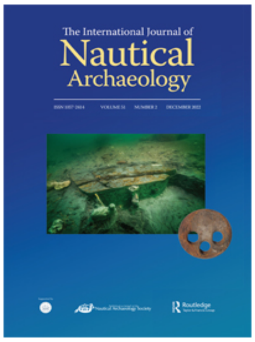


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# Windward Sailing in Antiquity: The Elephant in the Room

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**ABSTRACT**
The study of windward sailing in antiquity is subject to discord, misunderstandings and misinterpretations. This paper attempts to broaden the understanding of windward sailing by revisiting the theoretical basis of windward sailing, performing a critical review of previous works, reconstructing historic passages with new methods to re-evaluate them being considered as unfavourable wind passages, and considering the ancient mariner's limits of windward sailing. It is suggested that ancient ships had less windward capability than commonly perceived, and that the limits of the ancient mariners were more restrictive than ships' technological windward capabilities, highlighting the necessity to consider practical windward capabilities.

**KEYWORDS**
Windward sailing; Mediterranean; square sail; seamanship; antiquity; experimental archaeology

## La navegación en contra del viento en la antigüedad: El elefante en la habitación

**RESUMEN**
El estudio de la navegación en contra del viento en la antigüedad es objeto de discordia, malos entendidos e interpretaciones. Este artículo intenta ampliar la comprensión de la navegación en contra del viento, a través de la revisión de sus bases teóricas y la evaluación crítica de los trabajos previos, reconstruyendo pasajes históricos a la luz de nuevos métodos para reevaluar su carácter de pasajes de viento desfavorable, y mediante la reconsideración de los límites de los marineros de la antigüedad para navegar en contra del viento. Se ha sugerido que las embarcaciones de la antigüedad tenían capacidades menores de ceñir al viento de lo que comúnmente se percibe, y que los limites de los marineros de la antigüedad eran más restrictivos que las capacidades tecnológicas de las embarcaciones para navegar en contra del viento, lo que resalta la necesidad de considerar las capacidades prácticas de navegar en contra del viento.

**PALABRAS CLAVE**
Navegación en contra del viento (ceñir al viento); Mediterráneo; vela cuadra; marinería; Antigüedad; arqueología experimental

## 被视而不见的古代迎风航行

摘要
针对古代迎风航行的研究存在着分歧、误解和曲解的现象。本文试图以重新审视迎风航行的理论基础，对以往工作进行批判性回顾，用新方法重建历史航道以便重新评估为何其被认为是不利的风向航道，并通过考量古代水手对迎风航行的能力来拓宽对迎风航行的认识。此研究表明，古代船舶的迎风能力比普遍认为的要小，而古代水手的能力则比船舶的技术迎风能力更为局限，这就突出了需要考虑实际迎风能力的必要性。

关键词
迎风航行; 地中海; 方帆; 航海术; 古代; 实验考古学

## 被視而不見的古代迎風航行

摘要
針對古代迎風航行的研究存在著分歧、誤解和曲解的現象。本文試圖以重新審視迎風航行的理論基礎，對以往工作進行批判性回顧，用新方法重建歷史航道以便重新評估為何其被認為是不利的風向航道，並將古代水手的迎風航行能力納入考量來擴展對迎風航行的認識。此研究表明，古代船舶的迎風能力比普遍認為的要小，而古代水手的能力則比船舶的技術迎風能力更為局限，這就突出了需要考量實際迎風能力的必要性。

關鍵詞
迎風航行; 地中海; 方帆; 航海術; 古代; 實驗考古學

## الإبحار في مُواجهة الرياح في العصور القديمة: الفيل في الغرفة

المُستخلص
تخضع دراسة الإبحار في مُواجهة الرياح في العصور القديمة للخلاف وسوء الفهم وللتفسير الخاطئ. ولذلك فهذه المقالة ما هي إلا محاولة لتوسيع فهم الإبحار في مُواجهة الرياح وذلك من خلال إعادة النظر في الأساس النظري للإبحار في مُواجهة الرياح، وإجراء مراجعة انتقادية للأعمال السابقة إلي جانب القيام بإعادة بناء الممرات التاريخية بأساليب جديدة وذلك لإعادة تقييمها باعتبارها ممرات رياح غير مواتية، آخذين بعين الأعتبار حدود البحار القديم في الإبحار في مُواجهة الرياح. ويُقترح أن السُفن القديمة كانت لديها قدرة أقل في مُواجهة الرياح مما يُتصور عادةً وأن حدود البحارة القدامى كانت أكثر تقييدًا من القدرات التكنولوجية للسُفن في مُواجهة الرياح مُسلطاً الضوء علي ضرورة النظر في القدرات العملية لمُواجهة الرياح.

الكلمات الدلالية
الإبحار في مُواجهة الرياح;
البحر الأبيض المتوسط;
الشراع المربع;
فن الملاحة البحرية;
العصور القديمة;
علم الآثار التجريبي

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## Introduction

A central attribute of maritime links is wind dependency, and the most frequently discussed aspect of wind-driven sailing is that of ships' windward sailing capability. The light in which ancient sailing ships are perceived by scholars ranges from that of strictly downwind ships, very much at the mercy of the wind, to that of vessels capable of sailing in all directions, albeit with slower effective speeds to windward due to tacking. The complex physics of sailing and the intricacies of seamanship, with their plethora of associated terms, are alien to many, including scholars. Consequently, misinterpretations, misperceptions and confusion regarding windward sailing capabilities in antiquity have crept into scholarly works. Moreover, apparent lack of critical examination of the few sources commonly cited in regard to windward sailing is of concern, as is the potential introduction of unrealistic inputs for creation of new knowledge, such as network analyses.

This paper examines ship performance evidence related to vessels from the 5th century BCE up to the 4th century CE, but the conclusions are cautiously applied to the broader period of the Mediterranean single loose-footed square sail, also known as the brailed sail. This period extends from the end of the Late Bronze Age to the Islamic period – about 1300 BCE to 700 CE ('the period', hereafter). The authors are aware of the experimental archaeology activities in Roskilde, Denmark, in regard to reconstructed Viking-Age ships and the resulting data from these activities. However, as these fall outside the geographical and temporal scope of the present work, any comparisons between Mediterranean and Viking ships are carefully selected.

The authors claim that: (a) A critical review of the frequently cited sources on windward sailing is required in order to clarify the subject, suggesting that period ships possessed less windward abilities than commonly accepted; (b) The theoretical basis of windward sailing can scope the envelope of ships' windward capabilities and this basis should complement and support experimental sailings of replica (reconstructed) ships; and (c) Any windward performance that period ships may have possessed was overshadowed and further limited by the mariners' practical windward sailing abilities, and it was the practical windward sailing abilities that determined maritime mobility. It is suggested that the human factors in windward sailing should be realistically considered.

The study comprises a background consisting of a short primer on relevant sailing terms and definitions, and a review of scholarly literature concerning windward sailing, identifying the sources used for windward sailing data and the subsequent adoption and application of the data. The following discussion includes three sections: (a) A critical review of commonly used methods to determine windward capabilities, identifying views that have been accepted in subsequent research; (b) A revisit to the theoretical basis of windward sailing, closely following the well-organized work by Palmer (2009b); (c) Examining the relationship between ships' windward capabilities and the mariners' abilities and limitations to gain understanding of the relative weights of these factors affecting practical windward sailing.

## Background

### *Sailing Terms and Definitions*

The relevant sailing terms and definitions used in this paper are summarized in Table 1. The movement of a sailing ship in relation to the wind is defined as vectors (speed and direction) and angles between them. The vectors and the relationship between them are shown in Figure 1 as a generic example, not implying a particular ship or particular sea conditions. The 'heading' of a ship is the direction in which the bow i.e., the longitudinal axis of the ship, is pointing. The 'true wind' (TW) is that measured by a stationary observer. The 'apparent wind' (AW) is the speed and direction of the wind that is felt underway by the ship and its sail. The AW is the sum of the vectors of the true wind and the ship's movement. The difference between the 'apparent wind angle' (AWA) and the 'true wind angle' (TWA) is a function of (a) the ratio between the ship's speed and the 'true wind speed' (TWS) and (b) the TWA. When the ship is moving forward, the apparent wind will be ahead (closer to the bow) than the true wind.

When sailing close-hauled, the sideways drift of the ship, known as 'leeway', becomes more significant, and together with possible sea current, it defines the vector of movement of the ship over the ground, termed 'course made good'. The windward performance of the ship is the angle that can be achieved between the true wind and the course made good. This may be in the order of 20° to 30° greater than the heading maintained to the apparent wind (AWA). Figure 1 illustrates a ship sailing westward, heading 60° to the apparent wind (AWA), but when accounting for leeway of 10° and the difference of 12.5° between the true and apparent wind, the effective windward angle to the true wind, in this generic example, is only 82.5°. This exemplifies the typical magnitude of the difference between the heading to the apparent wind and the actual course made good to the true wind by period ships. Actual headings maintained to the apparent wind may differ, and values of leeway may change significantly depending on hull and sail efficiencies and on sea conditions.

