{*(\nu_1)}, \bar{\varepsilon}^{*(\nu_2)}] \\ \sigma_E \in [s_{\varepsilon}^{*(\nu_1)}, s_{\varepsilon}^{*(\nu_2)}] \end{cases} \quad (24)$$

#### 269 4. Model's efficiency and DEM-based error prediction

270 We have presented the theoretical basis of our horizon model and proposed a method to choose the best compromise  
 271 between the computation time and the corresponding model's accuracy. Nevertheless, this precision is only related to the ideal  
 272 DEM-based horizon and not to the real horizon, so the error induced by the not fully accurate DEM representation of the  
 273 Earth's topography has not been considered yet. As a result, we assess here the global accuracy of the final horizon estimates  
 274 and compare it to other existing models in order to evaluate our model's performances. Finally, we also propose a method for  
 275 predicting the horizon's DEM-based error.

##### 276 4.1. Model's efficiency: accuracy vs computation time

277 The efficiency of any numerical model can be regarded as the ability to describe accurately a phenomenon in the shortest  
 278 possible time. Therefore, we have firstly assessed the quality of our model by statistically comparing estimates with ground  
 279 measurements. Then, we have confronted these results and the corresponding computation time to those retrieved using other  
 280 typical models.



281 4.1.1. Model's accuracy: comparison with ground measurements and results from other existing models

282 In order to evaluate the accuracy of our model, we have compared horizon estimates with 10 *in situ* horizons collected  
283 during a measurement campaign achieved in Corsica in 2010; both the geographic distribution and the topographic situation of  
284 these sites are presented in Figure 7. The availability of an adapted material was one of the main reasons for choosing Corsica,  
285 the other one being the existence of many different types of terrain within a small area, which allowed retrieving a significant  
286 sample of measurements without difficulties. In order to measure the different horizons, we have used a topographic mapping  
287 device, the *Leica Builder 100* theodolite (azimuth accuracy = 9"; elevation accuracy = 6"). The operating principle of this  
288 accurate device, mainly used by topographers for measuring terrain slope and aspect, is depicted in Figure 8.

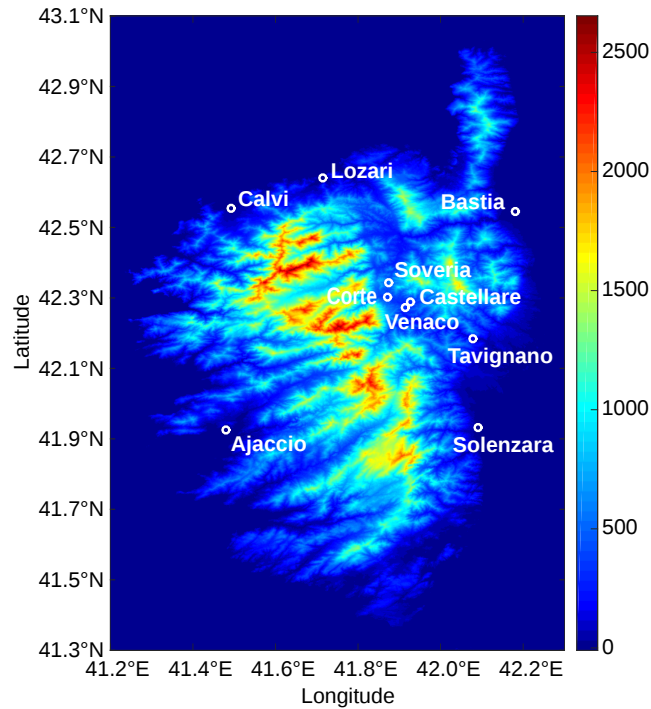


Figure 7: Topographic SRTM-DEM map of Corsica island (meters) with location of the measurement sites.

289 Furthermore, in order to endorse our model, it was also relevant to compare it to other ones. Thus, we have meanwhile  
290 analyzed the results of both the French software Carnaval and the r.horizon add-on of the GRASS GIS open source. Currently  
291 released by Sober Software (<http://www.sober-software.com>), Carnaval is based on the SRTM-3 DEM and only com-  
292 putes single horizons intended to be used with other solar simulation software. On the contrary, r.horizon is closer to our own  
293 model since it is dedicated to the integration of terrain effects into solar potential maps computed by the solar radiation model  
294 r.sun (Ruiz-Arias et al., 2009; Šúri and Hofierka, 2004). Besides, this model allows 2 different computing configurations using  
295 a DEM implemented by the user: the first one retrieves shading maps by computing angular elevation for a specific azimuth;  
296 the second configuration, and the one we have considered in this work, estimates the full horizon around a given point.

