Carrier Phase Ambiguity Resolution for Ship Attitude Determination and Dynamic Draught

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SUMMARY

A newly developed GNSS (Global Navigation Satellite System) carrier phase ambiguity resolution method to determine the full attitude and dynamic draught of ships is analysed. GNSS receivers placed onboard a ship can provide both absolute vertical motions relative to a fixed vertical reference on earth, to be used (in combination with nautical chart datum) to estimate the UKC (Under-Keel Clearance), and relative baseline measurements which are employed to estimate the attitude of the ship.

The advantage of the GNSS-RTK (Real Time Kinematic) solution compared to other techniques (e.g. Inertial sensors) is that it is driftless and, if carrier phase observations are used, still of high accuracy. The difficulties of using such method lie mostly in the ambiguity nature of the phase observations: in order to fully exploit their higher precision compared to the code measurements, the ambiguities must be solved. To apply the RTK technique for the application of this study, it is necessary to solve for the ambiguities in the shortest time possible, ideally on a single-epoch base; therefore one needs a reliable ambiguity resolution algorithm. The algorithm we make use of in this contribution is an extension of the well-known LAMBDA (Least-squares AMBiguity Decorrelation Adjustment) method, that is currently the standard method for solving unconstrained GNSS ambiguity resolution problems. Its modification, the so-called Constrained LAMBDA method, rigorously incorporates into the integer estimation process the nonlinear constraints as given by the known GNSS antennas geometry configuration. The main advantage of the method is that it avoids the use of multiple high grade antennas/receivers to be placed onboard the ship to estimate its attitude and UKC, providing a reliable baseline solution on an epoch by epoch base. The method is extensively tested on data collected onboard large ships sailing into the harbour of Hong Kong, and a performance comparison between the classical RTK approach and the new method is given.

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1. INTRODUCTION

In this contribution a newly developed GNSS (Global Navigation Satellite System) carrier phase ambiguity resolution method to determine the full attitude and dynamic draught of ships is tested. GNSS receivers placed onboard a ship can provide both absolute vertical motions relative to a fixed vertical reference on earth, to be used (in combination with nautical chart datum) to estimate the UKC (Under-Keel Clearance), and relative baseline measurements which are used to estimate the attitude of the ship.
GNSS-aided sinkage and attitude estimation have been analyzed and tested in [1-2]. Carrier-phase measurements collected from three geodetic quality dual-frequency receivers placed onboard were used to provide three sets of absolute coordinates with the aid of a reference station on land, as a classical RTK (Real Time Kinematic) configuration. The advantage of the GNSS-RTK compared to other techniques (e.g. Inertial sensors) is that it is driftless and, if carrier phase observations are used, still of high accuracy. The difficulties of using such method lie mostly in the ambiguity nature of the phase observations: in order to fully exploit their higher precision compared to the code measurements, the ambiguities must be solved. To apply the RTK technique for the application of this study, it is necessary to solve for the ambiguities in the shortest time possible, ideally on a single-epoch base; therefore one needs a reliable ambiguity resolution algorithm. The algorithm tested in this contribution is an extension of the well-known LAMBDA (Least-squares AMBiguity Decorrelation Adjustment) method [3], which is currently the standard method for solving unconstrained GNSS ambiguity resolution problems [4-8]. Its modification, the so-called Constrained LAMBDA method [9-15], rigorously incorporates into the integer estimation process the nonlinear constraints as given by the known GNSS antennas geometry configuration. The main advantage of the method is that it avoids the use of multiple high grade antennas/receivers to be placed onboard the ship to estimate its attitude and UKC, providing a reliable baseline solution on an epoch by epoch base. The method does not use the a-priori information to validate the baseline solution. Instead, it embeds the geometrical constraint in the ambiguity resolution algorithm, thus directly aiding the fixing process. The method is extensively tested on data collected onboard large ships sailing into the harbour of Hong Kong, and a performance comparison between the classical RTK approach and the new method is given.

