Journal of Archaeological Science 40 (2013) 1136–1143

Contents lists available at SciVerse ScienceDirect

Journal of Archaeological Science

journal homepage: http://www.elsevier.com/locate/jas

Tonnages and displacements in the 16th century

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ARTICLE INFO

Article history:
Received 22 May 2012
Received in revised form
10 August 2012
Accepted 12 August 2012

Keywords:
Tonnage
Metrology
Seafaring
16th century
Barrels

ABSTRACT

Questions associated with the size of ships suggested in historical documents are relevant to giving an idea of the volume of cargoes, the size of crews, cost of freights, or when trying to evaluate competitive advantages in war and commerce. Good estimates are often difficult to obtain from the written record, although some values concerning basic hull dimensions are sometimes mentioned. The establishment of reliable relations between registered capacity, as expressed in coeval documents, and displacement, as it is defined nowadays, would be helpful to both historical and archaeological research. This paper probes into the relations between a number of known formulas to calculate tonnages in the 16th century, and the reconstructed hull of the Pepper Wreck, an archaeologically excavated shipwreck dated to 1606.

1. Introduction

Questions associated with the size of ships mentioned in historical documents are frequently difficult to answer. Several factors tend to blur our understanding of the references to ship sizes and capacities in the records. The reliability of documents depends on the honesty and competence of their authors, and references to ships' basic dimensions, crew, or cargo capacity can be distorted for many different reasons. But to know the size of a given ship within a narrow range of dimensional values is often important, for instance when we attempt to identify a shipwreck. To know the size of ships in historical documents is important for the study of the history of shipbuilding, and the best way to understand and compare ship sizes from archival references is to establish a common scale. We have chosen displacement, as it is defined nowadays – the weight of the water displaced by the submerged volume of a given hull – and we are trying to establish relations between capacity, as expressed in coeval documents, basic hull measurements, such as beam, length of keel, or depth in hold, and the volume of a hull below the waterline.

At least from the 16th century onwards, capacity was sometimes calculated with formulas of which a small number survives, together with scattered values and equivalences of measuring units. These formulas and values can be tested against a growing body of data retrieved from shipwrecks to facilitate a better understanding of the questions related to ships' tonnages and displacements in the 16th and 17th centuries. Two factors must be weighed, however, related to the concepts of precision in the period under analysis, and the documented changes – in time and from place to place – of the values of units as important as the *ton*.

2. Precision in the 16th century

It is difficult to imagine anybody today demanding centimetric accuracy in the construction of a backyard swimming pool, as it unlikely that 16th and 17th century shipwrights concerned themselves too much with measuring the maximum beam of their ships to within a few *dedos* in width (a *dedo* in Portugal is thought to measure around 1.83 cm and in Spain 1.74 cm). If it is plausible that the *graminhos* – a set of geometric methods used to achieve fair longitudinal curves along a ship hull (Castro, 2007) – applied on the central frames to define the narrowing and rising of a ship's bottom were measured with care, possibly to less than one *dedo*, it is difficult to imagine the same care and precision being applied to the definition of a keel length. The rigor applied by Ticho Brahe to his celestial measurements, or by an astrolabe maker to his astrolabes, was certainly different from that required in the shipyards of any European country, when it came to laying a keel on the stocks. In other words, it is plausible that units used in Portuguese shipyards, such as the *palmo de vara* (22 cm) and *palmo de goa* (25.67 cm), which were defined by standards kept in municipal halls, were sometimes loosely applied in the construction of ocean-going ships through gauges made in the shipyards and copied from other gauges, possibly with accumulated errors. Several times I

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http://dx.doi.org/10.1016/j.jas.2012.08.033

have repeated a story I heard from J. Richard Steffy, who heard it from John Patrick Sarsfield, about a shipwright from Bahia in Brazil who told him that he used a certain *graminho* gauge, but "he always gave it a little bit more". These measurements were transferred to the timbers with inscribing tools, followed by sawyers working with large saws and sometimes under pressure to deliver the sawn timbers on time, and then modified by the shipwrights with adzes and axes to fit in the real ship, once mounted on the stocks.

This fact is clearly observed in the dimensions of timbers obtained from shipwrecks. For instance, in the case of the Pepper Wreck, believed to be the Portuguese Indiaman *Nossa Senhora dos Mártires*, lost in 1606 (Castro, 2005a), the sided dimensions of the floor timbers varied around an average of 25 cm (22–26 cm), and the side dimensions of the adjacent futtocks varied around an average of 22 cm (21–25 cm). We should not imagine, however, that ships were losely built by eye. Richard Barker cautioned us to consider that maritime cultures where locks and docks are common call for a particular care on the establishment of maximum values for beams and drafts. Still, we do not believe that even in these cultures measurements would be taken with the same accuracy as those used in the manufacture of furniture, let alone a nautical instrument, to cite just two examples.

3. Units of measurement

The second problem, related to the values of units recorded in different places and through the decades, also calls for reflection. Sometimes the value of a particular unit is difficult to estimate with any accuracy. For instance, in its origin a Baltic *last* seems to have been the volume of a cartload. The dimensional boundaries of such a concept are difficult to define, no matter what methodology is applied. In the 16th century, a *tonel* – a unit that sometimes measures weight and sometimes volume – meant different things in Portugal, Spain, France, and England.