297 The experiment achieved in 2010 consisted in measuring horizons on 10 different sites across Corsica, representing a full

Table 1: Comparison between measured and estimated horizons from our model, r.horizon and Carnaval over 10 sites in Corsica.

Site	Latitude	Longitude	Altitude (m)	Sample	This study			r.horizon			Carnaval		
					CC	RMSE (°)	MBE <sup>1</sup> (°)	CC	RMSE (°)	MBE <sup>1</sup> (°)	CC	RMSE (°)	MBE <sup>1</sup> (°)
Ajaccio	41.9255°N	8.7802°E	0	61	0.9705	0.349	0.077	0.9661	0.380	0.105	0.9660	0.398	0.159
Calvi	42.5540°N	8.7920°E	1	45	0.9971	0.115	-0.020	0.9943	0.166	-0.046	0.9853	0.270	-0.076
Lozari	42.6400°N	9.0149°E	1	51	0.9916	0.277	-0.042	0.9920	0.273	-0.065	0.9708	0.529	-0.236
Bastia	42.5452°N	9.4806°E	8	45	0.9961	0.184	0.087	0.9986	0.100	0.040	0.9970	0.148	0.067
Solenzara	41.9312°N	9.3903°E	19	56	0.9988	0.091	0.037	0.9981	0.113	0.052	0.9976	0.135	0.066
Tavignano	42.1831°N	9.3782°E	80	73	0.9079	2.816	-0.456	0.9194	3.486	-1.914	0.9210	4.384	-3.533
Castellare	42.2883°N	9.2272°E	325	73	0.9776	2.529	-2.028	0.9572	2.496	-1.669	0.9437	2.759	-0.702
Venaco	42.2727°N	9.2142°E	352	70	0.9537	2.323	-0.999	0.9402	2.374	-0.985	0.9656	2.941	-1.478
Corte	42.3011°N	9.1712°E	366	68	0.9962	0.321	-0.070	0.9977	0.263	-0.096	0.9933	0.469	-0.224
Soveria	42.3440°N	9.1744°E	514	73	0.9928	0.770	-0.102	0.9948	0.801	-0.410	0.9740	1.410	-0.088
Total				615	0.9762	1.555	-0.416	0.9761	1.712	-0.587	0.9564	2.116	-0.705

<sup>1</sup> Negative bias means model underestimation.

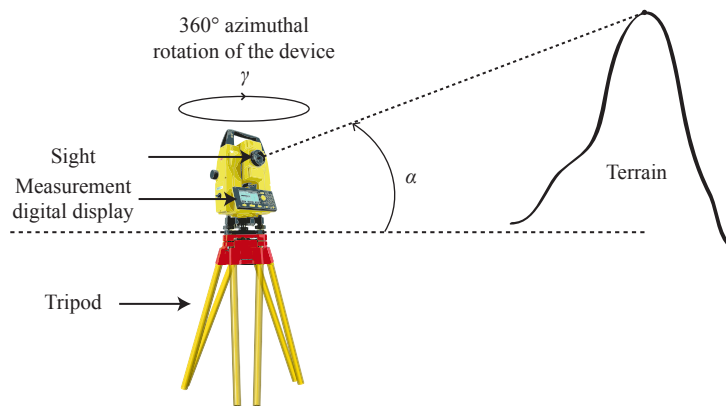


Figure 8: Theodolite operating principle. This device allows both the azimuth  $\gamma$  and the angular height  $\alpha$  of a given point to be accurately measured.

298 set of 615 points. Moreover, in order to compare the exact same points from both estimated and measured horizons, we have  
 299 linearly interpolated modeled horizons, at  $1^\circ$  azimuth step, over measured azimuths. Then, in order to assess the accuracy of  
 300 each model, we have considered the following well-known indicators: the root mean square error (RMSE), the mean bias error  
 301 (MBE) and the correlation coefficient (CC). All final results of the comparison are described in Table 1, where each location  
 302 is defined by the geographic coordinates and the DEM-based altitude of the given observation point.