**Table 1.** Glossary of sailing terms.

| | |
|---|---|
| Apparent wind | The wind felt or measured on board a moving ship. It is the sum of the vector of the true wind and of vector of the wind induced by the ship's movement. Also known as 'relative' wind. |
| Apparent wind angle (AWA) | The angle between the ship's bow and the apparent wind. |
| Apparent wind speed (AWS) | The speed of the apparent wind, usually stated in knots or metres/second. |
| Beating | The process of advancing to windward by alternating between port and starboard tacks which are conducted close-hauled at the limit of the no-sail sector. The ability to tack to windward assumes a ship capable of making good a course of less than 90° to the true wind. |
| Boat Speed / Ship Speed | The speed of the ship through the water without accounting for currents or drift. Usually stated in knots. |
| Close-hauled | See Points of Sail. |
| Course made good (CMG) | The direction of the ship's movement, including the effects of leeway and sea currents. It is usually stated in relation to the true wind, but may also be stated in relation to the compass. |
| Downwind | See Points of Sail. |
| Heading | The direction pointed to by the ship's bow (longitudinal axis). |
| Helmsman's Leeway | A reduction, relative to the wind, of the theoretical close-hauled course made good, due to the small steering errors of the helmsman. Steering a few degrees too high to the wind induces loss to leeward as does steering a few degrees too low off the wind. |
| Knot | A measure of speed. 1 knot (kn) = 1 nautical mile (NM) per hour. 1 NM = 1852 m (6080 feet). |
| Layline | A layline is the course at which is possible to sail directly to a destination at the limit of the no-sail sector without tacking. |
| Leeway | The sideways drift of the ship induced to provide lateral lift to the hull needed to counter the sideways force of the wind on the sail. |
| No Sail Sector | The sector upwind defining the angles to the wind which the ship is not capable of sailing. |
| Passage | A sailing journey from one port to another without intermediate stops. |
| Passage VMG (Velocity Made Good) | The overall speed of the passage calculated from the duration and the shortest possible sailing distance for the passage. |
| Point | A 1/32 division of the compass, 11.25°. The expression: 'seven points to the wind' indicates sailing at 78.75° to the wind. |
| Points of Sail | Description of the sailing angles in relation to the wind and the associated rig trim:<br>Close-hauled – sailing as close to the wind as possible.<br>Close reach – wind forward of the beam, but not as acute as close-hauled.<br>Beam reach – wind on the beam (i.e., sailing ~90° to the apparent wind).<br>Broad reach – wind on the rear quarter (i.e., ~135° to the apparent wind).<br>Run – sailing before a wind on the stern. |
| Reaching | See Points of Sail. |
| Running | See Points of Sail. |
| Tack | The side from which the wind blows and for which the sails are trimmed. In a port tack the wind is from the left and for a starboard tack the wind is from the right. |
| Tacking | (1) The process of advancing to windward by alternating between port and starboard tacks which are conducted close-hauled at the limit of the no-sail sector. The ability to tack to windward assumes a ship capable of making good a course of less than 90° to the true wind (also known as beating, see above).<br>(2) The manoeuvre of turning from one tack to the other by turning the ship's bow through the wind. |
| Tacking angle | The angle between the courses (GPS plots) of alternating tacks. Course made good to the true wind is half the tacking angle. |
| True wind | The movement of the air as would be measured or felt by a stationary observer. |
| True wind angle (TWA) | The angle between the ship's bow and the true wind. |
| True wind speed (TWS) | The speed of the true wind, usually stated in knots or metres/second. |
| Velocity made good (VMG) | See Passage VMG or Windward VMG. |
| Wearing | The manoeuvre of turning between tacks by turning the ship's stern through the wind. Also known as gybing. |
| Wind veering and backing | Backing = wind direction is changing anti-clockwise; veering = wind direction is changing clockwise. |
| Windward VMG | The effective velocity of the ship achieved in the direction of the wind by tacking. |

A vessel propelled by sails alone cannot sail closer to the wind than a certain angle. This defines the 'no-sail sector', shown in Figure 2. A ship with better windward sailing performance will exhibit a smaller no-sail sector. 'Points of sail' define the typical sailing attitudes to the wind with the related rig trims. 'Close-hauled' describes sailing as close to the wind as possible. 'Reaching' describes sailing with the wind, generally to one side from a less acute angle to the wind than close-hauled, and up to the wind on the rear quarter. Sub-definitions of reaching include: 'close reach' for wind forward of the beam but not close-hauled; 'beam reach' for wind on the beam; and 'broad reach' for wind on the rear quarter. 'Running' is sailing with the wind astern.

If a ship sails a course made good of less than 90° to the wind, then it possesses a degree of windward sailing capability. The smaller the angle to the wind, the better is the windward capability. As a ship cannot sail closer to the wind than its no-sail sector, windward sailing is achieved by beating (tacking), i.e., sailing alternately close-hauled on the port and starboard tacks. There are two possible manoeuvres to turn from tack to tack. Modern sailing vessels are able to tack, i.e., turn their bow through the wind, as were multi-masted vessels in the later 'age-of-sail'. Single-masted square-sail vessels in the period of this work would have likely only attempted to tack through the wind in optimal conditions. In very light wind (slow speed) or under high wind and sea conditions, period ships would have preferred the safety of changed tacks with the wind to the stern by 'wearing'. Wearing from tack to tack involves some loss of gained windward ground, reducing the effectiveness of windward sailing. The term 'layline' describes a case where sailing a close-hauled course, on the limit of the no-sail sector, leads to the destination (or intermediate target).

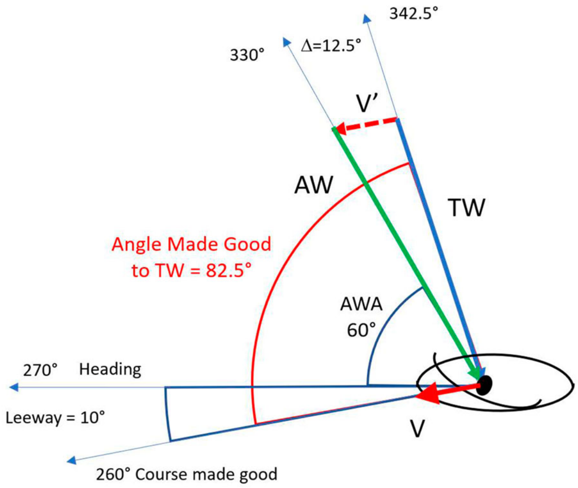


**Figure 1.** The vectors of a generic ship and the wind associated with sailing. The ship maintains a heading of 60° to the apparent wind (AWA), AW is the apparent wind vector. Assuming a boat-speed to true wind speed ratio of 25% the apparent wind will be 12.5° ahead of the true wind, TW is the true wind vector. V and V' are the ship velocity, and leeway is shown as 10°. The resulting angle made good to the true wind is 82.5° in this example (D. Gal).

A primary measure of windward sailing is the course a ship can make good to the true wind. An additional measure of windward sailing is 'windward velocity made good' (windward VMG), which is the effective vector of the ship's sailing velocity in the direction of the wind. Instantaneous windward VMG is a function of the ship's close-hauled velocity through the water and the angle of this velocity to the true wind. It is stressed that wind speed is a factor in the velocity of the ship, and therefore windward VMG is a function of both the ships' technological capabilities and of the wind speed. It is calculated as the cosine of the angle made good to the true wind multiplied by the 'boat speed' (BS) (Figure 3). A ship capable of only 90° to the wind will have windward VMG of 0 knots, that is, no windward capability. Similarly, a ship only capable of sailing more than 90° to the wind, will have a negative windward VMG, and in fact will be losing ground to windward.

VMG is used in an additional, and quite separate context of 'passage VMG', which is the overall speed of a sailing passage, and it should not be confused with windward VMG. It is simply an expression of the shortest possible sailing distance for the passage divided by the actual duration stated in knots (nautical miles/hour). This VMG term will usually be used in the context of a passage, i.e., non-stop sailing to a destination, but it may also be used in context with a voyage consisting of several passages with time spent waiting in port between passages. Windward VMG and passage VMG may only coincide in the singular case in which the passage destination is in the eye of wind throughout the sailing passage.

## Literature Review

Scholarly works concerned with windward sailing can be generally classified into four types: (a) Works of experimental archaeology that have measured windward performance of replica ships; (b) Works that indirectly calculated or derived windward sailing performance of period ships; (c) Works that referred to and used windward sailing performance in a qualitative context of suggesting aspects of seafaring in face of contrary winds; and (d) Works that referred to and used windward sailing performance as an input in quantitative studies such as network analyses to create new knowledge. The following chronological review of scholarly works concerned with windward sailing, describes the origins and flow of knowledge.

In Smith's dissertation (1880, p. 215), the author suggested that ancient ships could sail to windward at seven points to the wind (i.e., 78.75°), based on merchantmen of the 'age-of-sail' (16th–19th centuries). Smith suggested that 'it was less than eight points but more than six'. As will be shown, this legacy from the age of sail is quite prevalent among scholars.