2. GNSS-BASED ATTITUDE DETERMINATION AND UKC ESTIMATION

To estimate a ship's attitude and the sinkage, different sensors can be employed. A common solution is the use of inertial units coupled with sonars or other sensing devices to detect the distance from the seabed. This system presents some disadvantages, such as a time-dependent error due to the drift of the inertial systems. The GNSS technology overcomes this problem, since it is driftless and it only relies on external information, namely the GNSS signals. The absolute precise position of the ship is estimated making use of a classical RTK configuration. A receiver (or more, forming a network) placed inshore or at the berth is taken as a reference station, and one or more receivers - at least three are necessary to extract orientation angles - are placed onboard the ship. GNSS baseline processing between the antenna on the ground and the different antennas onboard provide the relative position of different points on the ship with respect to the ground station. If the absolute position of the latter is known, the precise absolute coordinates of the antennas on the ship are made available.

In order to have high-precision products, the GNSS carrier phase measurements are usually employed, which guarantee accuracies up to cm-level. Phase observations are, however, affected by integer ambiguities: only the fractional part of the phase of the incoming GNSS signal can be measured. The process of resolving the ambiguities as integers is non-trivial if one aims to a fast and reliable solution. Ideally, the positioning products should be available on a single-epoch base, hence the ambiguities should be resolved with a single epoch of data. To increase the probability of correct fixing, in practice a multi-epoch processing is often carried out, with the limitation that one needs a certain amount of time to recover from cycle-slips or losses of lock. Moreover, to enhance the ambiguity resolution process, a certain number of measurements from different GNSS frequencies can be used. A multi-frequency approach also allows correcting for some atmospheric errors, such as ionospheric delays. Multi-frequency receivers are, however, more expensive and heavier than single-frequency equipment.

Carrier phase GNSS-assisted UKC estimation was demonstrated to be a viable technique in [1-2][16]. A set of three dual-frequency GPS antennas/receivers installed onboard a ship provides accurate baseline measurements with respect to a dual-frequency antenna/receiver placed at the berth. The use of high-grade receivers guarantees good results. Here we present a method to reduce the costs for applications where a frame of antennas is firmly mounted on the ship, at known relative distances. Instead of using three high-grade receivers onboard, only one is necessary in our method to extract the baseline between the ship and the ground reference. The other two (or more) antennas/receivers onboard can be single-frequency, low-cost receivers. A reliable ambiguity resolution is achieved by a new ambiguity resolution method which exploits the a-priori information on the baseline lengths. Embedding the geometrical constraint strengths the observation model and achieves fixing rates comparable with those of unconstrained dual-frequency processing.

The two different methods are illustrated in figure 1, where a classical 4-antennas RTK configuration (on the left) is opposed to our low-cost solution (right), where only half of the high-grade receivers are used.

In the unconstrained approach, a standard ambiguity resolution algorithm based on the popular LAMBDA method is applied, whereas the constrained baselines are tackled with a nontrivial modification of LAMBDA, the Constrained LAMBDA (C-LAMBDA) method.
In the next section the two methods are reviewed.

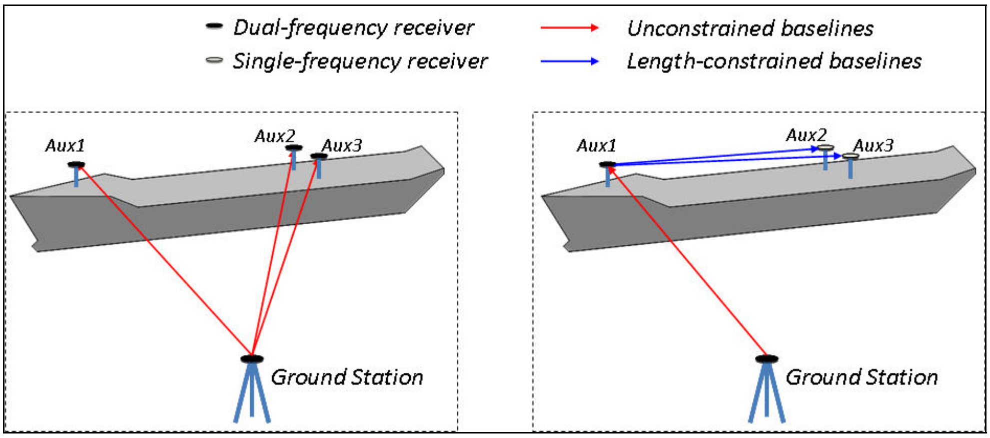

Figure 1 Scheme of a classical RTK approach (left) with four dual-frequency antennas/receivers compared to the low(er)-cost solution (right) where the number of dual-frequency equipment is halved.

