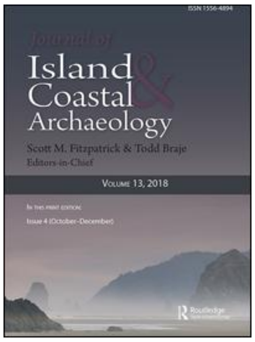

Routledge
Taylor & Francis Group

The Journal of Island and Coastal Archaeology

ISSN: 1556-4894 (Print) 1556-1828 (Online) Journal homepage: https://www.tandfonline.com/loi/uica20

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THE JOURNAL OF ISLAND AND COASTAL ARCHAEOLOGY
https://doi.org/10.1080/15564894.2020.1755394

Evaluating visibility at sea: Instrumental data and historical nautical records. Mount Etna from the Calabrian Ionian coast (Italy)

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ABSTRACT

Visibility has an encompassing importance in humans' perception of the landscape, since the first encounter with a new environment normally occurs through sight. In historical and archaeological studies, two main methods (i.e., the geometric method and the Geographical Information System [GIS] computation) have been employed to determine the distance from which an object can be recognized. However, neither is exhaustive when applied to a maritime context, where the main factor affecting the visibility radius is weather. To establish how far at sea an object can be seen, and how its visibility would have changed in different weather conditions, we adopted a method from Aerosol Optics based on a well-established mathematical model of the light scattering phenomena. We applied this method to compute the visibility radius in historical studies. To demonstrate its application, we choose to examine the visibility of a key point in both historical and current seafaring, namely Mount Etna (Sicily, Italy), from the Ionian coast of Calabria (Italy). The results obtained by the application of this method have been validated by comparing them with mentions of Mount Etna in both written sources and on-the-ground records.

ARTICLE HISTORY
Received 31 July 2018;
Accepted 8 April 2020

KEYWORDS
Visibility; aerosols optics; seafaring; ethnoarchaeology/experimental; coastal; Western Europe

Introduction

The term "visibility" indicates the distance to the visible horizon, and—according to the American Meteorological Society (2013)—it could be technically defined as "the distance, under daylight conditions, at which the apparent contrast between a specified type of target and its background becomes just equal to the threshold contrast of an observer."

Visibility has an encompassing importance in humans' perception of the landscape, since the first encounter with a new environment normally occurs through sight (Adrian 1989; Gillings and Wheatley 2001, 26). For this reason, the study of visibility

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Supplemental data for this article is available online at https://doi.org/10.1080/15564894.2020.1755394.

has successfully been applied to different research areas to explain a wide range of phenomena (e.g., Alonso, Álvarez-Martínez, and Palacín 2012; Brabyn and Mark 2011; Falconer et al. 2013; Fernandez-Jimenez et al. 2015; Geneletti 2008; Kizuka et al. 2014; Olsoy et al. 2015; Sklenicka and Zouhar 2018).

Commonly, the evaluation of a visual basin is entrusted to either manual ("geometric," used for the first time in archeological studies by Schüle (1970) and based on Henkel (1901)) or automatic methods (mainly carried out with common Geographic Information System [GIS] software (e.g., Alonso, Álvarez-Martínez, and Palacín 2012; Falconer et al. 2013; Olsoy et al. 2015), which are essentially based on the measurement and analysis of line-of-sight (intervisibility) or field of view (viewshed) elements. These methods allow us to either calculate the extension of a visual basin (geometric method) or identify areas that are visible or nonvisible from a given observer point (using the binary attribute 0 or 1). If, on the one hand, they provide the scientific community with a concise idea of how extended the visibility radius was, on the other hand, they drastically simplify a highly complex scenario (as noted by Chapman 2006; Lagner, Klouček, and Símová 2018) where other factors could have played a determinant role (e.g., presence of both natural and artificial obstacles, observers' skills, unique characteristics of the coast that facilitated the identification of a particular place). For this reason, an integration of on-the-ground visual observations with data derived from geometrical or GIS computations would be highly recommended to better understand a specific seascape.

In archeological and historical analyses, the study of visibility has made it possible to broaden the horizons of research, making it easier to understand how people perceived the landscape in the past and what use they made of it (McGrail 1991; Ogburn 2006; Sevenant and Antrop 2007; Smith and Cochrane 2011). Although visibility analyses in archeology have become increasingly common in the last decades (e.g., Criado Boado 1993; Jacobson 2007; Parcero Oubiña 2002; Ruiz Rodríguez and Molinos Molinos 1984), their potential in seascape studies has not entirely been exploited so far. In fact, most maritime archeological works either apply models from landscape studies without adjusting them to the nautical context (Friedman, Look, and Perdikaris 2010), or mention visibility only in a qualitative way (e.g., Agouridis 1997; Bar-Yosef Mayer et al. 2015; Braudel 1972, 216; Broodbank 2000, 2010; Horden and Purcell 2000, 393; Howitt-Marshall and Runnels 2016; Kealy, Louys, and O'Connor 2017).

In the last 30 years, scholars have sought to make visibility analyses match with on-the-ground visual observations by developing algorithms that involve further parameters (e.g., the presence of a lookout post on the viewpoint cell or the human eye recognition acuity) (Chamberlain and Meitner 2013; Fisher 1992, 1993, 1994, 1995, 1996; Ogburn 2006). Herein, given our primary focus on the maritime environment and its historical interpretation, our aim is to integrate specific weather conditions in visibility analyses. Indeed, in the case of seascapes, we consider weather as the main factor affecting visibility radius, whereas the presence of other obstacles (e.g., the presence of vegetation) is often not significant or—at least—reduced. As such, our research questions are (1) is it possible to include the effects of the atmospheric aerosols, whose composition is clearly affected by weather, in a model for visibility analyses?; (2) can this model be transformed into an algorithm for the efficient and reliable computation of a visibility basin (i.e., of the intervisibility radius between two objects)?; and (3) would the results inferred from the application of this algorithm match with data derived from historical written sources and on-the-ground visual observations?