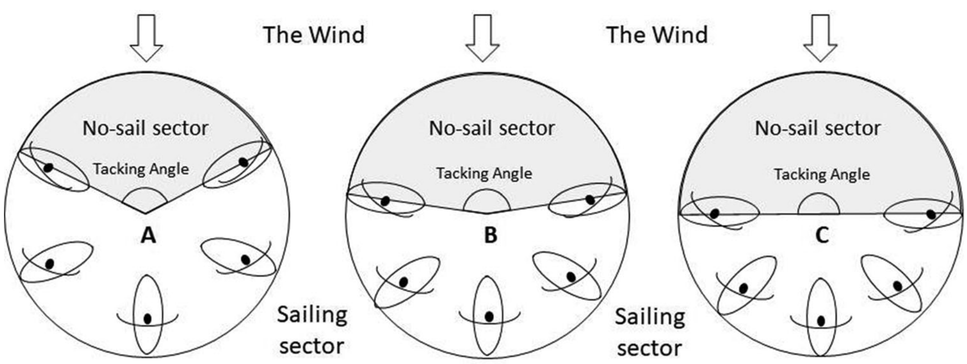


**Figure 2.** Schematic drawing illustrating the no-sail sector for three generic ships: (A) a ship with moderate windward capability; (B) a ship with marginal windward capability; and (C) a ship with no windward capability able to make good no more than 90° to the true wind. (D. Gal).

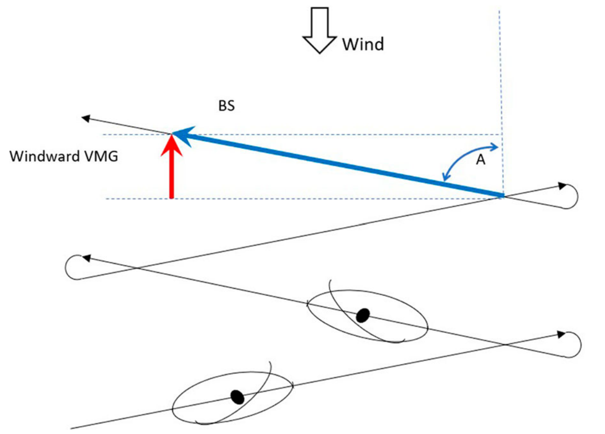


**Figure 3.** Schematic illustration of a ship beating to windward. The illustration indicates wearing (gybing) from tack to tack. The blue arrow is the boat speed (BS) vector representing the velocity of the ship's movement through the water. The red arrow is the windward velocity made good (VMG) vector. The angle of the ship's vector to the true wind is shown as 'A'. Windward VMG is the cosine of A multiplied by the boat speed (D. Gal).

Casson, in 'Speed Under Sail of Ancient Ships' (1951, pp. 137–138), asserted, without a reference, that in the case of unfavourable winds – 'those that blow from some point ahead', vessels were forced to tack at 80° to the wind. In Casson's later work, *Ships and Seamanship in the Ancient World* (1995, pp. 273–274), he cited Smith (1880, p. 215) and suggested that the ancient mariner could sail close-hauled, but 'he could probably point no closer to the wind than seven points'. Casson chose to derive windward sailing speed from the examination of historic passage records (1995, pp. 281–291), considering average passage speed, based on duration and distance (i.e., passage VMG), and whether the passage could be classified as lying with or contrary to the prevailing winds. Casson concluded: 'It would seem therefore that ancient vessels averaged from less than 2 to 2½ knots against the wind' (1995, p. 291). Casson's work can be classified as one calculating or deriving windward sailing performance.

Meijer, in *A History of Seafaring in the Classical World* (1986, p. 224) suggested that the shape of sail and the rig prevented ships from sailing sharply into the wind, 'probably no more than seven points into the wind'. This assertion follows the 'seven points' school of thought.

Pryor, in his seminal work 'Geography, Technology, and War' (1988, p. 33) discussed the windward abilities of ships including those of Roman square-rigged merchantmen. Pryor cited Casson (Casson, 1971, p. 274) suggesting that the Roman vessels could not point higher than seven points to the wind. He offered an estimation that medieval round ships in practice could have maintained a course of 90° to the wind 'only with great difficulty' (1988, p. 35).

Katzev summarized the sailings of the *Kyrenia II* replica ship in 'An Analysis of the Experimental Voyages of Kyrenia II' (1990) in the form of a narration of the ship's logbook. A key, and frequently cited, statement in this work is:

> Later in the afternoon the wind shifted to the south-west. During a two-hour period around sunset *Kyrenia II* sailed 50° to 60° off the eye of a 2 Beaufort wind, close-hauled, port tack, making over 2 knots speed – evidence of her ability to sail effectively into the wind. (Katzev, 1990, p. 254)

In a summary statement, he mentioned that the ship had proven, among other attributes, 'a remarkable ability to sail into the wind' (1990, p. 255). Casson (1995, p. 464), cited Katzev's report of 'advancing at 2 knots into the wind, 50° to 60° off its direction' as additional evidence in support of his previous derivation of windward sailing speed of 2 knots (1995, pp. 281–291). Katzev's work is classified as one of experimental archaeology, creating windward sailing performance knowledge.

Tilley, in 'Sailing to Windward in the Ancient Mediterranean '(1994), expressed his own judgement that it is inconceivable that ships did not have enough windward capability 'to keep a ship from wrecking on a lee shore' (1994, p. 310). He stressed that despite having limited windward capability, 'seamen have hardly ever made long passages under sail upwind', and would have preferred to wait for a route and season giving winds abaft the beam. Tilley did not cite any source in regard to windward sailing.

Roberts in his article, 'An Explanation of Ancient Windward Sailing', responding to Tilley (1994), concluded that although ships had the ability to sail close to the wind, 'it would be a misconception to think that this led to the regular undertaking of long courses to windward involving much tacking' (1995, p. 312). He suggested that it was vital to be able to sail closer to the wind than a beam reach, and he mentioned the necessity of a windward course of '35° nearer a prevailing wind direction than a beam course' (1995, p. 312). Roberts conducted an extensive discussion on the lateral forces affecting directional balance and control of sailing ships, but did not derive or calculate windward sailing capabilities, other than his expression of a need to possess some windward capability.

Cariolou (1997) in 'Kyrenia II: The Return from Cyprus to Greece of the Replica of a Hellenic Merchant Ship', provided a comprehensive report on the return voyage of the replica from Cyprus to Greece. In this work there is a reference to a single instance of windward sailing capability. He described the 'best close-hauled angle achieved' of 51° to the true wind direction in 23 knots of wind and at 20° of heel, and estimated the course made good as 60° to the true wind' (1997, p. 92). This work classifies as one that has created windward sailing performance knowledge.

Wachsmann, in *Seagoing Ships and Seamanship in the Late Bronze Age Levant* (1998, pp. 254–255), suggested that 'When winds were contrary, crews either bided their time at anchor or took to their oars'. Despite this statement, Wachsmann provided a brief review of the discord of scholars about windward sailing, citing Casson (1971, p. 274) who considered the square sail capable of only seven points off the wind, and Katzev (1990, p. 254) who described sailing 50° to 60° off the direction of the wind.

McGrail in *Boats of the World, from the Stone Age to Medieval Times* (2004, p. 94), asserted 'These conclusions are most readily formulated in relation to sailing ships which could make good a track at right angles to the wind', i.e., 90° to the true wind. This was in the context of a discussion regarding ancient Mediterranean routes.

'Windward Sailing Capabilities of Ancient Vessels' (Palmer, 2009b) provided the theoretical physical basis for calculating the windward capabilities of ancient ships as a function of the efficiency of the hull and the rig. This is known as the 'beta theorem', and the work is clearly classified as one that calculated windward sailing capabilities. In his article, Palmer also provided evidence on the efficiency of a range of traditional hulls and sails, giving scholarship an applicable toolkit to calculate the windward capabilities of period ships. Based on the data used and the calculation results, Palmer suggested that:

> The ability to sail to windward was much less widespread than is commonly assumed […] It appears that while ancient sailing vessels may have been capable of modest windward performance in moderate conditions and with a freshly-cleaned hull, this capability quickly disappeared as the hull became fouled and/or the wind and sea conditions deteriorated. (Palmer, 2009b, p. 314)

This work has been cited by several scholars, but only with reference to secondary evidence, such as the effects of waves, biological fouling, the ratio of ship speed to wind speed, or to Palmer's general assessment of windward sailing (Arcenas, 2021; Cvikel et al., 2014; Gal et al., 2021; Leidwanger, 2013, 2020; Perttola, 2022; Whitewright, 2011). The authors of the current paper are unaware of any previous scholarly work that has cited or used the core of Palmer's work, i.e., the beta theorem, to calculate windward sailing capability.