303 Globally, these results show higher accuracy of our model, while Carnaval presents the lowest one. Thus, our model  
 304 and r.horizon present the most homogeneous correlation for all samples with 2 close correlation coefficients (respectively  
 305  $0.9762$  and  $0.9761$ ). Meanwhile, our model also exposes a better RMSE ( $1.555^\circ$  against  $1.712^\circ$ ) and a lower negative bias  
 306 ( $-0.416^\circ$  against  $-0.587^\circ$ ). Finally, Carnaval presents the less fitted results regardless of the considered indicator: a correlation  
 307 coefficient of  $0.9564$ , a RMSE of  $2.116^\circ$  and a bias of  $-0.705^\circ$ . Furthermore, we can note that the increase by 10 of the horizon  
 308 azimuth resolution of our model only reduces RMSE by 0.1 %, from  $1.555^\circ$  to  $1.547^\circ$ , which validates the initial choice of a  
 309  $1^\circ$  azimuth step.

#### 310 4.1.2. Model's running time

311 By measuring horizons and comparing them with the estimates of other models, we have demonstrated the accurateness  
 312 and the relevance of the one developed in this study. Most of all, its theoretical basis will allow accurate estimation of any  
 313 horizon in the world, as long as the SRTM-based DEM exists. Nonetheless, as previously depicted, this model has been  
 314 primarily designed for considering shading effects within satellite-based solar radiation maps (Bosch et al., 2010; Haurant  
 315 et al., 2012; Pillot et al., 2013; Ruiz-Arias et al., 2010). Therefore, as with the previous optimization method, used to reduce  
 316 the area size required to compute all horizons of a given region, everything has been made to minimize computation time.

317 Firstly, as our model is written with the Matlab programming language, it takes benefit from the software specific matrix  
 318 calculations, which saves time for handling of large arrays. Thus, on the same machine and for the same viewing distance

Table 2: Approximate horizon per-thread computation time for a 50 km view distance around observation point.

Model	Running time (s)
This study	≈ 0.5
r.horizon <sup>1</sup>	≈ 2.0
Carnaval <sup>2</sup>	≫ 2.0

<sup>1</sup> Given by the GRASS GIS command window.

<sup>2</sup> Estimated by Sober Software.

(50 km), Table 2 shows our model is, per thread and per horizon, 4 times faster or more than r.horizon and Carnaval<sup>2</sup>. Besides that, our model is also directly incorporated into the process implemented for considering topography within radiation maps (Pillot, 2014; Pillot et al., 2013), which avoids extra time consumption during data transmission with external models. Finally, our model’s source code used to estimate all horizons of a given region is parallelized, which reduces running time as much as the number of available threads within the computer’s processor.

#### 4.2. DEM-based error prediction

A more detailed reading of Table 1 reveals that, regardless of the given model, error and bias also dramatically vary from one horizon to another. Indeed, some sites present very good estimates (Bastia, Solenzara or Calvi) while some others show both high RMSE and negative bias (Tavignano, Venaco or Castellare). If the original DEM error obviously affects the final quality of the horizon estimates, it is also interesting to know whether this error depends on some specific topographic parameters, which would have influenced the original SRTM precision. In that case, the resulting horizon error would also depend on some specific features; consequently, we propose a method for predicting this error, or at least to detect if the error of any given horizon will probably be significant.

Leaving aside possible measurement errors (angular height, azimuth or geographic coordinates of the observation point), the main idea is to connect the horizon error to the DEM error. To perform this, it is firstly necessary to know the kind of error existing within the SRTM DEM. It is possible to enumerate 2 main errors: vertical and georeferencing errors, respectively achieved on the altitude and the geographic coordinates of a DEM point (Farr et al., 2007; Rodríguez et al., 2006). In this study, we have only considered the vertical error, easier to implement and the one which mainly induces the angular elevation error.

In order to predict the error generated by the DEM quality, it is firstly relevant to express the RMSE of a given horizon

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<sup>2</sup>So as to get an idea of the computation time over areas, at 2 s/horizon, it would spend about 30 days, 2000 days or 250 years to retrieve all horizons from Corsica, France or Africa respectively.