A comparison of the various problems connected to the use of visibility tools has already been conducted by Cerezo Andreo, Pérez-Reverte Mañas, and Mauro (2016), employing as a case study the visibility of the seascape around the Cabo de Palos area (near Murcia, Spain). That study clearly emphasized the necessity, for both geometric and GIS methods, to be tuned with information provided by pilot books and on-the-ground observations. Since it reflected a preliminary stage of the research, however, it did not suggest any kind of adjustment. Herein, we are going to revisit this topic and the area in greater depth (see below) and propose a possible solution to this problem, introducing a model for computing visibility at sea. The model we propose is based on Mie's (1908) theory of scattering for light radiation in the presence of an aerosol. It can be applied with sufficient reliability to the study of historical seascapes in the last six millennia, with the assumption that climate has not changed dramatically from 4050 BCE onward (Agouridis 1997; Finné et al. 2011; Morton 2001; Murray 1987).[1] Like every mathematical model, this construction needs an input of several physical parameters. These can either be derived from complementary models of the underlying aerosol or be estimated from proper physical measurements. We will follow the latter possibility and use the measurements of the Aerosol Optical Thickness (AOT) to derive such parameters. We then apply this method to a case study to show how it could be employed (see the methods section below).[2] We have also chosen to examine another key point in seafaring (i.e., Mount Etna), and to consider its visibility from the Ionian coast of Calabria (between Capo Spartivento, in the municipality of Palizzi, and Capo dell'Armi, in the municipality of Motta San Giovanni). Even if Mount Etna does not represent in itself an archeological feature, its historical importance as a reference point across time (both for long-distance seafarers and local fishermen) clearly emerges from a careful reading of nautical sources. In our results we show the application of this method and then compare them with on-the-ground visual observations (documented by photographs), GIS results and ethnographic surveys (i.e., interviews with local fishermen from the selected area aimed at recording when Mount Etna is, or is not, directly visible from Capo Spartivento and Capo dell'Armi).[3] Finally, we emphasize how—despite having already been used in other scientific contexts with some success (Smirnov et al. 2002, 2009; Wilson, Milton, and Nield 2015)—the potential of AOT-based estimates in archeology has not been explored so far. Lastly, we highlight how their application to visibility studies in archeology constitutes a novel and useful approach which could facilitate a more trustworthy reconstruction of nautical historical contexts. At a broader level, we suggest that the application of AOT-based estimates could be used to infer other meaningful information, such as the reconstruction of both land and sea routes over different time frames, evaluating the visibility of natural or artificial features over the year, and/or better understanding how the landscape and seascapes were perceived.

Background to visibility

In archeological and historical studies, the analysis of visibility dates back long before the commercialization of GIS software, having developed as a result of the impact of positivism in the social sciences during the 1950s and 1960s. From the outset, visibility studies were conducted either by calculating the visual basin (Schüle 1970) or by evaluating intervisibility between different settlements thanks to personal observations supported by comparable cartography (Fraser 1983; Renfrew 1979). Interestingly, one of the first visibility studies in archeology was applied to the maritime context (Schüle 1970). In that paper, the author calculated the visual basin by applying the geometric formula, his aim being to identify from what areas of the Mediterranean it was possible to catch sight of land.[4]

Although a number of techniques were developed through the 1970s and 1980s, large-scale visibility analyses became common only in the early 1990s when GIS began to be more regularly used in archeological studies. In fact, GIS provides archeologists with standard functions for calculating line-of-sight products starting from digital models of surface topography. In such a way, it makes it possible to computationally derive intervisibility between two points in both vector and raster systems and to consequently picture what is (or is not) visible from a named source point.

From a technical point of view, GIS software is set with an algorithm which is able to establish visible areas by tracing imaginary lines on a Digital Terrain Model (DTM). These lines originate from the observation point and arrive at every point of the DTM which constitutes the first topographical obstacle in each direction, both in vertical and horizontal ways. The result of the application of this algorithm is an image which shows an area theoretically corresponding to the surface that could be seen from the place chosen as the observation point. Therefore, GIS analyses reveal hypothetical visible areas. Even if their usefulness is undeniable in archeological studies, as it is fairly known, GIS results do not reflect the complexity of reality, as they do not consider all the factors that could have an impact on visibility (Chapman 2006; Gillings and Wheatley 2001). Additionally, as Fisher (1992) demonstrated, the visibility tool in different GIS reports give different results, for they depend on the root-mean-squared error (RMSE) associated with the used Digital Elevation Model (DEM), a quantity that is in general not known *a priori* and thus has to be estimated or modeled. To achieve this, simulated error with prescribed mean and variance can be added to the DEM data, giving rise to fuzzy viewsheds (Fisher 1992, 1993, 1994, 1998) or the probable viewsheds (in which an estimate of DEM uncertainty is used; see Llobera 2007).

Currently, in GIS computation, it is possible to integrate atmospheric conditions by introducing the Refractivity Coefficient (Rrefr). This is done with the aim of modeling the refraction caused by the particles suspended in the atmosphere. However, this is a parameter of the model that has to be tuned by taking into account the sky conditions, the pressure/elevation, and the hour of the day.[5] The choice of a default value for this coefficient can produce misleading results, especially considering the arbitrary nature of sky conditions, and it may benefit from the use of experimental data from the site for it to be properly tuned. Taking a fixed value from a meteorological table, when considering standard conditions, gives back just a reference value. Furthermore, it is necessary to underline that this value could be applied only to locations with a height fluctuating between 40 and 100 m, so it cannot always be employed: for example, the average height of an observer located on a ship's deck is usually 4 m (Zamora Merchán 2012), being below 40 m, whereas on other occasions, it could be the case that either the observer or the observed point lay at more than 100 m. In this spirit, our proposal in "Justification