Built by hand according to tradition, the external dimensions and capacities of barrels varied considerably, even within a small sample. We have a first hand account of this fact from Johannes Kepler who, unhappy with the way the supplier of wine for his wedding gauged the barrels he purchased, theorized the calculus of barrel capacities for three different theoretical profiles: elliptical, parabolic or hyperbolic sides (Kepler, 1615). Notwithstanding the patent variation in their capacities, barrels were used as tonnage units for several centuries. The use of formulas seems to have gradually replaced the estimation of a ship's capacity with gauges and hoops, although the use of formulas in Portugal is not documented in the 16th century. These formulas add another difficulty to the study of ship sizes because it is not always clear where the measurements used in their calculations were to be taken (e.g. to the inner surface of the ceiling planking or inner surface of the hull planks; on the lower deck, along the weather deck, or below it, at the level of the maximum beam).

These problems call for special care in the interpretation of historical documents. The numerous replicas of Columbus' ships built since the 1880s speak eloquently to this problem (Gay and Ciano, 1997). This troublesome issue arose as recently as 1992, when a new set of replicas was built for the commemoration of the 500 years of the discovery of the Americas and exhibited in Seville, in the World Exhibition Expo'92. Historian José Luis Casado Soto showed that the replicas had tonnages that almost doubled those of the ones sailed by Columbus on his first voyage, as indicated in coeval documents (Soto, 2006).

At this stage of our research, the best solution for the problem of determining historic ships' sizes seems to hinge on a two-step strategy that encompasses: 1) the determination of displacements and hull coefficients of hulls archaeologically excavated; and 2) the establishment of mathematical relations between capacity and hull scantlings, as defined in contracts, shipbuilding treatises, or other reliable historical documents. Given a large enough sample, it should be possible to understand the orders of values within which a certain type of ship was built.

4. Units and regions

The Portuguese used a unit of linear measurement, possibly imported from Genoa, designated the *goa* or *côvado real*, and equivalent to 77 cm. It was related to a local unit designated the *vara*, of which a standard offered by king Sebastian (1554–1578) to the city of Tomar measured exactly 110 cm. A *goa* was divided into 3 *palmos de goa* (25.66 cm) of 7 *polegadas* each (3.67 cm), or 14 *dedos* (1.83 cm). The *vara* was divided into 5 *palmos de vara* (22 cm) of 6 *polegadas* or 12 *dedos*. The *goa* was the equivalent to half a *rumo* (1.54 m), the height of the standard *tonel*, which was the unit of capacity in use in Portuguese shipyards. The maximum diameter of this standard *tonel* was 4 *palmos de goa* (1.027 m), and its capacity was twice that of a *pipa* and four times the capacity of one *quarto* (Barata, 1996; Barreiros, 1838; Costa, 1997).

The exterior volume of the cylinder that contains this *tonel* is given by:

$$\pi \times r_{\max}^2 \times h = 1.276 \ \mathrm{m}^3 \tag{1}$$

With ($\pi = 3.14159$, $r = 1.027/2 = 0.51$ m, and $h = 1.54$ m). Kepler established a method to calculate a barrel's capacity considering the curvature of its sides elliptical:

$$1/3 \times \pi \times h \times \left(2r_{\max}^2 + r_{\mathrm{base}}^2\right) \tag{2}$$

or parabolic:

$$1/15 \times \pi \times h \times \left(3r_{\mathrm{base}}^2 + 4r_{\mathrm{base}} \times r_{\max} + 8r_{\max}^2\right) \tag{3}$$

where $\pi = 3.14159$, $r_{\max}$ is the maximum radius, r_{base} is the radius of the barrel's base, and h is the height of the barrel.

The values obtained through Equations (2) and (3) are similar, but to obtain them we need to estimate the radius of the barrel's base, the thickness of the staves and heads, and the height of the chimes. Data pertaining to the dimensions of barrel staves are scarce, but there are no strong reasons to suppose that these have changed drastically over the centuries. For lack of a better plausible source relating the thickness of barrel staves and the size of the barrels we have used late 19th century values and assumed that the thickness of barrels' staves and heads was 4 cm and the chimes 5 cm. In this case, the maximum interior diameter becomes 94 cm and the interior height 1.36 m (Special Consular Reports, 1891–1892, 3–89). Varying the diameter of the base between 80% and 95% of the maximum diameter, the capacities obtained with Equations (2) and (3) present differences smaller than 1%. For diameters of the base equal to 80%, 85%, 90% and 95% of the maximum diameter of the barrel, the elliptical model determines capacities of 831, 857, 884, and 913 L, and the parabolic 828, 855, 883, and 913 L, respectively.

In a collection of *barricas* – in Portuguese *quartos* – found on the Basque whaler *San Juan*, lost in 1565 at Red Bay, Canada, and carefully studied by Brad Loewen, the average relation between the diameters of the base and the bilge (maximum value) was 89% (Loewen, 1999, 59). Considering this value, the calculated capacities are 878 and 877 L for elliptic and parabolic sides, respectively, not far from the 52 *almudes* (873.6 L) traditionally referred to in the literature, at least if we accept the value of one *almude* as 16.8 L (Lopes, 2003, 155).