339 consisting of  $n$  points:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (\alpha'_i - \alpha_i)^2}{n}} \quad (25)$$

340 With  $\alpha'_i$  the  $i$ th estimated angular elevation and  $\alpha_i$  the  $i$ th measured one. Let us then focus on the  $i$ th point of this horizon,  
 341 of angular height  $\alpha_i$ ; it is known this point has a vertical error on its DEM altitude  $h'_i$ , with respect to the true altitude  $h_i$ , which  
 342 is propagated on the angular error  $\alpha'_i - \alpha_i$ . So, if it is possible to predict the vertical error  $h'_i - h_i$ , it is also possible to assess  
 343 the resulting angular error, by estimating  $\alpha_i$  from  $h_i$  using relation (9). Essentially, we have thus been led by the main idea  
 344 of looking for an empirical expression, allowing us to merely define the vertical error as a function of SRTM DEM-derived  
 345 parameters.

346 Validation of the SRTM has shown the vertical error can be regarded as a random variable following an almost normal  
 347 probability law, centered on 0 and having a standard deviation specific to each continent (Farr et al., 2007; Rodríguez et al.,  
 348 2006). Meanwhile, the Miliareis and Paraschou (2005) and Gorokhovich and Voustianiouk (2006) studies have highlighted  
 349 the error correlation with topographic features of a given terrain, typically both the slope and aspect of a DEM pixel. In this  
 350 study, we have only considered the slope  $S$ , since the aspect is less significant but also more difficult to model as it is highly  
 351 dependent on the study region. The slope is a function of the altitude gradient to the north ( $y$ ) and to the east ( $x$ ) (Zhou and  
 352 Liu, 2004):

$$S = \arctan \left( \sqrt{\left( \frac{\partial h}{\partial x} \right)^2 + \left( \frac{\partial h}{\partial y} \right)^2} \right) \quad (26)$$

353 Several methods exist for calculating  $S$ , among which the one developed by Fleming and Hoffer presents a good precision  
 354 (Jones, 1998). It is based on the formulation of the partial derivatives of the height  $h$  (Zhou and Liu, 2004):

$$\frac{\partial h}{\partial x} = \frac{h_E - h_W}{2R_{DEM}^x} \quad ; \quad \frac{\partial h}{\partial y} = \frac{h_N - h_S}{2R_{DEM}^y} \quad (27)$$

355 Where  $h_E, h_W, h_N, h_S$  are respectively heights of eastern, western, northern and southern pixels contiguous to the pixel of  
 356 interest,  $R_{DEM}^x$  the DEM metric resolution along  $x$  axis, and  $R_{DEM}^y$  the resolution along  $y$  axis. Table 3 summarize, for each  
 357 site, the main statistical parameters (mean, standard deviation and range) of the horizon slope, that is the slope of all DEM  
 358 pixels composing the horizon.

359 Both Miliareis and Paraschou (2005) and Gorokhovich and Voustianiouk (2006) studies have emphasized the increase of  
 360 the mean vertical error with the slope  $S$  (overestimation of the DEM altitude compared to the true altitude). Miliareis and  
 361 Paraschou (2005) especially have shown that, even though the error distribution was translated to the right, this distribution was  
 362 still close to the one for low slopes ( $S < 2^\circ$ ) with about the same flattening and asymmetry. Considering these assumptions, it  
 363 is then possible to define the vertical error as:

$$h' - h = r + f(S) \quad (28)$$

Table 3: Main characteristics of the horizon slope.

Site	Slope (°)		
	Mean	Std	Range
Ajaccio	10.1	7.4	0.0 - 33.5
Calvi	11.1	9.4	0.6 - 40.5
Lozari	8.7	8.7	0.0 - 46.9
Bastia	6.4	7.8	0.4 - 35.3
Solenzara	7.9	8.5	1.2 - 39.3
Tavignano	21.7	5.0	9.3 - 31.1
Castellare	16.0	6.2	4.0 - 35.8
Venaco	14.4	6.9	0.5 - 35.8
Corte	16.0	8.7	1.4 - 39.8
Soveria	17.3	7.3	2.0 - 38.0