Palmer, in 'Measuring Performance Under Sail' (2009a), described the complexity of obtaining accurate performance measurements in a sailing environment when using on-board instruments. He also showed that when close-hauled a typical difference of 30° might exist between heading to the apparent wind and the course made good (2009a, pp. 25–26, 30). He suggested that recorded GPS tracks provide accurate data regarding tacking angles and windward VMG (2009a, p. 30). Palmer provided sample GPS tracks from Viking-Age and other traditional or reconstructed ships, and therefore this work may be considered as one providing windward sailing knowledge based on experimental archaeology measurements.

Whitewright's work, entitled 'The Potential Performance of Ancient Mediterranean Sailing Rigs' (2011), is of particular interest as it is cited by numerous scholars, some creating additional knowledge on the basis of windward performance suggested by Whitewright (Alberti, 2018; Davey, 2015; Leidwanger, 2013, 2020; Perttola, 2022; Safadi & Sturt, 2019). Whitewright provided a range of potential windward performance parameters and laid down a structured argument to derive the suggestion that the Mediterranean square-sail vessel 'could attain a maximum of 2 knots VMG in suitable conditions on close-hauled courses' (2011, p. 9). Despite Whitewright's somewhat optimistic assessment of windward capabilities at the top of his range, he clearly expressed a reservation as to practical windward sailing ability:

> In the majority of cases it is unlikely that such performance would have encouraged ancient mariners to set out on a voyage against the wind. The practice of waiting for a suitable wind-direction must have been the norm. These figures simply illustrate that the ancient Mediterranean square-sail was not as one-directional (downwind) as is often thought. Ground could be made to windward if the conditions were right and circumstance required it. (Whitewright, 2011, p. 10)

The authors of the current paper are also not aware of any scholarly work noting this caveat of Whitewright, while many works have chosen the figures provided by Whitewright as the norm for windward sailing.

Leidwanger (2013) was an early adopter of GIS cost surface analysis in a quantitative work investigating potential maritime connectivity. The work, entitled 'Modelling Distance with Time in Ancient Mediterranean Seafaring', describes the quantitative model, which employed windward sailing performance suggested by Cariolou (1997), Casson (1995), Katzev (1990) and Whitewright (2011). Subsequently, the limit of the no-sail sector in Leidwanger's model was set at 60° to the true wind. This work is classified as one producing new knowledge based on inputs of windward sailing performance of period ships.

In 'The Ancient Sailing Season', Beresford (2013), devoted a section to windward sailing. He echoed Roberts (1995) and Tilley's (1994) assertion that period ships must have had some windward capability to prevent being swept on a lee shore. While citing Katzev (1990), he mentioned 'even when it came to sailing against the wind, the abilities of the brailed square sail have been consistently underrated'. However, in his conclusion to this section, he suggested:

> The procedure of beating against a headwind has always proven to be such a time-consuming and uncomfortable process that it was avoided whenever possible. Instead, ships' captains usually preferred to remain in port until they could take the advantage of wind blowing from a more favorable direction. (Beresford, 2013, p. 166)

Davey, in 'Sailing to Windward in Roman Times: The Spritsail Legacy' (2015), discussed the role of the spritsail in providing better stability and steering performance of Roman ships sailing close-hauled. He supported his conclusions with a broad discussion of windward sailing capabilities, rejecting the 'seven points off the wind' suggestions of Smith (1880) and Meijer (1986), preferring to follow the figures suggested by Whitewright (2011) for windward capabilities, and Cariolou's (1997) report on sailing *Kyrenia II*.

Warnking (2016), in 'Roman Trade Routes in the Mediterranean Sea', modelled routes and durations of several Roman maritime links, using sailing regatta weather-routing software. He considered using Whitewright's (2011, p. 10) windward conclusions, but found them optimistic. Therefore, Warnking (2016, pp. 59–65) suggested a hypothetical set of windward performance with no-sailing sector limit of 75° instead of the 60° to 65°, suggested by Whitewright. Warnking ran a set of comparative runs for both sets of windward performance data and found that his hypothetical set of performance parameters provided results that are closer to the historical record. This work may be classified as one producing new knowledge based on the input of windward sailing performance.

In 'TRANSIT: A GIS Toolbox for Estimating the Duration of Ancient Sail–Powered Navigation', Alberti (2018) provided a set of tools to measure expected ancient sailing duration, using GIS cost surface analysis. As input to the simulations, Alberti used Whitewright's (2011, p. 10) windward conclusions placing the no-sail sector limit at 67°. Alberti's work is classified as one creating new knowledge based on the input of windward sailing performance data.

Safadi and Sturt (2019), in a quantitative study entitled 'The Warped Sea of Sailing: Maritime Topographies of Space and Time for the Bronze Age Eastern Mediterranean', a unique method of presenting measures of maritime space by distorting cartesian scales, i.e., faster links appear to be closer. They employed GIS cost surface analysis combining sailing performance data from Whitewright (2011) and Katzev (1990). This work is consequently classified as one creating new knowledge based on the input of windward performance of period ships.

*Roman Seas: A Maritime Archaeology of Eastern Mediterranean Economies* is the title of a monumental work by Leidwanger (2020). The work demonstrated the quantitative use of sailing times generated by GIS cost surface analysis flowing as an input to subsequent network analysis of maritime space. This composite modelling required inputs of sailing performance, including windward performance. He applied windward data obtained from Whitewright (2011), Katzev (1990) and Cariolou (1997).

Perttola's article (2022) entitled 'Digital Navigator on the Seas of the Selden Map of China', is a quantitative study investigating historic sailing mobility in the South China Sea. Perttola used GIS cost surface analysis adapted to use dynamic wind data in a series of simulations (i.e., data changes during the simulated sailing passage). For sailing performance of ships, he followed Whitewright (2011) and set the limit of the no-sail sector at 67°. This work may be classified as one creating knowledge based on inputs of windward sailing performance.

## Discussion

### *A Critical Assessment of the Methods Used by Frequently Quoted Sources*

The review of previous scholarly works and their citations above reveals that scholars frequently refer to the works by Casson (1995), Katzev (1990), Cariolou (1997) and Whitewright (2011) as sources for windward sailing capabilities. The methods employed in these works are critically examined below, to assess the reasonability of the windward capabilities that these works have suggested.

### *Seven Points to the Wind and Tacking*

Casson asserted that ancient square-riggers were designed to sail with wind astern or on the quarter, but when pressed with a destination 'that lay well to windward', mariners could also tack (beat) to windward, however, not closer than seven points (i.e., 78.75°) to the wind (1995, pp. 273–274). This suggests the ability of mariners to conduct a windward passage while making good seven points to the wind. Such ability needs to be explored for its reasonability.

The average wind speed in the eastern and central Mediterranean basins is 10.1 knots. This is based on 1.2 million simulated sailings in the Mediterranean throughout 15 years (2004–2018) using ERA5 wind data (Gal et al., 2022). Wind roses for July also reflect the prevalence of winds of Beaufort force 0–3

(0–10 knots) (UK Hydrographic Office, 2005, p. 30). A period ship's speed when sailing at its close-hauled limit could be expected to be in the range of 20%–33% of the true wind speed (Gal et al., 2021, p. 4; Palmer, 2009b, p. 315). Assuming 25% gives a ship's speed of 2.5 knots. Windward VMG in our case is the cosine of 78.75° multiplied by 2.5, resulting in 0.49 knots. If we consider 10% loss of windward ground while wearing from tack to tack, and 3° loss to helmsman's leeway (see Table 1), then a typical 225 nautical mile (NM) passage in unfavourable winds, such as Paphos in Cyprus to Rhodes in the summer, would require non-stop sailing of 29 days, involving sailing a distance of 1725 NM over the water, definitely an unreasonable challenge.

If we consider the suggestion that period ships could not point closer than seven points to the wind to be valid, it is clear that an entire windward passage, as described, would be unreasonable for period mariners, considering their endurance and navigational abilities out of sight of land. Therefore, it is argued that the two assertions, i.e., seven points to the wind and that period mariners tacked to a destination well to windward, contradict each other.

## Windward Performance of Replica Ships

*Kyrenia II* has been widely referred to as a source of the windward capability of period ships (see Literature Review, above). However, based on the two published works related to the ship's sailing performance, there was no recording of onboard instrumentation, and no GPS or other external measurements of actual courses made good and resulting tacking angles (Cariolou, 1997; Katzev, 1990). Cariolou stated that wind direction data were taken by a handheld bearing compass and that wind speed data were those of apparent or relative wind (1997, p. 89). References made by scholars were to two single-point on-deck observations during the Cyprus voyage.

We consider the two single-point reports as accurately measured, without considering inevitable wind direction reading errors. These errors reduce the wind angle to the bow when close-hauled (due to deflection of the wind flow by the sail) affecting all positions on the ship (Palmer, 2009a, p. 25). Interpretation of these reports is given below, considering the terms and definitions of windward sailing.