In Spain the linear unit in use in shipyards was the *codo*, with two different values in the beginning of the 16th century: the *codo andaluz* or *castellano* (55.7 cm), equal to 2 *pies* (27.85 cm), 24 *pulgadas* (2.32 cm), and 32 *dedos* (1.74 cm), and the *codo cantábrico* or *de ribera* (57.5 cm), equal to 33 *dedos castellanos*. The *codo andaluz* equaled 2/3 of a *vara castellana*, which was equivalent to the *goa andaluz* (83.6 cm). The *tonel* was a unit of volume equal to 2 *pipas* and 8 cubic *codos*. When the *codos* considered in the composition of a *tonel* were *castellanos* the *tonel* was designated as *tonelada de carga* (1.382 m^3). When the *tonel* was composed of 8 cubic *codos cantábricos*, it was designated *tonel macho* (1.521 m^3). The capacity of a *tonel* is difficult to establish. Juan Escalante de Mendoza indicates 55 *arrobas* in 1575, or 632.5 L, if we consider one *arroba* equal to 11.5 kg (Duro, 1996, 5:461–462; Mendoza, 2008a, 69). Curiously, the *Enciclopedia general de la mar* indicates 436 L as the capacity of a *pipa de Castilla*, making the Castilian *tonel* 872 L, very close to the Portuguese one, of 877 or 878 L (Enciclopedia General de la Mar, 1982; Serrano, 1988).

When a ship was freighted, the payment was calculated by the state or the private freighter in *toneladas de sueldo*, which corresponded to the ship's capacity calculated in either *toneladas de carga* or *toneles machos*, plus 20 or 25% of that volume, to account for the space occupied by the crew, victuals, spares, and equipment (Soto, 1988).

In England linear units seem to have stayed around the same values from at least the 14th century. A *foot* (30.48 cm) of 12 *inches* (2.54 cm) was the unit in use in shipyards (Ross, 1983). The *ton* of the High Middle Ages seems to correspond to a volume between 240 and 252 *gallons* of wine (910–955 L), and was eventually considered 2000 *pounds* (907 L), considering the specific gravities of wine and water being roughly equal. Adding the weight of the barrel, around 10% of the weight of the wine, the resulting weight of the English ton was estimated at around 2240 *pounds* (1016 kg). The space occupied by a ton was fixed at 40 cubic *feet* (1133 m^3). As in Spain, the concept of cargo capacity and interior volume were expressed through different values, the later designated *tons and tonnage* and equivalent to the ship's capacity, designated *tons burden*, plus 30% for the space occupied by crew, victuals, spares and equipment (Lane, 1964; Loewen, 1999; Salisbury, 1966).

In France the linear units were the *pied* (32.66 cm until 1668) of 12 *pouces* (2.72 cm). According to Brad Loewen, the capacities of the barrels varied from trade route to trade route. In Bordeaux the *toneau* seems to have been the same as the one used in the north of Spain, possibly from the High Middle Ages onward. It was the equivalent of two *pipes* or four *barriques*. Each *barrique* contained 100 *pots* of 2.265 L each, or around 225 L, when the wine was sold in retail commerce, and between 106 and 110 *pots* when *barriques* were used in wholesale (c. 240 L). The study of the Red Bay shipwreck barrels showed that by 1565 the weight of a whale oil *barrique* was fixed at 400 *libras de Guipúzcoa*, or 4 *quintales* (196.8 kg), the equivalent to 213.2 L, considering the specific gravity of whale oil to be 0.923. This capacity was 9% smaller than that of a Bourdeaux *barrique* (Loewen, 1999, 50–55). These discrepancies are perhaps less meaningful when we consider that Brad Loewen found the capacities of 41 barriques analyzed to vary between 205.5 and 236.6 L or, in other words 221 L plus or minus 7%. To hand make a barrel with a precise capacity is extremely difficult. If the value of the chimes in the calculation of the Portuguese *tonel* are changed from 5 to 5.5 cm, we get 6 L less in the barrel's capacity.

Frederic Lane's analysis of the value of the English ton in the High Middle Age and Early Modern Age, 240–252 *gallons*, or 246 *gallons* (933 L) plus or minus 3%, seems plausible and even a little bit optimistic, when we consider the 7% variations found by Brad Loewen. Indeed, when we consider a variation around a median value for the capacity of a *ton* in these four countries, the values indicated above (872, 877, 884, and 907 L, for Spain, Portugal, France, and England, respectively) fall within a much tighter interval: 890 L more or less 2%. A variation of 7% around a median capacity of 890 L gives a working interval between 828 and 952 L.

5. Calculating the capacity of a ship

Documentary evidence suggests that during the Middle Age the tonnage of a ship was often estimated by the parties engaged in the shipping contracts on a case by case basis. An anonymous reviewer of this paper pointed out an interesting discussion of this subject, by Brian Dietz (1991). Frederic Lane referred to a case of a ship built in Königsberg (today Kaliningrad) in 1559, that departed to its first voyage without paying all its dues because its capacity could not be calculated until its return, fully loaded (Lane, 1964, 224–225).