364 Where  $r$  is a normally distributed random variable centered on 0 such as  $r \sim N(0, \sigma)$ , resulting of the SRTM validation  
365 (Rodríguez et al., 2006), and  $f(S)$  any function of the pixel’s slope  $S$ . From the Miliareis and Paraschou (2005) study, we  
366 can then consider, in first approximation, the error linearly increases with the slope. Finally, the expected value of the vertical  
367 error  $h' - h$  is given by:

$$E[h' - h] = E[r] + \beta S = \beta S \quad (29)$$

368 Where  $\beta$  is a strictly positive constant (distribution translated to the right). Getting  $h$  from relation (29), it is then possible to  
369 predict the value of the corresponding measured angular elevation  $\alpha$ , using equation (9). In order to evaluate the constant  $\beta$ , we  
370 have minimized the quadratic error between the measured RMSE of the full sample in Table 1 and the RMSE estimated with  
371 this method. Carnaval and r.horizon presenting different errors, the constant  $\beta$  is therefore different from one model to another,  
372 and is respectively equal to 0.357, 0.398 and 0.494 for our model, r.horizon and Carnaval. In addition, the correlation between  
373 the prediction and the measure for each model is given by the correlation coefficient. It is equal, for a 1 % significance level,  
374 to 0.9331, 0.9611 and 0.9800 for our model, r.horizon and Carnaval respectively. Finally, the consistency of the prediction  
375 method is depicted in Figure 9, with on the one hand the estimates vs measurements scatter plot, and on the other hand the  
376 comparison between 2 horizons presenting low (Corte) and high error (Tavignano).

377 Some aspects of this analysis must be emphasized. First of all, we have not taken into consideration the vertical error of  
378 the horizon observation point, although it also interferes in the global angular error. Indeed, if the many points composing  
379 the horizon allow *smoothing* the approximate formula (29), the possible bias introduced by the observation point would, on  
380 the contrary, impact all the points, and so could strongly distort the final estimate. This point leads to another aspect of

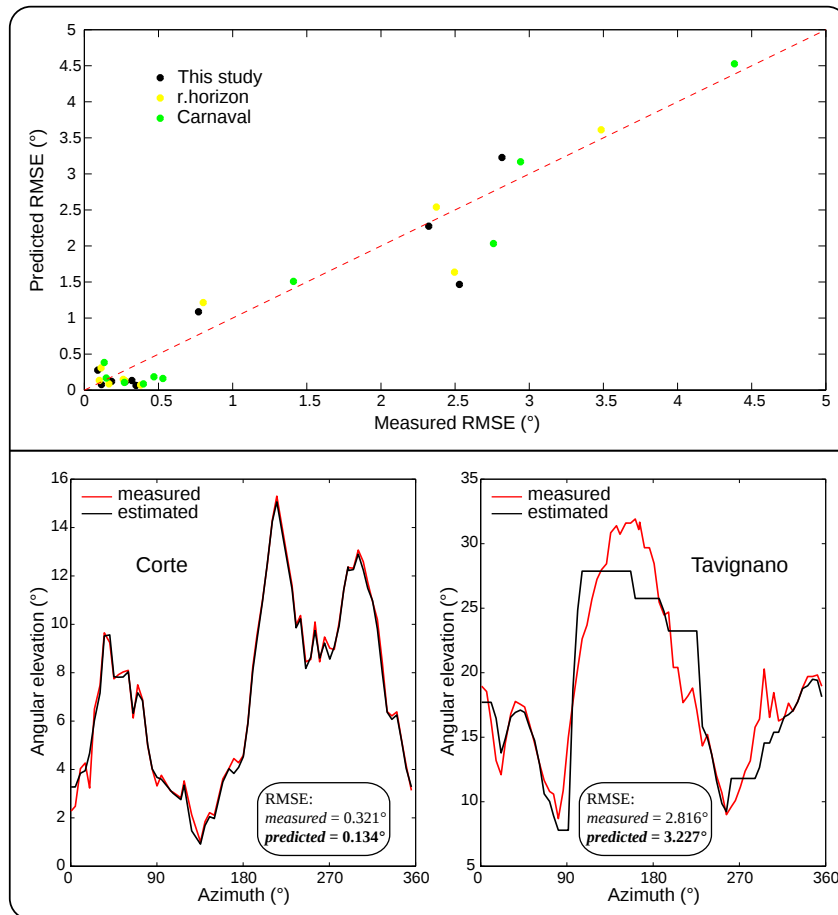


Figure 9: Predicting SRTM-3 DEM-based horizon error. Above is the scatter plot of predicted against measured RMSE values for the 10 horizons depicted in Table 1. Below is an example of horizon measurements and estimates over Corte and Tavignano, respectively for a low and a high error.