Katzev reported sailing 50°–60° off a force 2 Beaufort scale wind making over 2 knots (1990, p. 254). We take this as a true wind speed of 7 knots and a boat speed of 2.2 knots and calculate the true wind angle to the bow to be 67°–78° respectively. To establish the effective course made good to the true wind we need to add leeway, which can be expected to be 10° for an efficient hull and 15° for a less efficient hull (Palmer, 2009b, p. 317). However, to err on the optimistic side, we have considered a leeway of only 8°, bringing the course made good to the true wind to 75°–86° with corresponding windward VMG of 0.57–0.15 knots. The reported speed of over 2 knots should therefore not be erroneously considered as windward VMG – it is the boat speed through the water on the close-hauled course.

The second single-point report by Cariolou described heading at 51° to 'the true wind' with a 'true wind speed of 23.4 knots' and a boat speed of 6.8 knots, heeling at 20° (Cariolou, 1997, p. 92). Cariolou estimated the leeway at 10°. This report raises the question of whether the readings were actually in terms of the true wind, as Cariolou previously stated that all wind measures were in apparent wind terms (1997, p. 89). In order to try and answer the question, we will examine both options. If the wind values are indeed relative to the true wind, then the apparent wind condition would have been 28.2 knots, with a heading of 40° to the wind. It is suggested that maintaining such a heading to the apparent wind is more in the realm of modern yachts, and such a heading with a period square sail is questionable. Alternatively, if we consider the values as apparent wind measures, then the true wind angle to the bow would have been 66°, with a true wind speed of 19.8 knots. Leeway, in such wind and sea conditions, would have increased dramatically to over 20° (Palmer, 2009b), but we have conservatively applied 20° of leeway, giving a course made good of 86° to the true wind, with a windward VMG of 0.47 knots. This means that, at best, the vessel was exhibiting marginal windward capability.

The test sailings of reconstructed ships in recent years are well documented by GPS plots, reliably measuring tacking angles between intersecting tacks sailed by the ships (Palmer, 2009a, p. 27). These GPS plots provide hard evidence of the windward performance achieved in the particular test conditions and are independent of the inaccuracies inherent to onboard measurements of sailing parameters (Palmer, 2009a, p. 27). The course made good to the true wind simply equals half the measured tacking angles in the plots.

The first author has recorded courses made good to the true wind of 71° to 73° in experimental sailings of the replica ship *Ma'agan Mikhael II* in Beaufort 2 conditions with calm seas (Palzur & Cvikel, 2021; Gal, 2022). Figure 4 indicates tacking angles achieved in experimental sailing of *Ma'agan Mikhael II* in increasing wind and sea conditions. Best results were achieved in a Beaufort 2 light breeze. However, the 7–8 knot wind provided a boat-speed of only 2 knots with a corresponding instantaneous windward VMG of 0.6 knots. Net windward VMG was only 0.24 knots due to ground lost while wearing. A Beaufort 3 wind and sea reduced the windward performance to 81° made good to the true wind. In Beaufort 4 conditions the replica ship was not able to gain ground to windward and achieved only 90° to the true wind. In

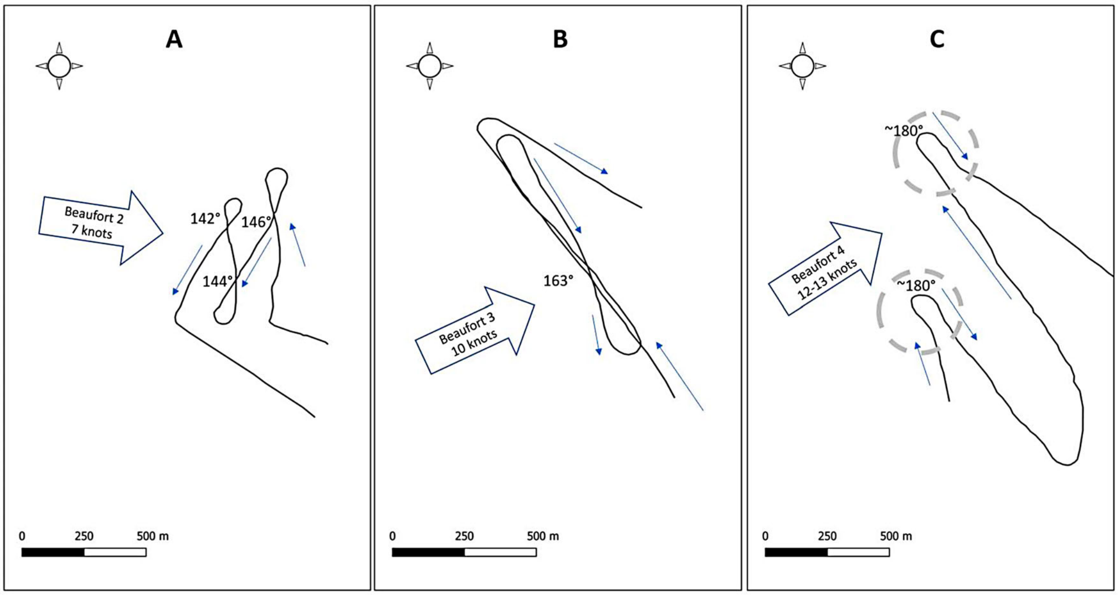


**Figure 4.** Tacking angles achieved sailing *Ma'agan Mikhael II* in various wind conditions when beating at 55° to the apparent wind: A indicates tacking angles of ∼144° in Beaufort 2 conditions with calm sea; B indicates a tacking angle of 162° in Beaufort 3 wind and sea conditions; and C indicates the replica ship being able to make no more than 90° to the true wind in Beaufort 4 conditions with associated swell and choppy wind waves (D. Gal).

all wind conditions beating was performed at 55° to the apparent wind, therefore the reduction in tacking angles is mainly attributed to the increasing leeway, resulting from reduced hull efficiency caused by the waves, and reduced sail efficiency from swell induced pitching and rolling.

There are additional examples of the dependency of windward performance on wind and sea conditions. The Hanse Cog has exhibited 74° to 76° course made good to the true wind in calm seas (Brandt & Holzkirch, 1995, fig. 10). However, the recorded performance of the Hanse Cog indicated loss of windward ground in 20 knots of wind with associated seas (Brandt & Holzkirch, 1995, fig. 11). The Hanse Cog cannot be directly compared with the Mediterranean ships, that are the subject of this paper, but the characteristic increase of leeway with increasing wind and waves is clearly a common phenomenon.

The authors suggest preferring the use of tacking angles, as measured from GPS plots, as the primary measure of representative ships' technological windward capabilities. Windward VMG measured in reconstructed ship sailings should only be considered as a secondary indicator of ships' windward performance as this is a function of ship speed, which depends on wind velocity. Reconstructed Viking ships, that in some cases display similar tacking angles to Mediterranean ships, will probably exhibit significantly higher measures of windward VMG due to totally different environmental conditions to which the Viking ships are well adapted. Therefore, direct comparisons between Mediterranean ships and Viking ships have been avoided.

## *Windward Capability Derived from Historic Voyage Passages*

Casson (1951, 1995) followed by Whitewright (2011), used sets of historic voyage passages with known durations to derive sailing speeds of period ships from the average passage speed (i.e., passage VMG, see Table 1). Their method was based on classifying recorded voyage passages into those 'done with wind abaft of the beam', i.e., with favourable wind, and those 'with a wind from ahead' requiring tacking, i.e., with unfavourable wind (Casson, 1995, p. 281). Casson suggested that when wind conditions were not mentioned in the literary evidence, 'we can often make some sort of a guess by using modern hydrographic information' (1995, p. 281). For the set of passages listed as been conducted with favourable winds, Casson concluded that ancient vessels averaged between 4 and 6 knots over open water (1995, p. 288). For the set of passages listed as having been made with unfavourable winds, he concluded: 'It would seem therefore that ancient vessels averaged from less than 2 to 2½ knots against the wind' (1995, p. 291).

A quick calculation indicates that the boat speed (BS) needed to provide windward VMG of 2 knots, while making good a close-hauled course of seven points to the wind (the limit given by Casson), is 10 knots. This is clearly too fast for period ships, and it calls for a closer look at Casson's method and related assumptions (1995, pp. 281–291). This method of deriving windward sailing speeds from historic passages was also used by Whitewright in conjunction with comparison to the windward VMG of a variety of reconstructed ships recorded in test sailings (2011, p. 9).

As we accept that the data on passage distances and durations for the set of non-stop passages are correct, then there are two possibilities: (1) Period ships might have had much better sailing capability than seven points to the wind, and they were capable of making good a course much closer to the wind; or (2) It is likely that the passages listed as having been conducted against the wind were, in fact, conducted in seasons when wind variability might have provided favourable winds in the other direction, or at least cross-winds; i.e., that the passages were not conducted in contrary wind conditions as Casson and Whitewright assumed, but rather with the wind on or abaft the beam. The first possibility is discussed below, under Revisiting the Theoretical Basis. The second possibility is examined by reconstructing the same passages applying the new method to measure potential sailing mobility developed by the authors (Gal et al., 2021, 2022).