In Portugal, the questions related to the calculation of a ship's capacity in the 16th century have been studied by Leonor Freire Costa (1997). Following a tradition of several centuries, in the beginning of the 16th century the cargo capacity of a vessel was determined by a team of specialized officers, using gauges and hoops to simulate the space taken by the standard barrels: *tonéis*, *pipas* and *quartos*. We do not know the dimensions of *pipas* or *quartos*, although we believe that their capacities were near 440 and 220 L, respectively half and one quarter of a *tonel*. The relation between volume and weight was expressed in equivalent quantities. For freight purposes, one *tonel* was the equivalent of 750 roof tiles, 500 sugar molds, 14 *quintais* of metal (1 *quintal* = 58.75 kg), or half an animal (ox or horse) and its food (Costa, 1997, 77). The earliest references to the use of formulas for tonnage calculation appear in Portugal toward the end of the 16th century, in a manuscript authored by father Fernando Oliveira titled *Ars Nautica* and dated to circa 1570 (Oliveira c. 1570, fls. 150v–151r). His method consisted, however, in adding the number of barrels that could be lodged in each *rumo* of the ship's keel length (1 *rumo* = 1.54 m, the height of a *tonel*). A decade later, in a manuscript titled *Livro da fábrica das naus*, Oliveira returned to this subject and stated that a *nau* of 18 *rumos* of keel could store $8 \times 8 = 64$ *tonéis* in the wider *rumo* of the keel, where the master frame was placed. His recipe for the ship under analysis prescribed a maximum beam between 36 and 48 *palmos de goa* (9.24–12.32 m), and a depth of hold of 35 or 36 *palmos de goa* (8.98–9.24 m), divided into three floors. The hold should be 14 *palmos de goa* high (3.59 m) and each one of the upper decks 9 *palmos de goa* high (2.31 m). The decks were a little bit over 1 *palmo de goa* thick. He cautioned his reader about the problem of the rising and narrowing of the ship's bottom and explained that the 64 barrels would not fit in the other *rumos* of the ship's keel, but did not furnish a solution to this problem. According to him, the multiplication of 64 tonéis by the length of the keel (18 *rumos*) yielded a number "over one thousand *tonéis*" and this ship could not carry "more than six hundred" (Oliveira, 1991, 89).

In Spain, tonnage was probably also calculated with gauges and hoops in the 15th century, but formulas to calculate a ship's capacity appear as early as 1520. Casado Soto has studied this subject in depth (Soto, 1988, 102–105). After the first quarter of the 16th century a ship's tonnage was calculated from three basic measurements (Fig. 1), taken between the inner surfaces of the hull planking: maximum beam (M = *manga*), length at the level of the maximum beam (E = *eslora*), and depth in hold, measured from the bottom planking to the level at which the maximum beam occurred (P = *puntal*).

Casado Soto found three formulas. Each used values in *codos* and the result, after being divided by eight (1 *tonel* = 8 cubic *codos*), is

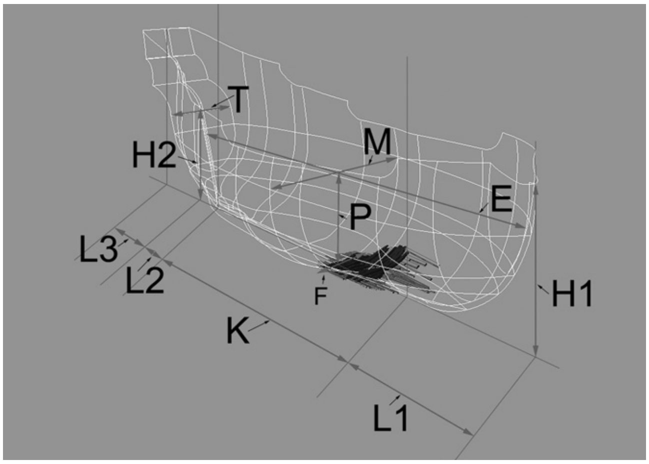

Fig. 1. Basic diagnostic dimensions of a ship: K – Keel length, L1 – Spring of the stem post, L2 – Rake of the sternpost, L3 – Span of the counters and stern castle bulworks, H1 – Height of the stem post, H2 – Height of the sternpost, T – Width of the transom, M – Maximum beam (in Spanish *Manga*), F – Flat amidships (in Spanish *Plan*), P – Depth of hold (in Spanish *Puntal*), and E – Length on the upper deck (in Spanish *Eslora*) (Kevin Gnadinger and Filipe Castro).

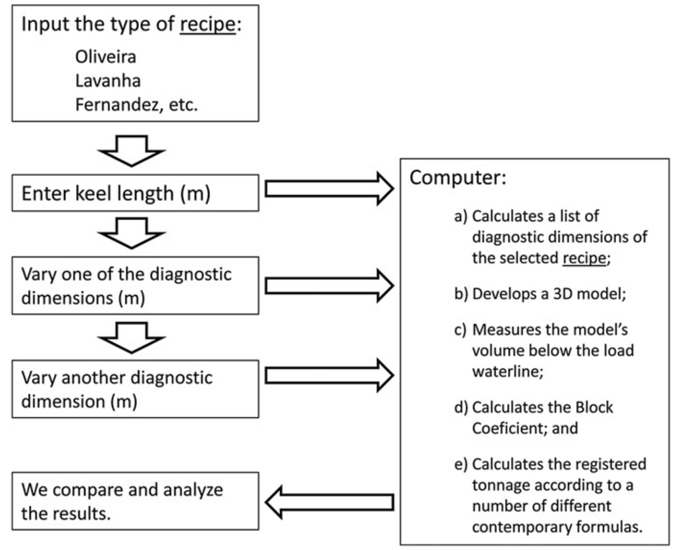

Fig. 3. Operations included in this project (Filipe Castro).

given in *toneles*. The first formula (4) was used in the Cantabrian region between 1520 and 1590, and refers to values in *codos de ribera* (57.5 cm) and *toneles machos* (1.521 m^3):

$$\begin{aligned}\text{Tonnage} &= 19/20 \times E \times [(M/2 + P)/2]^2/8 \\ &= 19/640 \times E(M/2 + P)^2 \qquad (4)\end{aligned}$$

Where E = *Eslora*; M = *Manga*; and P = *Puntal*; all measured at the level of the maximum beam.