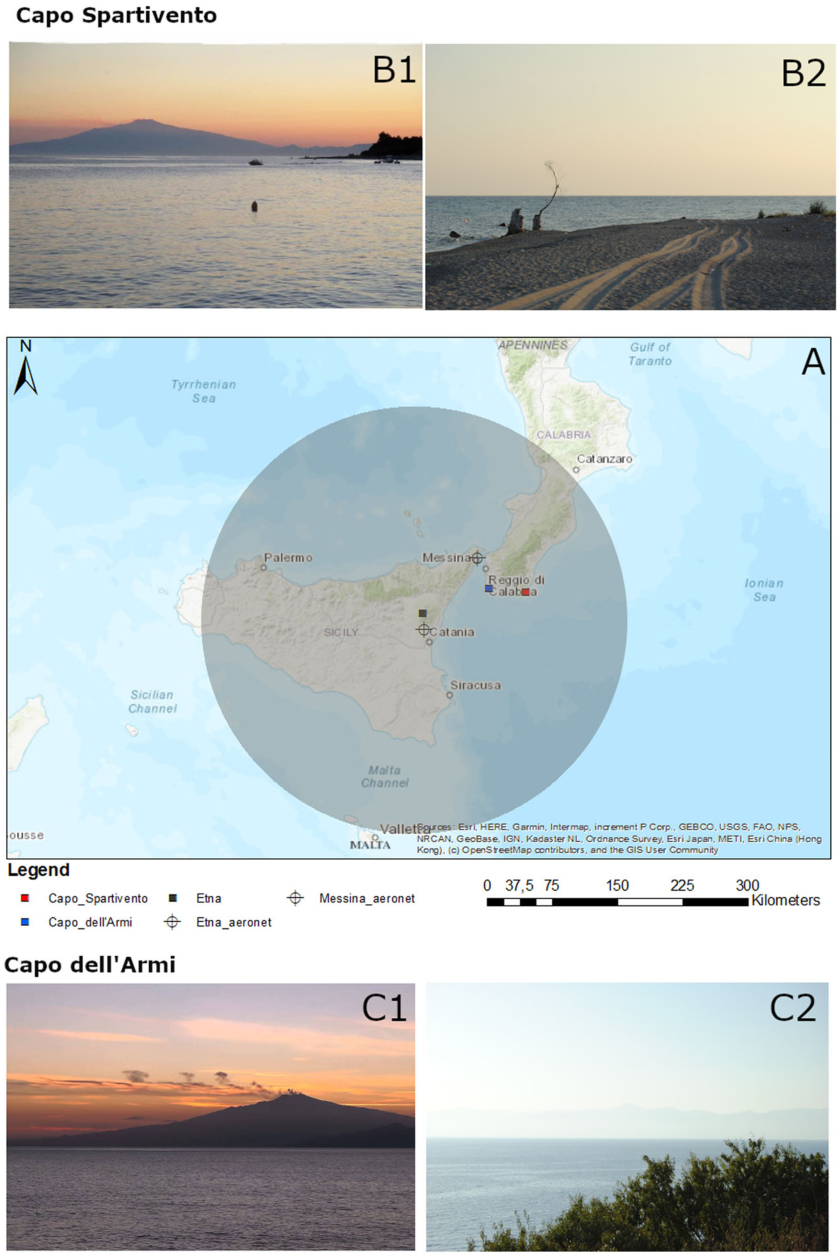

Figure 1. (A) The two selected points (Capo dell'Armi, blue square, and Capo Spartivento, red square), Mount Etna (black square), the two observatories (Messina and Etna Aeronet), and the volcano's radius of visibility computed by applying the geometric method (it corresponds to the area included within the gray circle). (B1) Photo taken from Palizzi (37° 55′ 04.1″ N–15°59′ 30.3″ E), the municipality to which Capo Spartivento belongs, when Mistral blows (28/07/2017). Photograph by G. Caserta. (B2) Photo taken from Palizzi (37° 55′ 03.1″ N–15° 59′ 09.7″ E), the municipality to which Capo Spartivento belongs, when the Sirocco blows (30/08/2017). Mount Etna is not visible, but in other atmospheric conditions it should have appeared just in the middle of the photo. (C1) Photo taken from Lazzaro di Motta San Giovanni (37° 57′ 15.7″ N–15° 40′ 44.8″ E) when the Mistral blows. (C2) Photo taken from Lazzaro di Motta San Giovanni (37° 57′ 15.7″ N–15°40′ 44.8″ E) when the Sirocco blows (30/08/2017). Mount Etna is not visible, but in other atmospheric conditions it should have appeared on the left.

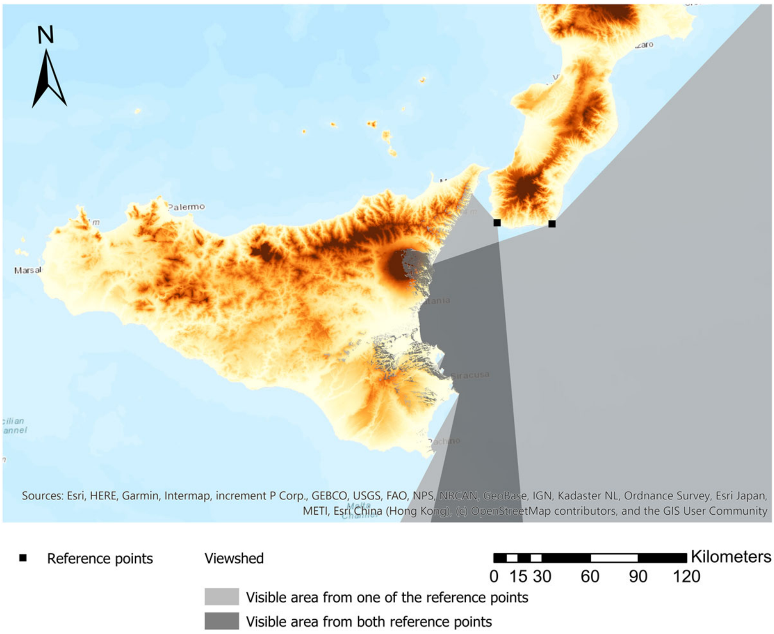

Figure 2. Viewshed analysis with ArcGis10.7. DEM from <https://land.copernicus.eu/> [20/11/2019].

of the Experimental Data employed" deals with the tuning of the model coefficients from actual instrumental data and thus refrains from the use of standard, and possibly deceptive, reference values.

Case study: Visibility of Mount Etna from the Ionian coast of Calabria

Area description

In order to show how atmospheric aerosols could be used to compute the visibility of a selected area (for the description, see the "Method" section), we have decided to analyze the visibility of Mount Etna (Sicily, Italy) from the Ionian coast of Calabria (Italy): in particular, we examine how variations in atmospheric conditions affect the visibility of the volcano in the area between Capo Spartivento (37° 55′ N–16° 04′ E, in the municipality of Palizzi) and Capo dell'Armi (37° 57′ N–15° 41′ E, in the municipality of Motta San Giovanni) (Figure 1A). The area we chose to analyze belongs to the Reggio Calabria district, and it presents homogeneous atmospheric conditions; these conditions can drastically change as one rounds one of the two headlands. Capo Spartivento and Capo dell'Armi were the two most important nautical reference points of this area,[6] they are still highly considered by local fishermen, and currently house active lighthouses.[7]

Capo Spartivento (literally "the promontory where winds change"), known from the period of Greek colonization as Heracleium, is considered as the southernmost promontory of the Italian Peninsula.[8] Once past this headland, the Ionian coast turns toward the west, and Mount Etna finally becomes visible on the horizon.[9]

The western boundary of the area corresponds to Capo dell'Armi, which is the southern entry point to the Strait of Messina. This headland is also known as Capo "Leucopetra," which literally means "white rock" and—as its toponym reveals—it is a fundamental nautical landmark: since antiquity, it has frequently been taken as a reference point owing to its easily recognizable color.[10]

As the observed point, we chose Mount Etna. Besides being the tallest active volcano in Europe, Mount Etna, due to its location on the east coast of Sicily (precisely between the Strait of Messina and the Strait of Sicily), is a fundamental reference point in the passage between the eastern and the western Mediterranean.[11] It is currently 3340 m high, though its height can vary slightly due to summit eruptions. Applying the geometric method, its theoretical visibility range is equal to 206.35 Km (Figure 1A). The distance between the highest point of Mount Etna and Capo dell'Armi headland as the crow flies is 64.22 km, whereas Capo Spartivento is located at a distance of 95.85 km. Therefore, from a theoretical point of view, the volcano should largely be visible from both headlands, as also GIS analysis confirms (Figure 2). Notwithstanding, this is not the case: as local seafarers testified, there are several days in which the volcano is not visible, even when the sky appears to be clear (e.g., see Figure 1B2 and C2).