381 this study: the greater the number of points composing the horizon, the more accurate the quadratic error prediction will  
 382 be. Furthermore, vegetation is also a subject of concern for the error estimation since depending on its type and density, the  
 383 wavelength of the C band might penetrate into the canopy (Farr et al., 2007). Accordingly, in vegetated areas, SRTM DEM  
 384 elevation is located between the ground and the top of the canopy, at a distance which varies significantly with the SRTM  
 385 DEM variability (Carabajal and Harding, 2006). As the shading effects are influenced by the canopy, this might lead to some  
 386 extra underestimation, mainly when the horizon is close. Finally, linear approximation between vertical error and slope as  
 387 well as the decision to leave aside DEM aspect and georeferencing may also explain the shift between measured and predicted  
 388 values. Even so, this method shows quite accurate estimates, and can further be generalized to all the SRTM-3 DEM, by  
 389 mainly regarding the predicted RMSE as a sensitivity coefficient allowing the horizon's level of quality to be assessed.

### 390 4.3. Error propagation to solar radiation

391 As depicted in previous studies, the integration of shading effects improves both the accuracy and spatial information  
392 provided by satellite-derived solar radiation maps (Haurant et al., 2012; Pillot, 2014; Ruiz-Arias et al., 2010). However, as  
393 described above, the DEM-based horizon computation results itself in some error, which necessarily propagates to the solar  
394 irradiation. In order to assess how this error affects the final irradiation estimation, we have used the *disaggregation* method-  
395 ology we have developed in another study (Pillot, 2014), coupled with the ESRA clear-sky model developed by Rigollier  
396 et al. (2000) and corrected in altitude by Geiger et al. (2002). This methodology includes shading effects into the global solar  
397 radiation by applying horizon-derived factors to its diffuse isotropic, diffuse circumsolar and beam components.

398 Besides, depending on both the sun path and the sky cloudiness, the final influence of the horizon on the solar radiation  
399 can be significantly different. In order to apprehend this double dependence, we have estimated the clear-sky daily irradiation  
400 throughout the year, and analyzed the influence of the solar radiation's diffuse component by acting on the key parameter of  
401 the ESRA model: the Linke turbidity factor  $T_L$  (Geiger et al., 2002; Rigollier et al., 2000). This coefficient usually varies from  
402 1 to 10,  $T_L = 2$  corresponding to a very clear atmosphere, and  $T_L = 8$  corresponding to a polluted atmosphere (Eltbaakh et al.,  
403 2012).

#### 404 4.3.1. Solar irradiation loss

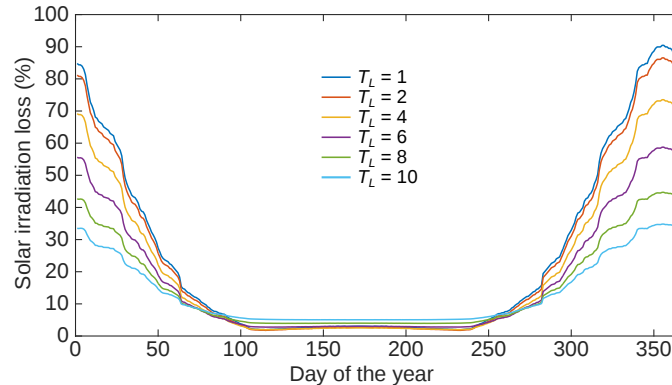


Figure 10: Relative irradiation loss (%) caused by the horizon at Tavignano site, with respect to the day of the year and the Linke turbidity factor.

405 In order to evaluate the solar irradiation loss potentially caused by the horizon, we have determined the daily clear-sky  
406 irradiation reaching the Tavignano site, with and without shading effects computed from the measured horizon. Figure 10  
407 depicts the final relative loss according to the day of the year and the Linke turbidity factor. As expected (Quaschnig and  
408 Hanitsch, 1998), shading effects affect more the beam component than the diffuse radiation: the irradiation blocked by the  
409 horizon decreases when  $T_L$  increases. When the sun is high however, between days 100 and 250, the loss remains low and  
410 similar ( $< 10\%$ ) regardless of the Linke coefficient. In that case, the most significant loss ( $> 50\%$ ) appears at the end of the  
411 autumn and the beginning of the winter, as a consequence of the low sun path.