The second formula (5) dates to circa 1560 and was in use in Seville and Cadiz, requiring values in *codos castellanos* (55.7 cm) and yielding values in *toneladas de carga* (1.382 m^3):

$$\text{Tonnage} = 2/3 \times M \times K \times P/8 = 1/12 \times M \times K \times P \qquad (5)$$

The third formula (6) was also used in Seville and Cadiz, between 1570 e 1590, it also used *codos castellanos* and *toneladas de carga*:

$$\text{Tonnage} = E \times [(M/2 + P)/2]^2/8 = 1/32 \times E(M/2 + P)^2 \qquad (6)$$

In the early 17th century a sweeping reorganization of the Spanish Navy included a number of regulations, issued in 1607 and revised in 1613 and 1618, and carefully studied by Blanca Rodriguez Mendoza (2008a, 2008b). The *Ordenanzas* of 1607 established that *manga* (M) and *eslora* (E) should continue to be taken between the inner surface of the planking, but from that time onward at the weather deck level and not above, as it was the practice previously. In other words, the maximum beam should occur at deck level and not above it, as it sometimes happened previously. The *puntal* (P) was to be measured from the upper surface of the ceiling to the upper surface of the weather deck. Not indicating a new formula for the calculation of tonnage, the *Ordenanzas* established a series of standard measurements of the *manga*, *eslora* and *puntal*, adding the keel length (*quilla*, K), the height of the fashion pieces on the sternpost (*rasel*, r, as indicated on Fig. 5), dividing the *puntal* between the height of the hold (P_1) and the height of the upper deck (P_2) and establishing the clearance under the castles (see Fig. 6). Each set of these measurements corresponded to a precise tonnage. There were 13 classes of vessels, ranging from *navíos* (151–238 *toneladas*), *galeoncetes* (298–487 *toneladas*) and *galeones* (568–1352 *toneladas*). None of the three formulas allows the determination of these tonnages from the corresponding values (Ordenanzas para la fabrica de de navíos de guerra y merchantes, 1607).

In 1611 Tomé Cano, a well-connected and respected Spanish shipper, published a treatise that was completed by 1607, titled *Arte para fabricar, aparejar naos*, proposing the implementation of some changes in the design of both merchant and warships. His book contains a formula for tonnage calculation (Duro, 1996, 5:36–97):

$$\text{Tonnage} = 0.95 \times M/2 \times P \cdot E/8 = 0.95 \times M \times P \times E/16 \qquad (7)$$

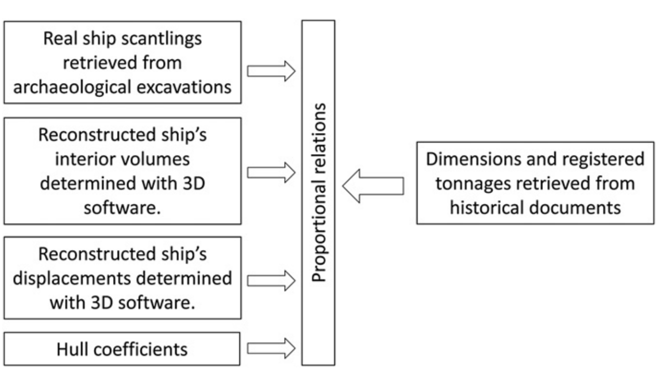

Fig. 2. Relations between historical and archaeological data (Filipe Castro).

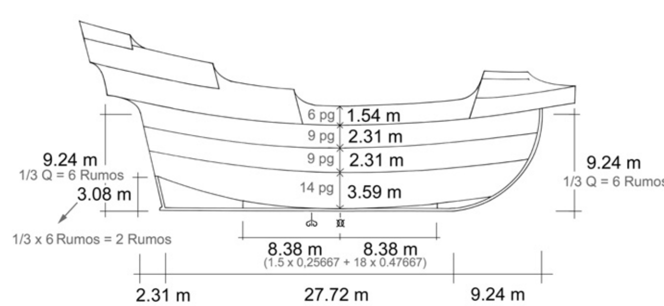

Fig. 4. A profile of the Pepper Wreck with some of the measurements indicated in Oliveira's treatise and the presumed positions of the ship's decks. The measurements indicated do not include the thickness of the pavements, which was slightly over 1 *palmo de goa* per deck (Filipe Castro).

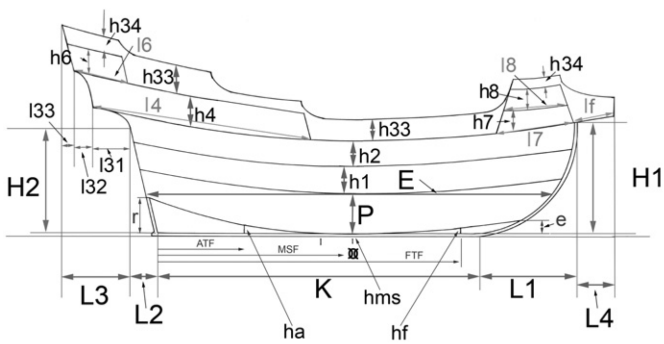

Fig. 5. Defining dimensions of an Iberian ship in the period under analysis, see Table 1 for explanations of the measurements indicated (Filipe Castro).

Where E = *Eslora*; M = *Manga*; and P = *Puntal*; all are measured at the lower deck level.