2.1 The GNSS observables and functional model

The GNSS observables are the code and carrier phase measurements collected at each receiver. With the assumption that the precise absolute coordinates of the ground station are available, only the relative distances between the antennas on the ships and the reference station have to be estimated. Thus, the differences between the measurements taken at two antennas are formed (Single Differences, SD). Furthermore, to eliminate the remaining clock errors we make use of the Double Differences (DD), where the differences between SD from two different satellites are built [17]. The $2n$ DD observations collected continuously tracking $n+1$ satellites on one or more frequencies (N_f) are modelled as

$$\begin{array}{l} E(y) = Aa + Bb \\ D(y) = Q_{yy} \end{array} \qquad a \in \mathbb{Z}^{N_f n} \quad ; \quad b \in \mathbb{R}^3 \tag{2.1}$$

where E is the expectation operator, a the unknown integer ambiguities and b the unknown real-valued baseline coordinates. We assume that the distances between the antennas are limited to a few kilometres, so that the atmospheric effects become neglectable after the differencing operations [17]. Also, we consider in the following a maximum of two frequencies. A and B are the design matrices that link the observables with the unknowns. A is the matrix of carrier wavelengths

$$A = \begin{bmatrix} 0 \\ \lambda_1 I_n \end{bmatrix} \text{ if single-frequency} \quad ; \quad A = \begin{bmatrix} 0 \\ \lambda_1 I_n \\ 0 \\ \lambda_2 I_n \end{bmatrix} \text{ if dual-frequency} \tag{2.2}$$

being λ_i the wavelength of the i-th frequency, whereas B is the matrix formed stacking the matrices of unit line-of-sight vectors G

$$B = \begin{bmatrix} G \\ G \end{bmatrix} \text{ if single-frequency } \; ; \; B = \begin{bmatrix} G \\ G \\ G \\ G \end{bmatrix} \text{ if dual-frequency} \tag{2.3}$$

The dispersion (D) on the observed data y is described by the variance-covariance (v-c) matrix Q_{yy}.

Model (2.1) describes the classical unconstrained model, where no geometrical constraints on the baseline coordinates b are given and the only constraint considered is the integer nature of the ambiguities $a \in \mathbb{Z}^{N_f n}$. For the baseline constrained configuration proposed in this work, the a-priori knowledge on the baseline length is used to constraint the coordinates of the baseline vector b

$$\begin{array}{c} E(y) = Aa + Bb \\ D(y) = Q_{yy} \end{array} \quad a \in \mathbb{Z}^{N_f n} \; ; \; b \in \mathbb{R}^3 \; ; \; \|b\| = l \tag{2.4}$$

In the following section, the solution of both the unconstrained and constrained models is given.

2.2 Ambiguity Resolution methods

The models (2.1) and (2.4) are solved applying the Integer Least-Squares (ILS) theory [18], an extension of the least-squares principle for linear systems where a subset of the unknowns is integer-valued. The LAMBDA method is a fast and reliable implementation of the ILS principle, while the C-LAMBDA method is a recent extension of the classical LAMBDA method. The C-LAMBDA method has been developed to tackle baseline constrained applications, such as GNSS-based attitude determination.

2.2.1 The LAMBDA method

Three steps are involved in the solution of the system (2.1). First step is the derivation of the float solution $\left(\hat{a}, \hat{b}\right)$, i.e., the least-squares solution derived disregarding the integer constraint. The float solution is obtained solving the normal system of linear(ized) equations

$$\begin{bmatrix} A & B \end{bmatrix}^T Q_{yy}^{-1} \begin{bmatrix} A & B \end{bmatrix} \begin{pmatrix} \hat{a} \\ \hat{b} \end{pmatrix} = \begin{bmatrix} A & B \end{bmatrix}^T Q_{yy}^{-1} y \tag{2.5}$$

The precision of the float solution $\left(\hat{a}, \hat{b}\right)$ is characterized by the v-c matrix

$$\begin{bmatrix} Q_{\hat{a}\hat{a}} & Q_{\hat{a}\hat{b}} \\ Q_{\hat{b}\hat{a}} & Q_{\hat{b}\hat{b}} \end{bmatrix} = \begin{bmatrix} A^T Q_{yy}^{-1} A & A^T Q_{yy}^{-1} B \\ B^T Q_{yy}^{-1} A & B^T Q_{yy}^{-1} B \end{bmatrix}^{-1} \tag{2.6}$$