#### 4.3.2. Horizon error propagation

In order to assess how the RMSE of  $1.555^\circ$  (Table 1) ends up affecting the solar estimation, as well as the evolution of this influence, we have statistically analyzed the daily irradiation with shading effects reaching the 10 sites of Table 1, using either the horizon measurements or the estimates from our model. To do this, we have computed the relative root mean square error (RRMSE) between both the results, according to the day of the year and the Linke turbidity factor, depicted in Figure 11. Again, as expected, the beam radiation is more impacted by the horizon shadowing than the diffuse radiation, as the final error decreases with the rise of the Linke coefficient. Also, the RRMSE is significantly variable over the year, compared to the smooth tendency of the solar radiation loss; it can probably be explained by the original variability of the sign of the bias between the estimate and the measured horizon elevation depending on the azimuth. Essentially, in this study, depending on the day and the diffuse fraction, the horizon mismatching results in a final error ranging from approximately 0.5% (high sun path) to 5.5% (low sun path) of the daily solar irradiation.

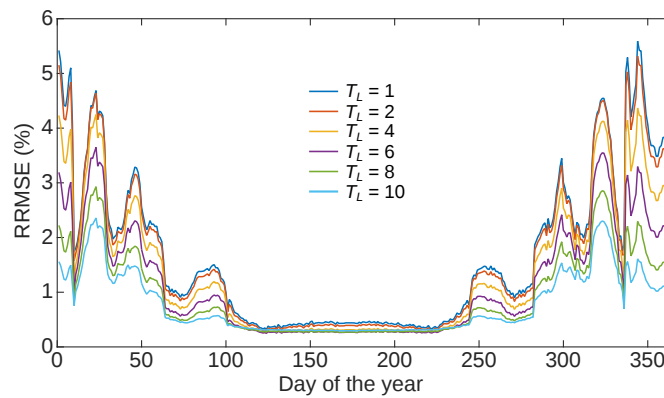


Figure 11: RRMSE (%) between solar irradiation with shading effects computed from horizon measurements and estimates for all sites of Table 1, with respect to the day of the year and the Linke turbidity factor.

## 5. Conclusion

Many models now retrieve solar radiation from satellite data, but are still limited to an atmospheric characterization without any consideration of the interaction between radiation and Earth's surface. Therefore, in order to improve the accuracy of these satellite-based estimates, some post-processing methods have been proposed for integrating terrain-based effects into final solar irradiance or irradiation maps using DEMs. The main process of all these methods consists in estimating the obstructed horizon around every DEM pixel, in order to evaluate direct and diffuse shadowing. Nevertheless, depending on the size of the study area, computation can also be really time consuming. That is why we have developed and validated a new efficient horizon model, combined with an optimization method and a DEM-based error prediction study.

We have developed this model using the global DEM retrieved from the SRTM, as it is currently the most consistent and accurate available DEM. We have furthermore only based this model on the mathematical statements used to represent the

433 DEM, avoiding any region-specific empirical assumption so as to allow the model to be used at any world location with the  
434 same expected accuracy. Then, we have assessed its efficiency by comparing its precision and computation time with those  
435 of other models. Precision has been retrieved using a statistical comparison between estimates and *in situ* horizons measured  
436 with a theodolite. Finally, we have demonstrated the implementation of our model was relevant, since it is both more accurate  
437 (RMSE of 1.555° against 1.712° or more for other presented models) and less time consuming (at least 4 times faster than  
438 other models).

439 In addition, we have also proposed an optimization method for reducing horizon computation time in the case of large  
440 areas, as well as an empirical approach for predicting the DEM-based error on final estimates. The first one takes into  
441 consideration the Earth's roundness in order to limit the maximum zone required to fully describe any horizon of a given  
442 region. Hence, it allows knowingly decreasing of modeling accuracy with running time, and thus get the best compromise  
443 between them depending on the purpose of the regarded study. The second evaluates the impact of the SRTM DEM original  
444 error on the final horizon precision by correlating it to the DEM slope, and has been validated using the *in situ* horizon sample  
445 collected in Corsica.

446 Finally, we shall note that, in this study, we have not considered the distortion effects of the atmospheric refraction  
447 onto the apparent position of objects on Earth, and so on the resulting angular elevation, known as terrestrial refraction  
448 (De Graaff Hunter, 1913). This approach seems relevant since, in mapping applications, the additional computation time  
449 required for modeling this phenomenon, and its related parameters such as object distance or temperature and pressure condi-  
450 tions, would not necessarily be worth the final accuracy gain. Nevertheless, future research could still improve the accuracy  
451 of our current model by focusing on this part.

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