Two years later a new set of *ordenanzas* was issued. The *Ordenanzas* of 1613 modified the classification established in 1607 and divided the existing ships into *pataches* (70–94 *toneles machos*), *navíos* (148–258 *toneladas*) and *galeones* (316–1073 *toneladas*). Three months later an addendum titled *Regla del arqueo* acknowledged the complaints of many shippers, Spanish and foreigners, pertaining to the correct ways of calculating tonnage, abolished all the formulas in use, and established three new formulas for tonnage calculation, all in *toneles* machos, incorporating the value of the flat of the floor (*plan*) on the master frame, hereafter F, and reducing the calculated tonnage by considering only half of the depth in hold in the calculations. No reasons or instructions are given for the situations in which each of the new formulas was to be used (Mendoza, 2008b; Serrano, 1989). The first formula considered three situations, depending on the relation of the flat of the floor to the maximum beam. If the flat equaled half of the maximum beam, this was the formula prescribed:

$$\text{If } F = M/2 \rightarrow \text{Tonnage} = [M \cdot P/2 \times (E+K)/2]/8 \tag{8}$$

When the flat of the floor (*plan*, P) was larger or smaller than half of the maximum beam, the final tonnage was to be increased or reduced by the value obtained multiplying $|(M/2 - F)/2|$ by the expression $P/2 \times (E + K)/2$. In other words:

$$\text{If } F > M/2 \rightarrow \text{Tonnage} = [(M \cdot P/2 \times (E+K)/2) + (F - M/2)/2 \times P/2 \times (E+K)/2]/8 \tag{9}$$

$$\text{If } F < M/2 \rightarrow \text{Tonnage} = [(M \cdot P/2 \times (E+K)/2) - (M/2 - F)/2 \times P/2 \times (E+K)/2]/8 \tag{10}$$

Where E = *Eslora*; M = *Manga*; F = *Plan*, K = *Quilla*, or Keel length; and P = *Puntal*; all measured at deck level.

The second formula is similar, but established a new value for the beam in the calculation, in the following way:

$$\text{If } F > M/2 \rightarrow M_1 = M + (M/2 - F)/2 \tag{11}$$

$$\text{If } F < M/2 \rightarrow M_2 = M + (F - M/2)/2 \tag{12}$$

The resulting formulas are:

$$\text{If } F = M/2 \rightarrow \text{Tonnage} = [M \cdot P/2 \times (E+K)/2]/8 \tag{13}$$

$$\text{If } F > M/2 \rightarrow \text{Tonnage} = [M_1 \cdot P/2 \times (E+K)/2]/8 \tag{14}$$

$$\text{If } F < M/2 \rightarrow \text{Tonnage} = [M_2 \cdot P/2 \times (E+K)/2]/8 \tag{15}$$

The third formula is independent of the relation between the maximum beam and the flat of the floor:

$$\text{Tonnage} = [(3/4M + 1/2F) \times P/2 \times (E+K)/2]/8 \tag{16}$$

In 1618 new *ordenanzas* were issued, but the 1613 formulas were not changed.

In England Matthew Baker introduced the “cubic number” ($E \times P \times M$) in the last quarter of the 16th century as a number that could be used to compare ships of different sizes and deduce, through simple rules of proportion, the values of the length overall, beam, and depth in hold of ships. This rule implies that ships were not radically different, namely in what pertains to what nowadays would be called the block coefficient: the ratio between the submerged volume of a fully loaded hull, and the box that contains it, whose volume is calculated multiplying the length, beam, and draft on the load waterline. As in Spain the depth in hold was measured at the point of maximum beam.

During the 16th century Baker’s “cubic number” evolved into “Mr. Baker’s old rule”, used to calculate ship’s tonnages when divided by a certain value (100, 97.5, or 90), which transformed the

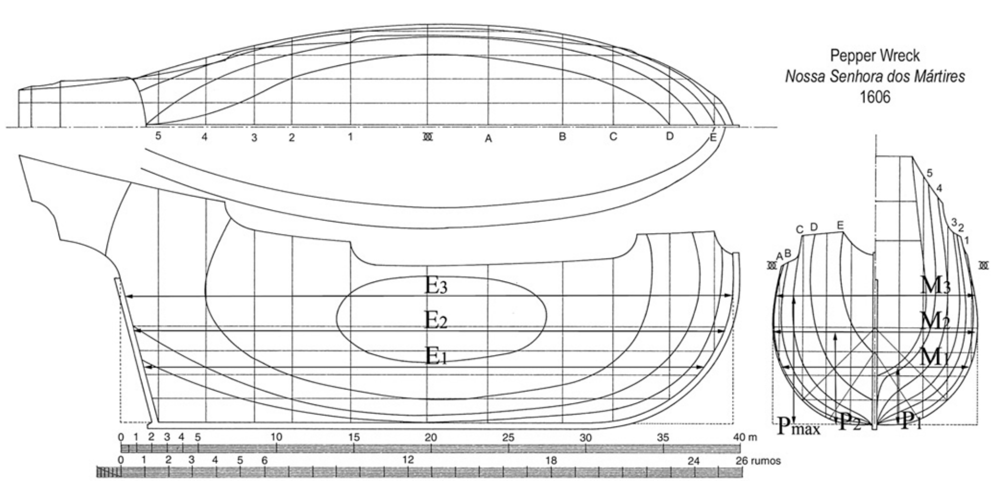

Fig. 6. Basic measurements of the reconstructed Pepper Wreck (Filipe Castro).

result from cubic feet into tons (56–60 cu. ft.), and somehow discounted the rising and narrowing of the ship's bottom (Salisbury, 1966).

$$\text{Tonnage} = \text{E} \times \text{M} \times \text{P}/100 \quad (17)$$

$$\text{Tonnage} = \text{E} \times \text{M} \times \text{P}/97.5 \quad (18)$$

$$\text{Tonnage} = \text{E} \times \text{M} \times \text{P}/90 \quad (19)$$

From the mid-17th century onwards, formulas to calculate tonnage proliferated and replaced empirical rules.