Justification

Justification of the selected object

The choice of a natural landmark was mainly due to the goal of this study. After having studied the advantages and disadvantages of the different methods in a previous stage (Cerezo Andreo, Pérez-Reverte Mañas, and Mauro 2016), our aim was to propose an alternative solution, which could also take into account the effects of the atmospheric aerosols on visibility. Since our objective was to test the actual compliance between theoretical results and what can actually be observed (that is, to check if the obtained data reflected on-the-ground visual observations and if they matched with variations in atmospheric conditions), we needed to select a diachronic object, that is, something unchanging over time. It should have been something which could and can still be observed, having roughly the same height through the centuries.

For these reasons, we found that the choice of an archeological object would not have been significant since none of the archeological sites preserved in this area have kept their original height.[12] This would not have allowed us to potentially validate obtained data with ethnological surveys and on-the-ground visual observations. Therefore, Mount Etna and its radius of visibility were the best choice to act as an experimental countercheck of our initial proposal. As a matter of fact, the volcano presented all the requirements that we were looking for: historic importance as nautical landmarks for both long- and short-distance routes, and the possibility it offered to conduct on-the-ground visual observations and ethnographic surveys.

Numerous mentions of Mount Etna in literary sources, pilot charts, and nautical handbooks over time testify to its importance in seafaring (*Mediterranean Pilot* 1978, 7 and 229). Already in the Aeneid, Virgil makes reference to the volcano for identifying the location of a harbor (3.570–571) or for determining the point of the Ionian coast starting from which the mount could be seen (3.551–557).[13] In medieval and modern nautical charts, Mount Etna is often represented, being one of the few features *infra-terram* to appear.[14] As nautical charts usually only provide information that is essential to seafarers (e.g., depth along the coastline, safe harbors and natural hazards), the inclusion of Mount Etna should be read in light of its significance in directing sea routes.

Justification of the experimental data employed

An implicit assumption for the use of experimental data collected from the AERONET network (i.e., for the use of *any* experimental data collected in the very near present for this task) is that the composition of the aerosols, and more generally the climatic variation, in the last six thousand years do not differ drastically from the time of the measurements. To substantiate this claim, we can refer both to classical observations of the wind patterns (Morton 2001; Murray 1987; Pryor 1995) matching historical sources and to data collected in the field, both in the review by Finné et al. (2011) covering the issue of climate during the past six millennia in the geographical zone from E13° to E50° and from N46° to N20°. According to them, we can describe the current climate as being "characterized by hot, dry summers and mild, wet winters, mainly controlled by the region's position between the subtropical highs and the northerly westerlies" (i.e., the so-called "Mediterranean" climate). This trail seems to have been the one in place throughout the latter part of the Holocene, thus following the dryer and cooler period, close to the last Ice age, and the wetter first half; for details, we refer once again to Section 3.2.2 in Finné et al. (2011). Thus, we assumed that the AOT data could be taken as a reference and that they were sufficiently reliable when applied to seascape analysis referred to periods following 4050 BCE. We then verify the effectiveness of the AOT data and their adherence to ethnological comparison, thus affirming the strength of our model. Further visibility analyses, or applications to other archeological contexts, will only need to apply it by using the supposed height of a building and the Koschmieder equation with the relative extinction coefficient value.

Method

In this paper, we use a mathematical model from the field of Aerosol Optics whose predictions could be used to compute the limits of the visibility range. Such a model describes the scattering and absorption of light caused by the atmospheric aerosol (i.e., the physical phenomenon causing visibility with respect to the limit case of the absence of atmosphere). It is well known that the possibility of seeing an object is related to the contrast of the object itself with its background. The greater the relative difference in light intensity of the two is, the easier it is to perceive them as two separate objects. Therefore, if we individuate the distance from the target as x, the relative difference between the light intensity of the background at a distance x as $I_B(x)$ and the light intensity of the target as $I(x)$, then the visual contrast is given by:

$$V(x) = \frac{I_B(x) - I(x)}{I_B(x)}, V(0) = 1, \tag{1}$$

from which we recover the visibility range by stating the Koschmieder Equation (1925):

$$x_{range}(\lambda) = \frac{|ln(V_{con})|}{\kappa_{ext}(\lambda)} = \frac{|ln(0.02)|}{\kappa_{ext}(\lambda)}, \qquad (2)$$

in which $V_{con} = 0.02$ represents the threshold contrast of the observer at the wavelength λ, i.e., the sensibility of an observer to a change in the contrast of an object with respect to the background, while $\kappa_{ext}(\lambda)$ is the extinction coefficient (i.e., the coefficient representing the effect of both the atmospheric conditions and the aerosol on the light). In simpler terms, it means the smallest difference in visual contrast (see Equation (1)) that the human eye is able to perceive. If the change is smaller than that, then the object is indistinguishable from the background. For the choice of the value $V_{con} = 0.02$ we refer to Campbell and Green (1965). Clearly, other choices are possible (e.g., this value can be tuned according to the different physiological characteristics of the observer such as limited eyesight that would produce a reduced threshold sensibility). Moreover, even if in his original work Koschmieder suggested a threshold contrast of 0.02, some have suggested that the more appropriate value should be taken from $V_{con} = 0.01$ to $V_{con} = 0.2$ (World Meteorological Organization 2010) and, in meteorology, it is usually assumed to be $V_{con} = 0.05$. For obtaining the visual range by Equation (2) we also need to estimate the extinction coefficient $\kappa_{ext}(\lambda)$ that can be obtained by essentially following one of two options: either a theoretical derivation from some assumptions on the chemical and physical properties of the aerosol (i.e., by applying the theory developed by Mie (1908) [see the Supplementary Data for further details on this aspect]), or by retrieving its value from experimental data. Even if the first approach seems appealing for its possible generality, this is not the case in our settings, as we also pointed out that for the refractivity coefficient tabulated, standard or reference values can be highly misleading. Moreover, as observed in Smirnov et al. (2002), the measurements made in the coastal zone of inland seas, which represent our focus, show that the optical conditions are greatly influenced by continental aerosols and the time of the year. Therefore, guessing the composition of the aerosol for the quantification of the various constants entering the computation can return results that are as wrong as the use of the refractivity coefficient. To overcome this difficulty, instrumental optical data can be a useful tool for estimating $\kappa_{ext}(\lambda)$. To this end, we have considered the use of the data from the AERONET project (O'Neill et al. 2003; Smirnov et al. 2009), which computes, at a variety of locations around the world, also with maritime missions, the Aerosol Optical Thickness (AOT) $\tau(\lambda)$ that is related to the extinction coefficient in (2) by

$$\tau(\lambda) = \int_0^h \kappa_{ext}(\lambda, z)dz, \qquad (3)$$

where h is the top of the atmosphere (usually 65 km) and z is the vertical axis along which the altitude is measured. By reasonably supposing (see once again Kokhanovsky 2008) that the aerosol is contained in a column of about 1 km above ground in which the variation with the altitude of $\kappa_{ext}(\lambda, z)$ is negligible, i.e., $\kappa_{ext}(\lambda, z) \approx \kappa_{ext}(\lambda)$, we can retrieve the value of the extinction coefficients simply as the value $\tau(\lambda)$ of the (AOT):

$$\tau(\lambda) = \int_0^h \kappa_{ext}(\lambda, z)dz \approx \int_0^1 \kappa_{ext}(\lambda)dz = \kappa_{ext}(\lambda) \cdot 1 \rightarrow \kappa_{ext}(\lambda) \approx \tau(\lambda). \qquad (4)$$

Note that since the integral in Equation (4) is computed along a vertical line, we are further assuming that: (1) the extinction coefficients measured on a horizontal or on a vertical path are equal; and (2) the instrumental measure of the AOT values is not influenced by the vertical extinction.