Out of the passages listed by Casson and by Whitewright as windward passages (Figure 5), four mentioned by Mark the Deacon were selected for reconstruction, as the season in which they were conducted could be established (Hill, 1913). The method of reconstructing the passages by the authors (2021, 2022) used a 15-year set of modern meteorological data at high spatiotemporal resolution (Hersbach et al., 2020). As a prerequisite, it was established that the Mediterranean wind patterns have not changed in the last 3000 years based on historic comparison (Murray, 1987), as well as on paleoclimatic analyses (Gal et al., 2021; Pryor, 2014). For each passage, 5479 daily sailings were simulated, using weather routing software, in order to determine the efficient routings. The set of resulting passage summaries were divided between the set of passages that would have been reasonable to sail and those deemed unreasonable, by applying a set of criteria. This provided the basis for the statistical summaries for each passage provided in the Supplemental Material. The simulated sailings on these passages have provided measures of potential sailing mobility for each passage for each month of the year.

We learn that Mark the Deacon’s passage from Caesarea to Rhodes departed on 25 September and took 10 days. According to Hill (1913) the passage was conducted in the year 401 CE:

> […] and coming to Caesarea I found the most holy bishops making ready for the voyage; and after two days we put to sea and sailed on the twenty-eighth day of Gorpiaios (which is according to the Romans the twenty-third of September), and by the mercy of Christ making a fair voyage after ten days we put in at the island of Rhodes. (Marcus Diaconus, *Life of Porphyry*, 34)

The mobility mapping for this passage (see Supplemental Material 1) shows that wind variability gave increasing opportunities for favourable sailing

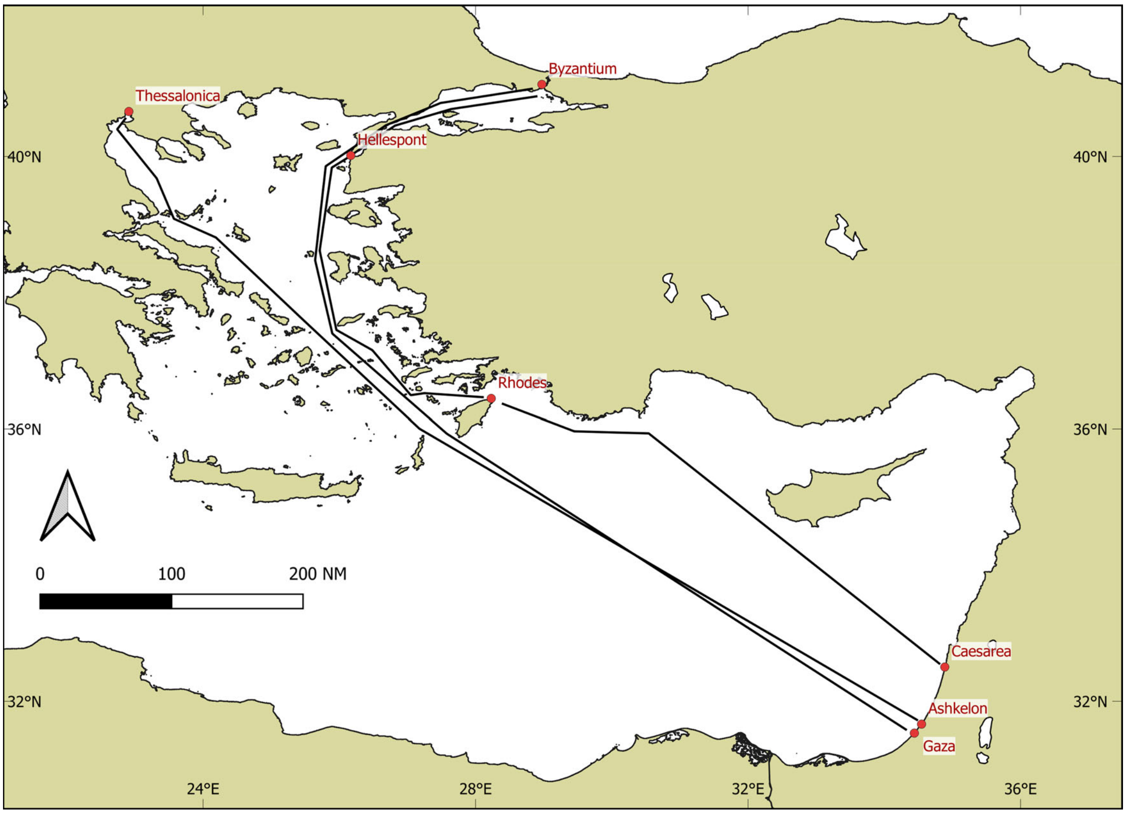


**Figure 5.** The four historic passages, documented by Mark the Deacon, that were considered as having been made to windward: Caesarea to Rhodes, Rhodes to Byzantium, Ashkelon to Thessalonica, and Gaza to Byzantium (D. Gal).

mobility in late September or early October after virtually no mobility in the passage direction during the summer months due to contrary Etesian winds. In October there is an average duration of close to 8 days with a passage VMG of 2.16 knots. Examination of data related to points of sail show that 55% of the sailing would have been spent close-hauled, 29% reaching and 16% running. The destination was in the no-sail sector 13.5% of the time. Average ship speed was 2.87 knots, and the distance sailed was 1.3 times the shortest distance. Average true wind speed would have been 8.2 knots (Gal et al., 2022). These parameters indicate that mariners had options of sailing with varying wind close to the beam. It is suggested that this passage was most likely a cross-wind passage at worst, and not a windward passage.

The onward passage of Mark the Deacon from Rhodes to Byzantium departed on about 16 October 401 CE, and took 10 days: '[…] we sailed and after other ten days came to Byzantium' (Marcus Diaconus, *Life of Porphyry,* 37). Mobility mapping derived from Rhodes to the entrance to the Dardanelles (see Supplemental Material 2) shows an average duration of less than 5 days for October (2–3 days need to be added for the remaining passage to Byzantium), with an average passage VMG of 2.77 knots. Points of sail show the opportunity for cross-wind passages in October, with 49% of the time sailing close-hauled and the destination above the layline for 17% of the time. Average true wind speed would have been 10 knots (Gal et al., 2022). Accordingly, it is argued that in the case of this passage, October wind conditions provide for cross-wind sailing or better, and windward sailing would not have been required.

The passage taken by Mark the Deacon from Gaza to Byzantium is shown by Hill to have occurred between late February and late July 398 CE, with a duration of 20 days (Hill, 1913):

> And having indited letters to the most saintly and holy John, who was at that time bishop of Constantinople, whose glory and praise is remembered of all men, he sent me away in a ship, and after twenty days we arrived. (Marcus Diaconus, *Life of Porphyry,* 26)

The mobility mapping from Gaza to the entrance of the Dardanelles (see Supplemental Material 3), indicates restricted westbound mobility during the summer months, beginning in mid-May (Gal et al., 2022). It is therefore suggested that the passage occurred in April or early May at the latest. Average duration to the Dardanelles would have been 13–14 days (plus 2–3 days more needed to reach Byzantium). Average passage VMG would have been 2.5 knots, and points of sail indicate mainly cross-wind passages from February to May. Average true wind speed would have been 10–11 knots. It is therefore suggested that this passage was most likely not conducted in contrary winds.

The date or season of the fourth passage from Ashkelon to Thessalonica, which took 13 days, was not provided by Mark the Deacon. However, we do learn that the return voyage was conducted 3 months after arriving in Thessalonica:

> Straightway I went down to Ascalon and found a ship and put to sea, and after thirteen days, having made a fair voyage, we came to Thessalonica […] and when I had gathered all together in the space of three months I put to sea again, and came after twelve days to the port of Ascalon. (Marcus Diaconus, *Life of Porphyry,* 6)

This suggests that the outbound passage was probably conducted in the spring before the limited westbound mobility of the summer winds. Mappings for April (see Supplemental Material 4), indicate an expected passage duration of 14 days with a passage VMG of 2.3 knots. Points of sail reveal predominantly cross-wind passages during April. Average true wind speed would have been 9.85 knots. The months of February and March offer similar sailing mobility (Gal et al., 2022). The authors suggest that this passage may also be considered as one that was not conducted with contrary winds.

The mapped passage VMG of 2–2½ knots for the above passages matches the values of the speeds which Casson considered as being made against the wind. However, it is strongly suggested that this is not related to windward VMG, as he concluded, but rather corresponds with the ships' speed through the water, when most of the passages involved sailing close to the destination's layline. These sailing speeds characterize cross-wind sailing. Whitewright used the same voyage passages as reference (2011, p. 9), did not clearly differentiate between passage VMG and windward VMG, and also concluded that the windward VMG of period ships was 2 knots.