The application of formulas to dimensions retrieved from the archaeological record, and the comparison of the values obtained with those mentioned in historical documents will certainly yield interesting results. These results may in turn be compared with real volumes, obtained from ship reconstructions with 3D computer software and scantling lists retrieved from archaeological excavations, as indicated in Fig. 2.

At a second phase of this study computer graphics will be utilized. Preliminary experiments yielded promising results with results clustering around plausible values, both for timber scantlings and hull coefficients (Cook, 2011). The results of future studies may help us predict the real size of a ship – its hull displacement within a range of plausible values – from the scantlings and some partial basic dimensions retrieved from the archaeological record. This knowledge would in turn help establish feedback and try to relate the real size with its calculated capacity, using historical formulas and recipes or sets of basic values used to build ships, included in ship treatises, contracts, and other contemporary documents. Below is a flowchart with the basic operations of such a study (Fig. 3).

6. The Pepper Wreck as a case study

An example of such a study is the analysis of the hull reconstruction of the Pepper Wreck (Castro, 2003, 2005a, 2005b and 2009; Castro and Fonseca, 2006; Castro et al., 2010). From its archaeological remains we have reconstructed the entire ship as a three-decker with a length of keel 27.72 m (18 *rumos*), and its related measures, following father Oliveira's method, indicated in Table 2 and Fig. 4.

On Table 1 below are indicated some of the values that defined the shape of a vessel in Portugal in the late 16th or early 17th centuries. Not all the measurements indicated in the drawing are used in the calculations presented below, but they are all relevant for the definition of the hull shape. The nomenclature of the upper hull dimensions is not considered in this study.

The ratios Beam/Keel/Length overall are 1/2.1/2.9 on the Pepper Wreck. The *Block Coefficient* is around 0.5, varying slightly around this value as the load waterline moves up and down. Before discounting the spaces occupied by equipment, the interior volume of the ship as reconstructed is 719 m^3 in the hold, 1455 m^3 for the combined volume of the hold and the lower deck, and 2337 m^3 for the combined volume of the hold, middle and upper deck (Santos et al., 2007). The ship's displacement is 1330 tons for a draft of 5.0 m.

Considering only the ship's hold, the tonnage calculated with the formulas described above is given in Table 3. Column three presents the percentual error of the values calculated when compared with the Pepper Wreck registered tonnage (600 *toneladas*), and column five presents the volume equivalent to the tonnage calculated as a percentage of the volume of the hold (the volume below the lower deck) of the reconstructed Pepepr Wreck (719 m^3).

Table 1
Definition of the basic dimensions used for hull calculations.

Ref.	Definition of the basic dimensions
M	Maximum beam.
M_3	Beam at upper deck level.
M_2	Beam at 2nd deck level.
M_1	Beam at hold level.
F	Width of the flat portion of the midship frame.
T	Width of the transom (see Fig. 1)
K	Length of keel.
E	Length for calculation of capacity.
E_3	Length at the upper deck level, commonly designated length overall (or LOA).
E_2	Length at the second deck level.
E_1	Length at the hold level.
H2	Height on the top of the sternpost
L2	Rake of the sternpost measured horizontally.
H1	Height of the top of the stem post.
L1	Spring of the stem post.
FTF	Distance from the aft end of the keel to the position of the fore tailframe.
MSF	Distance from the aft end of the keel to the position of the master frame.
ATF	Distance from the aft end of the keel to the position of the aft tailframe.
hf	Total rising on the fore tailframe.
hms	Foot of the master frame.
ha	Total rising on the aft tailframe.
nf	Width on the fore tailframe, obtained by subtracting the total narrowing from the flat of the floor timber (F).
na	Width on the aft tailframe, obtained by subtracting the total narrowing from the flat of the floor timber (F).
r	Runs, or height at which the fashion pieces connect to the sternpost.
e	Entries, or height at which the line of the lower ribband touches the stem post.
P_{max}	Depth in hold.
P_2	Depth at the second deck level.
P_1	Depth at the hold level.
h1	Clearance on the lower deck, above the hold.
h2	Clearance on the second deck.

The volume was calculated considering one *tonel macho* 8 *codos de ribera*^{3} (1.521 m^3), one *tonelada de carga* 8 *codos castellanos*^{3} (1.382 m^3) and one *ton burden* 40 pés^3 (1.133 m^3).

It is evident that formulas (10), (15) and (16), used in the 17th century, underestimated the cargo capacity by around 20%, but we

Table 2
Values of the basic dimensions used for calculations.