To uphold this assumption, we base the estimate in our example by including only the AERONET Level 2 data (i.e., the cloud-free data), otherwise the presence of clouds would invalidate both Assumptions 1 and 2—clearly the AOT measured through a cloudbank would be highly misleading. Moreover, these data also automatically include a correction for the Rayleigh scattering, allowing us to use the standard version of Equation (2), without needing to account for eventual correction to enforce Assumption 1 (Eck et al. 1999; Holben et al. 1998). We emphasize that in the model we are using high values of the AOT parameter that suggest a high concentration of particles in the aerosols causing higher scattering of light and resulting in lower visibility. The other issue that has to be taken into account for our intended usage is the possible presence of pollutants in the current composition of the aerosols. This implies that whenever we choose an observation point we have to avoid highly industrialized areas and metropolises since this is clearly a situation that is not diachronic (see, for example, the difference in the result we obtain by using two different observatories in "Results").

Application of this technique for the inverse and much more complex purpose of estimating the AOT from the visibility range, in the context of correction of satellite data, has been addressed (e.g., in Wilson, Milton, and Nield 2015). Conversely, we are addressing the problem in the easier and more reliable case. Below, we validate the mathematical predictions obtained with this model by applying it to a concrete case study: the visibility of Mount Etna from the Ionian coast of Calabria. Specifically, we apply Koschmieder's formula (2) on the relative Level 2.0 AOD data, where pre- and post-field calibration have been applied; moreover, the effect of clouds has been automatically cleared and manually inspected (Giles et al. 2019). Therefore, we simply compute the division in (2) by using for the denominator the approximation in (4) (i.e., all the computation is reduced in reading the values for the AOT from the relative AERONET tables and perform the division in Equation (2) with the selected value of the contrast); see below for a description of the dataset.

Application of AOT to the case study

To apply this method to the selected case study, we consider the use of the data from the nearest available observatories of the AERONET network—the ETNA (37° 36′ 50.39″ N–15° 1′ 8.4″ E, 736 m) and the MESSINA AERONET observatories (38° 11′ 49.20″ N–15° 34′ 1.2″ E, 15 m) (Figure 1A)—for computing the visibility range. The data from these observatories comes as a CSV file in which several quantities are reported (see <https://aeronet.gsfc.nasa.gov/new_web/data_description_AOD_V2.html> for details on all the available measurements [28/11/2019]); however, we use both the monthly weighted average of the AOT measurements and the daily averages for these months. We emphasize that the distribution of the data points in the dataset varies throughout the months and the hour of the day. For what concerns the internal months (i.e., excluding January and November, which have been thus excluded from the

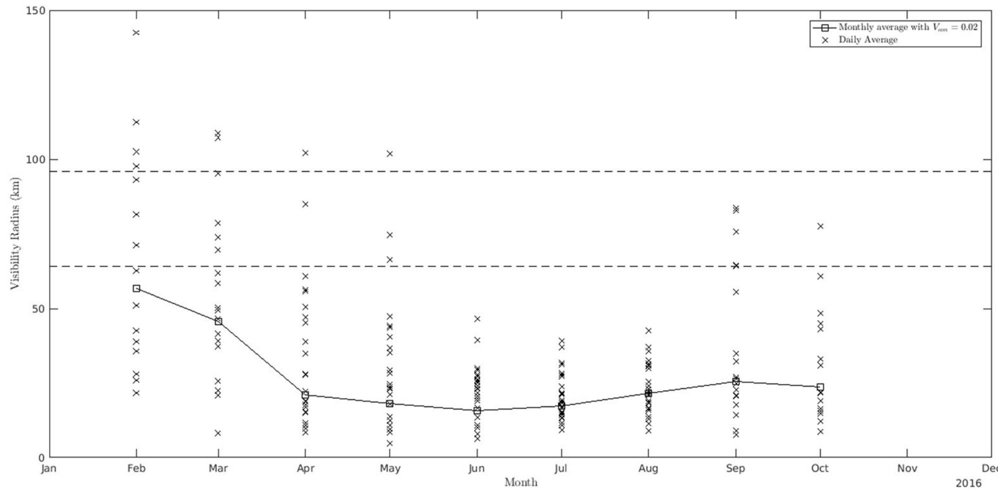

Figure 3. Visibility range for the ETNA observatory (km) computed by applying the Koschmieder formula (4) with the contrast thresholds of 0.02. The data line corresponding to the square marker is the monthly average—i.e., these data are calculated using the weighted daily average for each day to compute the monthly average. On the other hand, the data corresponding to the x marker are the daily averages for each month.

analysis) the data sampling covers most days, whereas the number of measurements per day is of about 20 data points. The solid line in Figure 3 represents the month average for a fixed value of the threshold contrast $V_{con} = 0.02$ together with the daily averages for each month represented as crosses disposed on a vertical line. As we have discussed in "Method", the choice of $V_{con} = 0.02$ is not unique, thus in Figure 4 we consider also the case in which we select $V_{con} = 0.05$ as suggested in (World Meteorological Organization 2010); see the description of the results. All the computations have been performed according to the "Method" section.

Results

The results of this procedure are presented in Figures 3 and 4. By means of the weighted averages, we observe the expected variations on at least two timescales.

- On the coarser one, we have seasonal variations: these can be explained in light of the wind patterns in the zone, as further discussed and analyzed below.
- On the finer one, we can look at the daily averages. These show us that even if on a seasonal/monthly average Etna is not visible, there are still days on which this is not true; see also Figure 3.