This examination of selected historic passages has indicated that they were most likely conducted with favourable winds and that they should not be considered as representing windward passages. Casson and Whitewright, at time of writing, did not possess the latest data science tools enabling them to simulate and reconstruct the examined passages, illuminating favourable wind windows of opportunity and their implications for mariners. Whitewright did recognize the impact of mariners' limitations, and voiced reservation in his summary regarding the practical windward performance of the square sail (2011, p. 10). Unfortunately, this clear understanding of the limits of practical windward ability has not been heeded by the numerous scholars who have referred to his work.

## Revisiting the Theoretical Basis

Scholarly works reviewed in the Literature Review, with the exception of Palmer (2009b), have not applied the theoretical basis of windward sailing capability of period ships in their investigations. To be able to obtain accurate theoretical measures of potential performance, accurate input data are needed. This includes, for example, the efficiency of the hull and the sailing rig, which involves wind-tunnel and tow-tank testing. Neither can fully simulate the dynamics of open-sea sailing. The authors, therefore, suggest applying the theoretical approach using a range of hull and sail measures of efficiency, to provide a domain in which the windward performance of period ships is most likely to be found.

The 'Beta theorem', also known as the 'Course theorem', provides the angle β, which is used to designate the angle between the apparent wind and the course made good. The theorem requires knowledge of the efficiencies of the hull and the sail in terms of lift to drag ratios (L/D) (Garrett, 1997, p. 67; Palmer, 2009b, p. 315). When stably maintaining a heading to the wind the total sail-induced force is in balance with an equal opposing hull-induced force (Figure 6). The hull creates this force by pointing windward in relation to the water flow, and the required pointing angle of the hull is the leeway. The total sail force has lift and drag components, and so does the total hull force.

The angle made good to the apparent wind, $\beta$, is equal to the sum of the two drag angles designated as $\varepsilon_s$ and $\varepsilon_h$ in Figure 6. This can be proved by showing that $\varepsilon_s'$ plus $\varepsilon_h$ plus $\alpha$ equals 90° and also $\beta$ plus $\alpha$ equals 90°. The actual windward performance is measured in relation to the true wind; therefore the difference between the apparent wind and the true wind needs to be added to $\beta$. More efficient sails and hulls will create relatively more lift to drag, and they will have smaller drag angles, thus reducing $\beta$.

The beta theorem has an inherent pitfall as it assumes concurrently applying the minimal drag angles for both the sail and the hull, while in reality, the two 'best points' are very unlikely to coincide. The sail is normally operated to achieve maximum lift to drive the ship, and not necessarily a minimum drag. The consequence of this is that windward ability will always be less than that predicted by the use of the beta theorem (Palmer, 2009b, p. 315).

The chart in Figure 7 can be used to determine the windward capability of a sailing vessel. The plots consider the apparent to true wind adjustment to be based on close-hauled boat speed, being 25% of the true wind speed. The intersection of the sail L/D (x axis) and the hull L/D (y axis) gives the angle of the course made good to the true wind. This, of course, requires the knowledge of the L/D values for the vessel in question.

Lift to drag ratios can be drawn from results of wind-tunnel and tow-tank tests for hulls and rigs, similar to those of Mediterranean square-sailed ships. Palmer (2009b, pp. 318–326) details the required adjustments to hull efficiency when accounting for hull fouling and wave resistance, as well as adjustments to sail efficiency accounting for loss to porosity. Based on Palmer's ranges of efficiencies encompassing period ships and considering an average fouled hull with typical Mediterranean waves at a direction of 60° to the waves, we suggest applying hull L/D ranging from 1 to 1.9. Considering cotton or linen sails, the sail L/D range is suggested to be from 1 to 1.5. The intersection of these two ranges (shaded in Figure 7) defines the technological windward performance domain of the period Mediterranean single-square sailed ship in open sea conditions.

The beta theorem indicates a windward ability of 90°±10° in typical open sea sailing. However, the caveat of the beta theorem, that it always errs on the optimistic side, needs to be considered. The theoretical approach, together with available technical data, suggests that the technological windward ability was less than commonly assumed (see Literature Review), and it corresponds, at best, with the notion of seven points off the wind.

## Between Technological and Practical Windward Sailing

Scholars have expressed the belief that although ships had some technological ability to sail to windward, it was unlikely that the ancient mariners would depart on a passage to a destination well to windward, implying that there is a difference between technological and practical windward sailing abilities (Roberts, 1995, p. 313; Tilley, 1994, p. 310; Whitewright, 2011, p. 10; 2018, p. 39). The authors attempt to develop understanding on where the border between the technological and practical windward sailing abilities lies by discussing three examples.

The first example examines the practicality of sailing windward to a destination in the eye of the wind, where windward VMG and passage VMG coincide, as depicted in Figure 8A. The implications of sailing such a course are summarized in Table 2, for an array of incrementally better performing ships, making good from 85° up to 70° to the true wind. The subsequent calculations consider practical windward losses due to helmsman's leeway and due to wearing between tacks. The two main limiting factors for period mariners would have been endurance and navigational ability when land was not in sight. Endurance is a factor of passage VMG and the shortest possible route to the destination, which is represented in Table 2 by columns labelled 'windward VMG' (identical to passage VMG in this singular case),

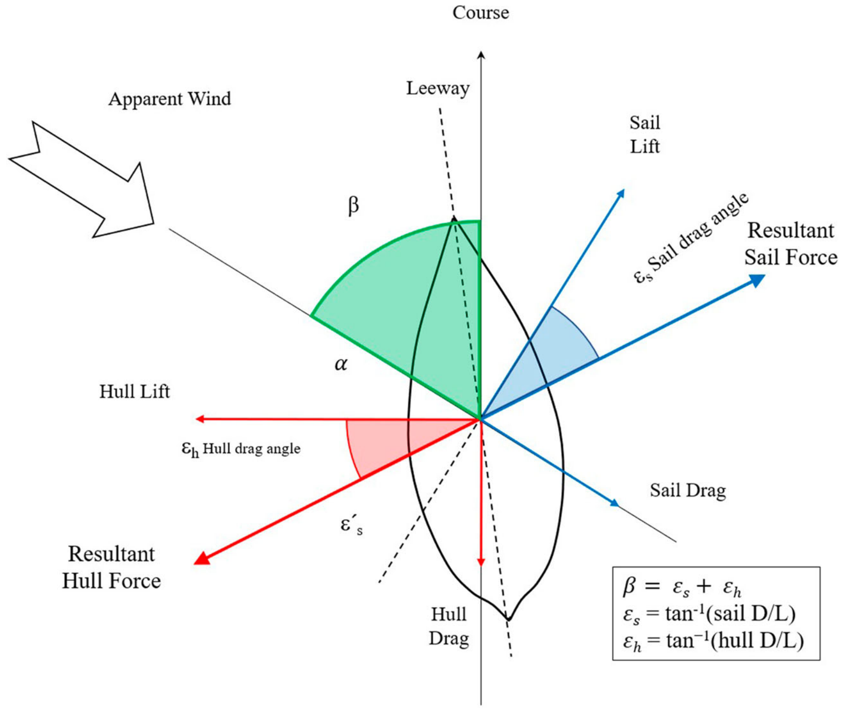


**Figure 6.** The beta theorem. Resultant hull and sail forces are opposing and equal. Sail and hull drag angles are a function of their efficiency. Angle β, giving the angle between the apparent wind and the course made good, is equal to the sum of the hull and sail drag angles (D. Gal, following Garrett, 1997, p. 67; Palmer, 2009b, p. 315).

'windward gain' and 'duration'. The ancient mariners' ability to navigate out of sight of land consisted of being able to maintain a general heading relative to stars, wind, and waves, and some ability to conduct mental dead-reckoning (Morton, 2001, pp. 215–228). Navigation ability would have been largely affected by the degree to which the path actually sailed deviated from the direct course to the destination, e.g., by tacking. This is reflected by the columns 'distance ratio' and subsequent 'actual distance sailed' to achieve a windward advance to the destination.

These results clearly indicate that windward sailing to a destination in the eye of the wind would not be practical for period mariners. Even with a ship capable of making-good 70° to the true wind, the duration for a 225 NM passage of 14 days could have possibly been feasible. However, deviating 380% from a direct passage distance is suggested to be unreasonable for the mental dead-reckoning navigational abilities of the mariners.

The second example considers a case where the destination lies on the limit of the no-sail sector (as shown in Figure 8B), where the ship is sailing a close-hauled layline (see definition in Table 1) directly to the destination. In this case the passage VMG would have equalled the boat speed of 2.5 knots, the distance ratio would have been exactly 1, with no deviation needed from the direct route, and the duration for the 225 NM passage would have been 3.75 days. If we consider almost 4 days on a close-hauled passage, albeit with no tacking, as reasonable for period mariners, then sailing at the limit of the no-sail sector would have been clearly within period mariners' windward abilities.