Assuming the vector of ambiguities a known, the solution of the system (2.1) would give the conditional (on a) solution for b. Based on the expressions (2.5)-(2.6), the conditional baseline solution and its v-c matrix are

$$\hat{b}(a) = \hat{b} - Q_{\hat{b}\hat{a}} Q_{\hat{a}\hat{a}}^{-1} (\hat{a} - a)$$
$$Q_{\hat{b}(a)\hat{b}(a)} = Q_{\hat{b}\hat{b}} - Q_{\hat{b}\hat{a}} Q_{\hat{a}\hat{a}}^{-1} Q_{\hat{a}\hat{b}} \tag{2.7}$$

The least-squares principle applied to the system (2.1) aims to minimize the weighted squared norm of residuals $\|y - Aa - Bb\|_{Q_{yy}}^2$, where $\|\bullet\|_{Q_{yy}}^2 = (\bullet)^T Q_{yy}^{-1} (\bullet)$. The sum-of-squares decomposition based on the float solution reads [17]

$$\|y - Aa - Bb\|_{Q_{yy}}^2 = \|\hat{e}\|_{Q_{yy}}^2 + \|a - \hat{a}\|_{Q_{\hat{a}\hat{a}}}^2 + \left\|b - \hat{b}(a)\right\|_{Q_{\hat{b}(a)\hat{b}(a)}}^2 \tag{2.8}$$

where $\hat{e}$ is the vector of residuals. The right hand side of the equation shows that the minimization involves the second term only, since the baseline term can always be made zero by imposing $b = \hat{b}(a)$. Hence, the residuals are minimized through the solution of the ILS problem

$$\breve{a}^U = \arg\min_{a \in \mathbb{Z}^{N_f n}} \|a - \hat{a}\|_{Q_{\hat{a}\hat{a}}}^2 \tag{2.9}$$

The integer vector $\breve{a}^U$ minimizes the distance with respect to the float solution $\hat{a}$, in the metric of $Q_{\hat{a}\hat{a}}$. The search for the integer minimizer $\breve{a}^U$ is efficiently performed via the LAMBDA method. The integer vector is searched inside a certain set of admissible candidates (the search space), which is extensively explored until the minimizer of (2.9) is extracted. The search is made fast via a decorrelation of the matrix $Q_{\hat{a}\hat{a}}$, that smoothes the spectrum of admissible integer candidates [17].
The fixed vector of integer ambiguities $\breve{a}^U$ gives the fixed baseline vector $\breve{b}^U = \hat{b}(\breve{a}^U)$.

2.2.2 The C-LAMBDA method

The solution of the baseline constrained model (2.4) requires a non-trivial modification of the approach described in the previous section, although the solution follows the same conceptual steps of the classical LAMBDA method.
The float solution is firstly derived, following equations (2.5)-(2.7). The sum-of-squares decomposition (2.8) shows that for the baseline constrained case it is not possible to make the last term on the right hand side equal to zero, due to the nonlinear constraint $\|b\| = l$. Therefore the minimization problem is formulated as

$$\breve{a}^C = \arg\min_{a \in \mathbb{Z}^{N_f n}} \left[\|a - \hat{a}\|_{Q_{\hat{a}\hat{a}}}^2 + \left\|\breve{b}(a) - \hat{b}(a)\right\|_{Q_{\hat{b}(a)\hat{b}(a)}}^2 \right]$$
$$\text{with} \quad \breve{b}(a) = \arg\min_{b \in \mathbb{R}^3 ;\, \|b\| = l} \left\|b - \hat{b}(a)\right\|_{Q_{\hat{b}(a)\hat{b}(a)}}^2 \tag{2.10}$$