The other prominent effect requiring attention is related to the spatial position of the observatories. As we suggested above, their collation in the urbanscape does affect the relative order of magnitude and of the reliability of the results. Specifically, consider that whereas the ETNA observatory sits in a scarcely urbanized area, the one in Messina is indeed inside a city with a noticeably different level of pollutants; so, we expect that the data coming from the latter must be less accurate for describing the

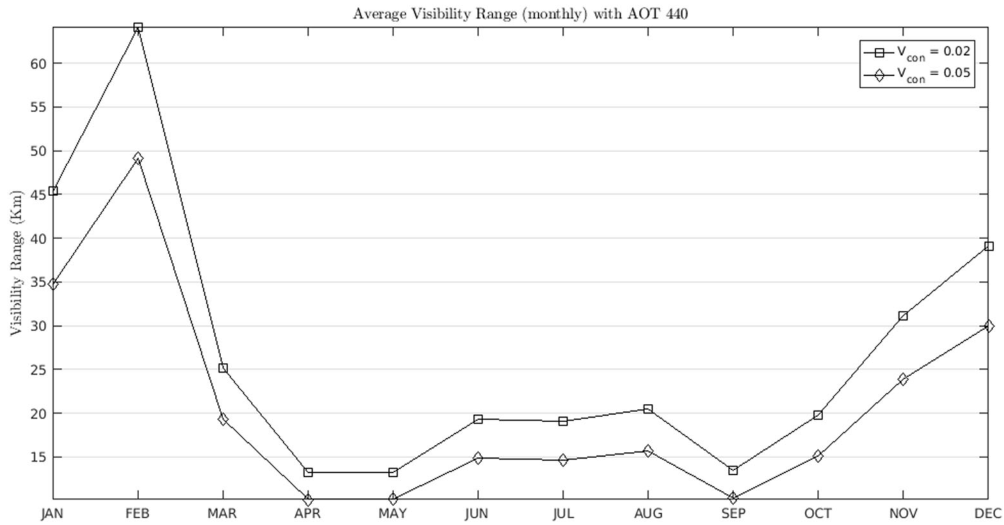

Figure 4. Visibility range for the MESSINA observatory computed by applying the Koschmieder formula (4) with the two contrast thresholds of 0.02 and 0.05.

visibility in a historical context. And, indeed, this explains why the visibility values obtained from the MESSINA Observatory are lower in absolute value than the one obtained for the ETNA Observatory. Nevertheless, this does not alter the identification of the seasonal pattern we have highlighted (i.e., we can use a cross-referencing approach by means of data from the two observatories for inferring the existence of a general pattern that is then not caused by the presence of pollutants, or by the happenstance of the location of the observatories).

These results strengthen our belief that if only a theoretical analysis is used for estimating either the correct aerosol composition or the derivation of the extinction coefficient, or even the refractivity coefficient for the correction of simple geometric or GIS methods, this can lead to erroneous or inaccurate results. For example, in the viewshed analysis reported in Figure 2, we have computed the GIS visibility analysis using the same observation points used for our analysis based on the AOT and reported in Figure 1. The resulting visibility range tells us that Mt. Etna is always included (i.e., that it is always visible from Capo Spartivento and Capo dell'Armi). On the other hand, our analysis is able to delineate the complex behavior of the visibility phenomenon with the presence of seasonal and monthly patterns quite clearly (see again the results given in Figures 3 and 4).

Lastly, we propose an *a posteriori* explanation of the seasonal behavior shown in our results in terms of wind pattern; a general observation regarding the visibility that, clearly, one could have also made *a priori*, but that would have been very difficult to transform into a quantitative approach.

Discussion

The AOT-based results demonstrate the seasonal nuances of visibility at sea in the study area. Contra to the optimal distances generated by geometric and GIS measurements,

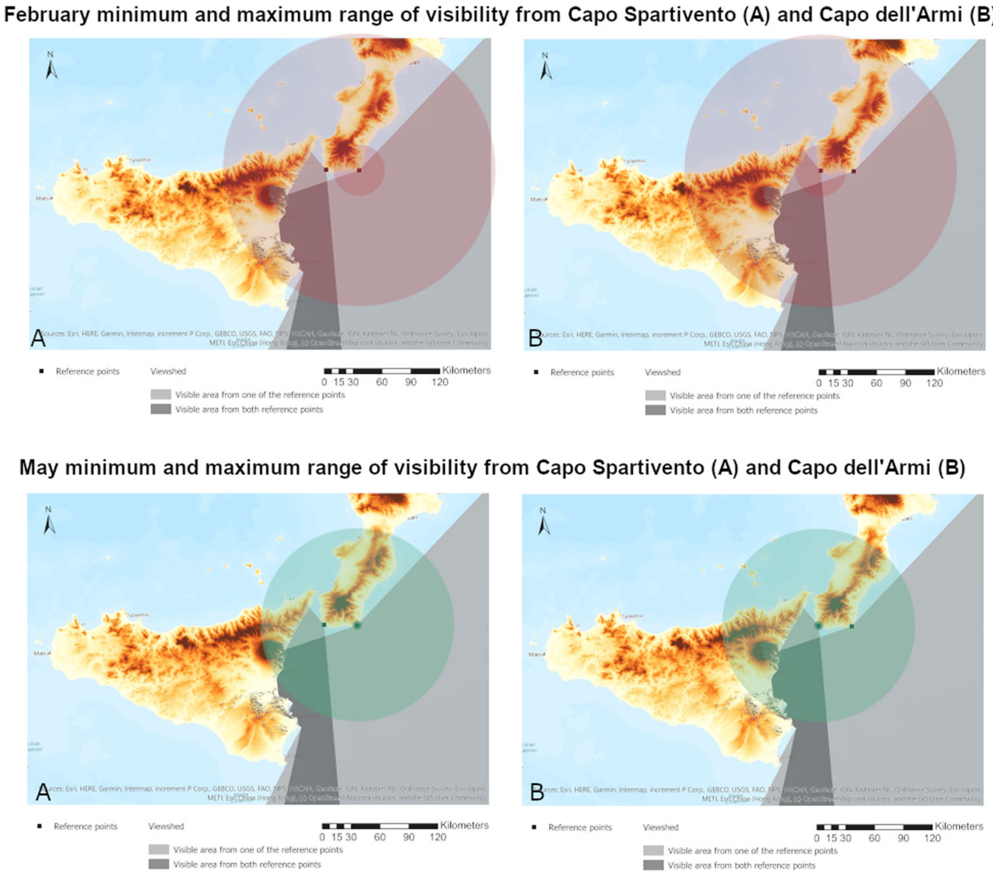

Figure 5. Map showing the differences in viewshed between GIS computation (in gray) and AOT-based results (Figures 3 and 4). Comparisons made for the months of February and May, showing the minimum and maximum range of visibility (in red and green) from Capo Spartivento (A) and Capo dell'Armi (B). As it can be seen, in days with low visibility (small circles), AOT-based results clearly show as Mount Etna is not visible neither from Capo Spartivento nor from Capo dell'Armi.

the AOT-based measurements clearly show that, despite its height, Etna is not always visible year-round, due to seasonal differences in atmospheric conditions (Figure 5). This is further supported by nautical and written sources, which stress how the volcano's visibility changes according to different atmospheric conditions, occasionally mentioning the fact that it was not always (clearly) visible. References to variations in the visibility of Mount Etna due to different atmospheric conditions can be found in Strabo (6.2.8),[15] Ibn Jubayr (in Broadhurst 2008, 29),[16] Bell (1830: vol. II, 504),[17] Waring (1843, 104, and 221–223),[18] and Leith Adams (1847, 240).[19] These documents are verified by data collected through ethnographic surveys and on-the-ground visual observations.