The third example, shown in Figure 8C, considers a destination located somewhere inside the no-sail sector, between the edge of the no-sail area and the eye of the wind (shown schematically by the yellow shaded area). In the case of a constant wind direction, a destination close enough to the edge of the no-sail sector could have been reached with an acceptable amount of beating to windward without exceeding the mariners' endurance and navigational limits of reasonability. Alternately, the wind may have been exhibiting typical variability by backing and veering such that the heading to the destination would have been intermittently in or out of the no-sail sector, forcing some reduction in passage VMG and increase of distance ratio, but within the limits considered reasonable for the mariners. The subject of mariners' limits of reasonability was studied in depth by the authors. Based on the results of hundreds of thousands of simulated sailings, a set of hypothetical criteria was established, and tested for sensitivity, in regard to measures of potential sailing mobility (Gal et al., 2021, paragraphs 2.6, 4.2).

The amorphous zone near the edge of the no-sail area is of particular interest in the study of period windward sailing, as it is in this zone that the variations in measures of potential sailing mobility would have occurred. All three factors of sailing mobility – the wind, the mariners' limits of reasonability,

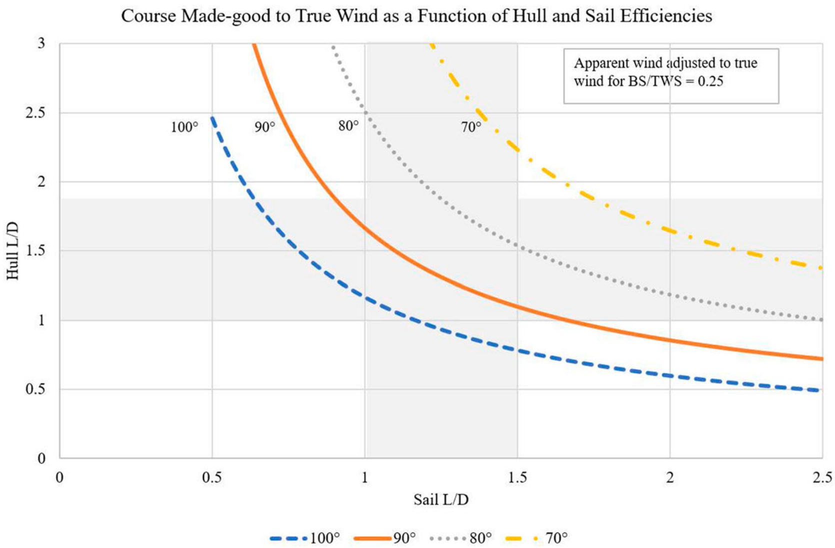


**Figure 7.** Course made good to the true wind as a function of hull and sail efficiencies. The intersection of the shaded ranges designates the suggested domain of the period Mediterranean square-sailed vessels in open sea conditions (D. Gal, following Palmer, 2009a).

and ship technology, come into play in this marginal area. Variability of the wind is the prime effect on sailing mobility. If, in the case of Figure 8C, the wind had backed for periods of time such that the destination would no longer have been in the no-sail sector, there would have been more windows of opportunity to conduct a direct passage to the destination with favourable winds. The backing of the wind would have also brought other, more windward, destinations into the zone of reasonability of the mariners' windward limits. A technological improvement in the ships' windward capabilities would reduce the arc of the no-sail sector, marginally exposing more reasonable passage opportunities. Finally, mariners more risk prone or having more capable endurance and navigational skills would have expanded the zone of reasonability closer to the wind, adding opportunities for reasonable passages, and also marginally increasing measures of sailing mobility.

The wind clearly remains the dominant factor in windward sailing mobility. Seasonal variabilities of the wind would provide significant increases of potential sailing mobility in passages that are mostly contrary to prevailing winds (Gal et al., 2021, 2022). Variations in the mariners' windward sailing limitations were very unlikely to allow sailing a period ship to a destination in the eye of the wind, as shown in Table 2. Similarly, technological improvements to period ships, e.g., a wineglass hull shape, would not have met mariners' limitations well enough to allow sailing to a destination in or near the eye of the wind.

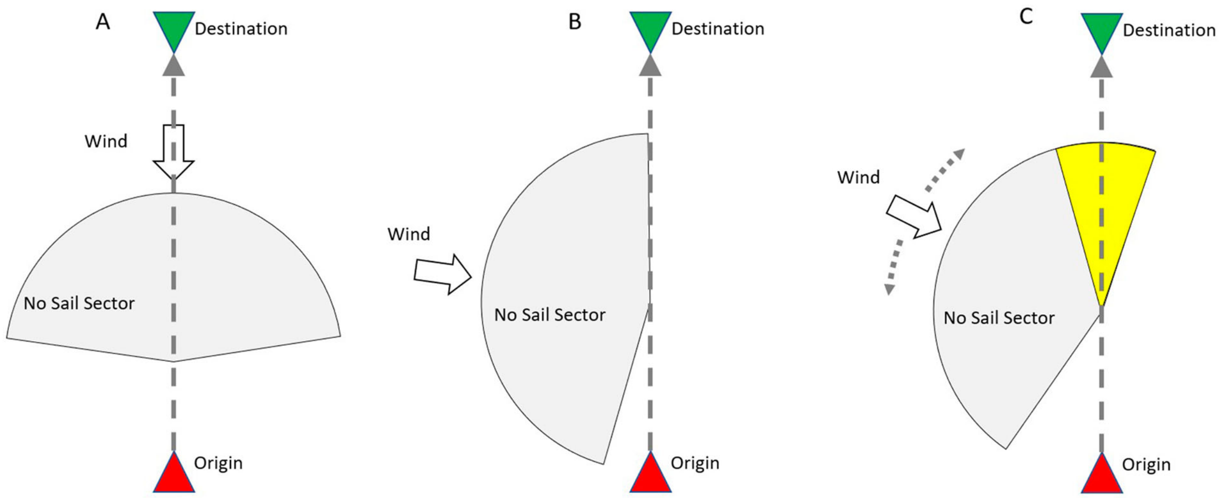


**Figure 8.** Course to destination relative to the no sail sector. In case A the destination is in the eye of the wind at the heart of the no sail sector; in case B the destination is on the edge of the no sail sector; and in case C the destination is either partially or intermittently in the no-sail sector (schematically by the yellow shaded area), noting the variability of the wind backing or veering (D. Gal).

**Table 2.** The possible implications to mariners presented by period ships with differing technological windward abilities.

| Technological close-hauled course made good (CMG) degrees | 85 | 80 | 78.75 | 75 | 72 | 70 |
|---|---|---|---|---|---|---|
| Loss due to helmsman's leeway (degrees) | 3 | 3 | 3 | 3 | 3 | 3 |
| Effective CMG (degrees) | 88 | 83 | 81.75 | 78 | 75 | 73 |
| Boat speed (BS) (knots) | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 |
| Windward VMG (knots) | 0.09 | 0.30 | 0.36 | 0.52 | 0.65 | 0.73 |
| Loss of windward ground due to wearing (%) | 10 | 10 | 10 | 10 | 10 | 10 |
| Windward gain (NM/day) | 1.9 | 6.6 | 7.7 | 11.2 | 14.0 | 15.8 |
| Distance ratio (dist. sailed to dist. made good) | 31.5 | 9.0 | 7.7 | 5.3 | 4.3 | 3.8 |
| Duration for a 225 NM upwind passage (days) | 119 | 34 | 29 | 20 | 16 | 14 |
| Actual distance sailed for a 225 NM Passage (NM) | 7092 | 2031 | 1725 | 1190 | 956 | 847 |

The column of 78.75° represents seven points off the wind. The example of a directly windward passage is that from Paphos in Cyprus to Rhodes having a range of 225 NM.

## Conclusions

The analysis shows that period sailing ships of this type could not, in practice, sail upwind to any significant extent. A reasonable mariner would not consider attempting passages against an unfavourable wind in the no-sail sector. Therefore, only secondary importance should be given to ships' technological capabilities, as these only provided a marginal contribution to the overall potential sailing mobility. The human factor, i.e., the limits of mariners' reasonability, significantly outweighed the ships' windward sailing abilities.

Upwind mobility was achieved by waiting for windows of opportunity to sail with favourable winds provided by seasonal wind variability, and not by sailing to windward to a destination located in the no-sail sector. These seasonal windows of opportunity are specific for different passages in the Mediterranean and their appearance would have been well known by the period mariners. Mariners could have coped with wind variability causing the destination to be beyond the layline and in the no-sail sector for portions of the passage, provided that the added duration and navigation deviations were within the mariner's limits of reasonability.

The majority of period sailing would have been conducted at the close-hauled or close-reach points-of-sail. This is evident, as out of the four cardinal directions in relation to the prevailing wind, only the downwind direction would involve reaching or running with wind from the aft sector. Two of the cardinal directions would trivially involve cross-wind sailing (i.e., close-hauled or close-reached). To sail in the fourth direction, contrary to the prevailing winds, crews would have waited for seasonal wind variability to expose a layline to the destination, again predominantly involving close-hauled sailing.

## Author Contributions

David Gal: research definition, conducting the research and writing original draft. Hadas Saaroni: supervision, reviewing and editing. Deborah Cvikel: supervision, reviewing and editing.

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No potential conflict of interest was reported by the author(s).

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