Basic dimensions	Ref.	Pepper Wreck	× K
Beam at the upper deck level	M_3	12.45	0.45
Beam at the 2nd deck level	M_{h1}	13.00	0.47
Max. beam (at $y = 6.16$ m)	M	13.05	0.47
Beam at the hold level	M_p	12.20	0.44
Flat amidships	F	4.62	0.17
Transom width	T	6.66	0.24
Length overall	E	39.27	1.42
Length at 3rd deck level	E_3	39.25	1.42
Length at 2nd deck level	E_2	38.15	1.38
Length at max beam level	E_{mb}	38.00	1.37
Length at hold level	E_1	36.20	1.31
Keel length	K	27.72	1.00
Height of the sternpost	H2	9.24	0.33
Rake of the sternpost	L2	2.31	0.08
Height of the stem post	H1	9.24	0.33
Spring of the stem post	L1	9.24	0.33
Runs	r	3.08	0.11
Entries	e	1.23	0.04
Depth at the upper deck	P_{max}	8.98	0.32
Depth at the 2nd deck	P_2	6.42	0.23
Depth at max. beam level	P_{mb}	6.16	0.22
Depth of hold	P	3.85	0.14

Table 3
Depth of hold = 16 *palmos de goa*.

Formula	Tonnage	% of 600 tons	Volume	% of P. Wreck
(4)	560 *toneles machos*	−7	368 m^3	51
(5)	628 *toneladas de carga*	+5	375 m^3	52
(6)	648 *toneladas de carga*	+8	387 m^3	54
(7)	584 *toneladas de carga*	−3	349 m^3	49
(10)	464 *toneles machos*	−23	305 m^3	42
(15)	523 *toneles machos*	−13	344 m^3	48
(16)	464 *toneles machos*	−23	305 m^3	42
(17)	600 *tons burden*	0	530 m^3	74
(18)	616 *tons burden*	+3	544 m^3	76
(19)	667 *tons burden*	+11	589 m^3	82

Table 4
Tonnages considering the hold and the lower deck.

Formula	Tonnage	% of P. Wreck	Volume	% of P. Wreck
(4)	994 *toneles machos*	+66	654 m^3	45
(5)	1014 *toneladas de carga*	+69	666 m^3	46
(6)	1046 *toneladas de carga*	+74	688 m^3	47
(7)	994 *toneladas de carga*	+66	654 m^3	45
(10)	782 *toneles machos*	+30	515 m^3	72
(15)	890 *toneles machos*	+48	591 m^3	82
(16)	838 *toneles machos*	+40	551 m^3	77
(17)	1124 *tons burden*	+87	992 m^3	68
(18)	1153 *tons burden*	+92	1018 m^3	70
(19)	1249 *tons burden*	+108	1103 m^3	76

must keep in mind that the contracts were paid in *toneladas de sueldo*, precisely 20% more expensive than the *toneladas de carga*. If we consider the remaining formulas, the calculated tonnages fall within an interval of 600 ± 8% *toneless* or *toneladas*, or even *tons burden*, except the Baker formula (19), which is 11% above the 600 *toneladas* value. Even formulas (10), (15) and (16) seem to work when they are transformed into *toneladas de sueldo*.

Since the reconstructed Pepper Wreck is a three-decker and the majority – if not all – of these formulas were deduced to calculate the capacity of ships with one or two decks, we were not sure how to apply the foreign formulas to a Portuguese ship. Moreover, given the large size of the Portuguese Indiamen of this period, and considering that the maximum beam of our reconstruction occurs slightly below the second deck, at a depth of hold of 24 *palmos de goa* (6.16 m), we have also calculated the tonnages for the volume below the second deck, and obtained the values indicated on Table 4. The percentage of Pepper Wreck's 600 tons is indicated on column 3, as in Table 3.

As on Table 3, volumes on Table 4 were calculated considering one *tonel macho* 8 *codos de ribera*^{3} (1.521 m^3), one *tonelada de carga* 8 *codos castellanos*^{3} (1.382 m^3) and one *ton burden* 40 pés^3 (1.133 m^3). The depth of hold was measured at the level of the second deck (25 *palmos de goa*).

7. Conclusions

The analysis of Table 4 demonstrates that the calculation of the registered tonnage of a ship was performed considering uniquely the capacity of the hold, even for ships with three decks, such as the Portuguese Indiaman under analysis.

At this point, and having in mind the disparity of units and formulas considered, it seems possible to conclude from this preliminary study that the formulas analyzed estimate the registered capacity of a ship such as the Pepper Wreck within a workable margin.

The same convergence of values seems to emerge from the calculations of the volumes of the barrels analyzed, which have capacities that also fall within workable ranges of values: 890 L plus or minus 7%. Only further study, however, over a larger sample of reconstructed hulls, and references to dimensions of barrels, will allow reliable conclusions regarding the establishment useful relations between lengths of keel, overall lengths, beams, depths of hold, tonnages, and displacements. As mentioned above, two complementary studies are being developed in parallel, one concerning relations between scantlings, tonnages, and displacements, and the second analyzing the variation of block coefficients through types of hulls. As information about shipwrecks of this period slowly becomes available through publications, we hope that a growing body of data will help develop these lines of investigation. We believe that these studies will help us better evaluate the size, dimensions, and hull shape of early modern European ships both from documental and archaeological sources.

Acknowledgments

I am greatly indebted to Nuno Fonseca, Richard Unger, and Richard Barker, whose precious comments helped improve both the quality of this paper and my knowledge on this subject enormously. Richard Barker has a rather different opinion on the subject of precision and cautioned me against some of my assumptions, emphasizing for instance the difference between an *observation* – one ton corresponding to about 2000 pounds of contents and about 2240 pounds gross weight – and a *definition* – one foot being equal to 12 inches; or alerting me for the fact that coopers could adjust the capacity of a barrel when they positioned the upper head. I have taken carefull notes of each of their questions, and all my future research will focus on trying to answer them. I am both honored and grateful that these great scholars agreed to spend time on my work.

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