We compare in light of local wind, even if theoretically Mount Etna should be chiefly visible from the Ionian coast of Calabria and Eastern coast of Sicily, written sources disclose that there are days on which either the volcano is no longer visible from the coast

(Waring 1843, 221–223) or its outline's contrast is not perfectly clear. The sea-travel during which Waring states to have been unable to catch sight of the volcano took place in March, and from the account he left (i.e., "at noon a south-easterly breeze sprang up" and "the atmosphere was so thick and hazy"), we can suppose that the "breeze" he was describing was actually the Sirocco. The Sirocco is a wind coming from Africa that blows from S-SE along the Ionian Calabrian coast. It tends to occur year-round without a favored month[20]; however, strong gale-force Siroccos (between 5 and 8 Bft) are most common during the spring (i.e., particularly in March, April, and May) and in September (*Mediterranean Pilot* 1978, 48). The Sirocco picks up dust and sand from the desert, so that visibility becomes very poor and is extraordinarily reduced when it blows (*Mediterranean Pilot* 1978, 17; Waring 1843, 221–223) (i.e., the extinction cross-section increases, thus reducing the denominator in Equation (4)). Furthermore, along the eastern Calabrian and Sicilian coasts, this wind is sometimes accompanied by rainfalls named "Blood" or "Red rains," which are precipitations where red sand is mixed with falling rain.[21] This situation tends to lower the visibility in this area, as we have photographically documented (Figure 1B2 and C2), and as local fishermen testified during the interviews. In Figures 3 and 4, this local behavior is suggested by the reduction of the average visibility range recorded between the months of April and September. These observations and data are again based on measurements that are taken at the present time (i.e., with the current [average] level of dust transported by the Sirocco). Some recent studies (e.g., Evan et al. 2016; Goudie and Middleton 2001; Husar 2004; Mulitza et al. 2010) infer that there was an increasing amount of sand transported during these events in the 1980s, followed by a decrease in the 1990s and 2000s (Conte, Colacino, and Piervitali 1996; Evan et al. 2016); thus, we cannot exclude that, in principle, similar phenomena of very large-scale variability have not occurred at other times in history. Nevertheless, as observed in Smirnov et al. (1998, 28090) the "volume size distributions are qualitatively consistent with optical depth data and show relative stability between each dust event." This means that in principle, we could use the time series from Conte, Colacino, and Piervitali (1996) and Evan et al. (2016), and the AERONET data to estimate how the situation could deteriorate (or ameliorate) with differing quantities of dust. It is sufficient to consider the value of AOT measured today at a time in which the quantity of dust coincides with the one observed from the time series. We emphasize that from the point of view of the seasonal variations we have observed, this behavior of the Saharan dust on a larger time scale alters only the magnitude of the mean visibility in the summer, leaving the presence of a seasonal variability unchanged.

In almost every other condition, Mount Etna is visible from the selected area, especially when the movement of air removes mist and sand, and maintains clear visibility. This situation has been photographically documented, and is confirmed by both historical written sources and the survey we conducted with local fishermen (Figure 1B1 and C1). In particular, the conditions of optimal visibility can be noticed when northerly winds blow. Winds from the north are characteristically strong, cold, and dry, and they usually bring bright and clear weather (*Mediterranean Pilot* 1978, 16). Between Capo Spartivento and Capo dell'Armi, the northern wind is perceived as blowing from the Straits of Messina and it is for this reason that it is commonly known among local fishermen as "u ventu du canali" (literally meaning "the wind which blows from the

Strait"). Though it occurs in all seasons, it is more common in winter (*Mediterranean Pilot* 1978, 16), and it is probably for this reason that Leith Adams (1847, 240), describing Mount Etna's conditions of optimal visibility, states that they are reached in "fine weather," identifying with this expression "clear winter days." Both Figures 3 and 4, which show the results of the AOT data, prove that there is a high level of visibility during winter time, which we know from the fishermen's interviews and from nautical sources, and which can be attributed to the high presence of northern winds blowing toward the Straits of Messina in this period. Therefore, even in this case, although at first glance data deriving from the AOT method might seem contrary to what common sense would suggest, they are perfectly plausible in this geographical context, where winters are windy and rainfalls infrequent.

Conclusions and future developments

In this paper we have sought to briefly outline major limitations of both geometric and GIS methods when they are employed to compute visibility. In particular, we have emphasized that, when studying a seascape, it is necessary to attune results with information provided by nautical sources and on-the-ground visual observations. However, these kind of data (i.e., nautical sources, ethnographic surveys, and on-the-ground visual observations) are not always easily accessible and they often necessitate extra costs in terms of time and economic and human and resources. Therefore, to have a clear picture of what could (or could not) be seen, we have proposed a solution for its explanation and practical application that would allow a visibility study to match nautical sources and on-the-ground visual observations without the need to forcibly resort to the latter. The method that we have applied has been borrowed from Aerosol Optics and it is grounded in a mathematical model of light scattering. As we explained in the Introduction, it has already been successfully applied to other fields, but its employment in historical and archeological studies constitutes a novelty.

In this paper, we have maintained that the AOT data can be used to better understand how visibility at sea was affected by changes in atmospheric conditions, and we have used the case of Mount Etna's visibility from the Ionian coast of Calabria to showcase its application and validate data coming from nautical sources, ethnographic surveys, and on-the-ground observations. We consider that, once its validity has been demonstrated, this method can be employed in different contexts and in different ways, according to the aim of the study. We would like to note that, even if in this case we selected a geological feature for the reasons explained above, in the future, new studies could apply it directly to compute the visibility of archeological features (e.g., towers, lighthouses, religious buildings strategically located in prominent places).

In our opinion, the use of AOT data presents fewer critical issues and it allows us to overstep simple theoretical models, depicting a reference plan as close as we can get to reality, as we have sought to demonstrate by comparing various kinds of data coming from this area. In particular, it overlaps data coming from nautical and written sources, ethnographic surveys, and on-the-ground visual observations. For this reason, and thanks to its reduced costs and easy application, we consider that this technique could be very useful, if applied to archeological studies, to suggest a possible reconstruction of nautical historical contexts. Moreover, within its advantages, AOT data are entirely open access: this means that anyone can easily download and use them by browsing through the NASA Web site (<https://aeronet.gsfc.nasa.gov/> [28/11/2019]).

Although it would be desirable to make more use of this kind of analysis in island and coastal archeology to better decode specific seascapes, it is also necessary to underline the biases that it presents. First, it should be remarked that the application of AOT data could not currently be extended to every geographical area, since it is subject to the presence—or absence—of available observatories taking measures of the AOT (like the AERONET network). Even so, as it stands, the non-availability of AOT data derived from the AERONET network is limited only to Siberia, Greenland, and Antarctic, where the 870 observatories covering most of the geographical spectrum currently exist. Secondly, when observatories are chosen, those located near highly industrialized areas and larger cities should be avoided (or their records should be tuned with the selection of other observatories located in rural areas), since they clearly reflect a situation that cannot be applied diachronically to preindustrial periods.