The search for the integer minimizer $\breve{a}^C$ is now complicated by the tight coupling between the terms of (2.10). The sought-for vector $\breve{a}^C$ weighs both the distance to the ambiguity float solution (weighted by $Q_{\hat{a}\hat{a}}$) and the distance between the adjusted float solution $\hat{b}(a)$ and the sphere of radius l (weighted by $Q_{\hat{b}(a)\hat{b}(a)}$). The evaluation of the cost function (2.10) requires

a longer computational time than the unconstrained case (2.9), and a direct search-based method such as LAMBDA turns out to be inefficient.
The C-LAMBDA method has been designed to efficiently solve for the problem (2.10). After a decorrelation of the set of admissible candidates, which has different shape and size compared to the unconstrained case, the search is made faster via the introduction of novel search techniques as the *Search and Shrink* approach [14-15][19] or the *Expansion* approach [11] [20]. These search algorithms adaptively adjust the size of the search space shrinking or expanding the set of candidates as the search proceeds. Both techniques have been proved to work efficiently, with computational efficiency comparable to the one of the LAMBDA method.
The advantage of the C-LAMBDA method lies in the major strength of the functional model. The baseline coordinates are constrained by the knowledge of the distance between the antennas. Embedding this information in the ambiguity resolution process enormously benefits the search for the correct integer ambiguity vector. This allows to down-grade the GNSS equipment requirement in case of a static configuration of antennas, such as the case of antennas firmly installed on moving platforms.

3. TEST RESULTS

In 2005 the Centre for Marine Science and Technology, Curtin University of Technology, performed a series of tests on the account of the Hong Kong Marine Department. A detailed study of the sinkage and dynamic draft of containerships entering and leaving Kwai Chung, the busiest container port in the world, was performed. Full-scale trials were carried out on some of the largest containerships, ranging in overall length from 294 m to 352 m, in order to accurately measure sinkage, trim and roll [2][16]. We here compare some of the results obtained by using the four dual-frequency receivers configuration with results based on our proposed configuration of two dual-frequency receivers (one on ground and one onboard the ship) plus two single-frequency receivers onboard the ship.

3.1 Description of the experiments

Five different containerships were involved in the field test, entering or leaving the harbour of Hong Kong.

Table 1 Basic information about the ships involved in the experiment

Ship	Length [m]	Transit direction	Displacement [tonnes]	Test date and time (GMT)
Anna Maersk	352	Outbound	96600	3-4/2/2005 23:51 ÷ 01:10
Katrine Maersk	318	Inbound	107200	12/2/2005 00:48 ÷ 02:18
Maersk Dortmund	294	Inbound	55000	5/2/2005 00:39 ÷ 01:46
Sally Maersk	347	Outbound	111300	8/2/2005 01:41 ÷ 02:27
Sofie Maersk	347	Outbound	110200	7/2/2005 05:34 ÷ 06:36
Coordinates reference station: *N 22° ; E 114°*				

A ground station was setup at the berth (Trimble 5700 receiver connected to a Trimble Zephyr antenna). Three other receivers/antennas (of same manufacturer and type) were installed onboard, one at the bow, two on the bridge (one at port and one at starboard side).