Because we believe that these instrumental data could help to revolutionize and accelerate historical seascapes analysis, we want to make two further suggestions that could make the implementation of the AOT method in archeological studies more effective: to use AOT measurements for validating the data on a coastal zone of reference and to use instrumental data for obtaining the extinction coefficients directly in the zone of interests by giving the possibility of inserting them directly into a GIS analysis software. As part of these efforts, we are currently developing an extension (add-in) for ArcGIS for producing a new viewshed tool that can easily use AOT data, which should help others in analyzing a wide array of coastal areas that were important for seafaring groups to use in navigation.

Notes

1. Especially in comparison to larger glacial-interglacial changes (Wanner et al. 2008). Despite that, it is necessary to underline that some climate fluctuations did occur within the Holocene (Di Rita et al. 2018, and references therein) and that they should probably be connected to Holocene cold events over the North Atlantic (Brayshaw, Rambeau, and Smith 2011; Sabatier et al. 2012).
2. Analogous considerations were independently reached by Brugge (2017), who has preliminarily presented a different model based on (not open access) measures obtained with a transmissometer instead than with a solarimeter, as our proposal does.
3. With “direct visibility” we refer to the possibility of recognizing Mount Etna’s outline against the background. This concept differs from “indirect visibility,” which refers to the possibility of identifying features (in this case: peak covered with snow, sheets of lava, smoke) that can be used to assume the presence of an object (in this case, Mount Etna).
4. $d \approx 3.57\sqrt{h}$. It is necessary to stress that this formula does not consider any correction due to imperfect roundness of the Earth (Arnaud 1993), nor the effect of atmospheric refraction. Currently, several GIS software (e.g., QGIS, ArcGIS, and GRASS GIS) incorporate corrections for the curvature of the Earth and for the refractivity coefficient of light (see below).
5. The default value for the Rrefr in ArcGis is 0.13, which is considered suitable to represent standard atmospheric pressure during daytime conditions with a limpid sky for locations whose height ranges between 40 and 100 m (Yoeli 1985, 93). To factor different

atmospheric conditions on visibility, other Rrefr values can be used (comprised between 0.0 and 1.0).

6. E.g., see *Portulano del mar Mediterráneo o vero rottero alla spagnola*, 16th century, Biblioteca Nacional de España, Mss/1072, 37; *Derrotero general del Mediterráneo Tomo II*, 1858, Biblioteca Nacional de España, **GMM/2660,** 137–138; *Derrotero y navegación del Mar Mediterráneo*, 18th century, Biblioteca Nacional de España, **Mss/9023, 34**–35.
7. Capo Spartivento: lighthouse built in 1952. ARLHS ITA-043; EF-3384; Admiralty E1782; NGA 10580. See also *Mediterranean Pilot* (1978, 246). Capo dell'Armi: lighthouse built in 1933. ARLHS ITA-014; EF-3380; Admiralty E1780; NGA 9744. See also *Mediterranean Pilot* (1978, 245).
8. Strab. 4.1.7: "Then comes Heracleium, which is the last cape of Italy and inclines towards the south."
9. See note 8 and *Mediterranean Pilot* (1978, 246). On easily recognizable headlands due to their color, see Mauro (2019, 127) and (Morton 2001, 189–190).
10. Strab. 6.1.7: "As one sails from Rhegium towards the east, and at a distance of fifty stadia, one comes to Cape Leucopetra—so called from its color—in which, it is said, the Apennine Mountain terminates." See also *Mediterranean Pilot* (1978, 245).
11. *Mediterranean Pilot* (1978, 229).
12. Theoretical attempts aimed at reconstructing the original height of ancient freestanding towers based on their diameters could be found in Thielemans (1982) and Young (1956). According to them, the height of a freestanding tower was roughly between 2 and 2 ½ times its outer diameter; however, these attempts are based on chronologically and topographically limited studies and, in our opinion, cannot be universally extended.
13. Interestingly, he states that Etna could be seen after the Scylaceum's shore, a point probably corresponding to Capo Spartivento. Cf. Strab. 6.2.8 ("Etna dominates especially the seaboard in the region of the Strait").
14. E.g. *Liber de Existencia Riveriarum et Forma Maris Nostri Mediterranei*, *c.* 1200 AD (see Mons Gibellus, 1.2222); *Viaggio dalla Sicilia a Madrid*, 1579, Biblioteca Nazionale Vittorio Emanuele III di Napoli, MS XII.D.43; *New Chart of the Mediterranean Sea,* 1797, by W. Heather; *Carta Esférica que comprende las Islas de Sicilia y Malta construida en la Dirección Hidrográfica*, 1835, Biblioteca Nacional de España, MA00090138.
15. Strabo states that the crater is visible *on windless days*.
16. Ibn Jobayr specifies that the volcano could be seen for more than 100 miles exclusively in "fine weather." His estimation is then more restricted than what the geometric method should imply (see "Area Description").
17. Bell states: "From Malta Etna is not visible but *in the most favourable conditions*."
18. In his letters from Malta and Sicily, Waring states (1843, 104): "I am surprised to find that Mount Etna, though at a distance of about one hundred and ten miles, is distinctly visible from the island *in clear weather*." On the other hand, during a sea-travel that he carried out on March from Augusta towards Catania, he writes (1843, 222–223): "*The atmosphere was so thick and hazy*, that Mount Etna, the grand object of interest, was entirely obscured nearly the whole of the day."
19. "Sicily, *in clear winter days*, is visible from Malta, from whence the eruptions of Etna have been seen." (Leith Adams 1847, 240).
20. A Sirocco's duration may be as short as half a day or may last several days.
21. Even Theophr. *Signs*, 20, 36 describes the Sirocco as a dry wind bringing rain and clouds.

Acknowledgements

We would like to thank Stefano Corradini and Stefano Pignatti for their efforts in establishing and maintaining ETNA and MESSINA observatories used in this investigation. Furthermore, we have been fortunate to receive, at an earlier stage of this project, Marcos Llobera's helpful comments and input; his suggestions have been greatly appreciated and contributed in a significant way to the improvement of this manuscript. We would like to express our appreciation to the Editor, Scott M. Fitzpatrick, and the referees for their thorough reading of the paper, helpful commentaries and suggestions, and for pointing out relevant typos and mistakes; and to Rocio Pérez-Campaña (UCM) for helping us with the viewshed analysis. Lastly, our gratitude goes to all the local fishermen from Lazzaro di Motta San Giovanni (Antonino Arecchio and his daughter Giada Arecchio) and Palizzi ("Siso" Polimeno, Domenico and Franco Rosato) who have actively contributed to this study.

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