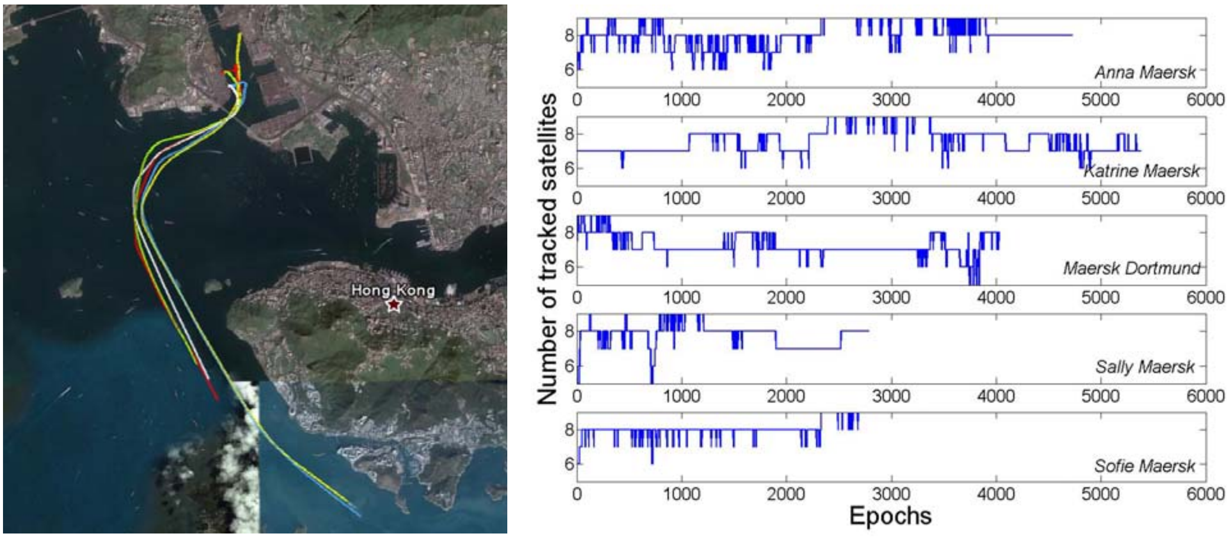

Figure 2 Trajectory of the 5 ships used for the tests in the Hong Kong harbor (left) and number of tracked satellites by all the antennas onboard for each test (right).

Table 1 reports some information about the different ships involved in the experiment. The number of (common) tracked satellites from all the antennas for each test was for most part of the trials seven or eight, with few excursions to nine and few drops to six and five, see figure 2, right. For each ship we computed the precise absolute positioning as well as its attitude (Heading, Roll and Pitch). The estimation of position and attitude, together with the area bathymetry, provide the information needed to estimate the UKC of the ship.

3.2 **Precise GNSS-based absolute positioning of the ships**

The absolute positions are computed resolving the ambiguities and baseline coordinates from

Figure 3 Precise trajectory of the five ships within the docking area. Absolute positions are resolved within 0.1 decimeter error.

one of the antennas on the ship and the reference station. First, we processed the baseline between the ground station and the antenna placed at the bow. The data collected have been resolved with the TGO (Trimble Geomatic Office) software. Figure 3 shows the trajectories of the five ships in the docking area. The different manoeuvres can be easily recognised.

The absolute position of the ship is needed to locate the ship's hull in the harbour, as well as its distance with respect different features of the seabed so to keep the UKC constantly monitored.

3.3 GNSS-based attitude determination of the ships

The ship's attitude is extracted resolving the baselines between the antennas onboard. This can be carried out differencing the baselines formed between the ground station and the antennas on the ship or directly resolving the baselines between the antennas onboard. The latter approach is tackled making use of the C-LAMBDA method.

The first approach was initially analysed, with all the dual-frequency receivers and antennas employed to determine the relative positions of the antennas and the attitude of the ship. The whole amount of data was processed via the TGO software, which solves for the ambiguities on a multi-epoch base, working on all the acquired frequencies (GPS L1 and L2 in this experiment). This approach has been compared with our proposed method, where only the single-frequency observations (GPS L1) collected from the three antennas on the ship have been used.

To illustrate the feasibility of real-time monitoring of ship sinkage and attitude, we looked - for the second case - into the single-epoch performance, which represents the most challenging scenario. The ambiguity resolution takes place at each epoch independently from the previous epochs of data. This allows a total independence from changes of satellites configuration, losses of lock, carrier phase cycle slips and other time-dependent effects.

Table 2 Single-frequency, single-epoch success rate for the three baselines formed by the antennas on the ship: one at the Bow, two on the bridge, Port side and Starboard (Stbd) side.

Ship	Receivers	*Baseline length [m]*	Single-frequency, single-epoch unaided (GPS-only) success rate	
			LAMBDA [%]	C-LAMBDA [%]
Anna Maersk *(outbound)*	Port-Bow	*253.65*	14.5	55.3
	Stbd-Bow	*249.48*	35.2	78.9
	Port-Stbd	*36.565*	26.1	68.6
Katrine Maersk *(inbound)*	Port-Bow	*213.91*	16.4	76.4
	Stbd-Bow	*213.86*	16.8	75.7
	Port-Stbd	*42.515*	38.5	93.4
Maersk Dortmund *(inbound)*	Port-Bow	*223.51*	14.1	61.5
	Stbd-Bow	*223.53*	17.6	75.6
	Port-Stbd	*30.27*	12.1	69.8
Sally Maersk *(outbound)*	Port-Bow	*242.23*	19.9	80.5
	Stbd-Bow	*242.22*	16.9	71.6
	Port-Stbd	*36.09*	32.6	89.5
Sofie Maersk *(outbound)*	Port-Bow	*242.21*	27.6	77.4
	Stbd-Bow	*242.17*	29.9	77.2
	Port-Stbd	*36.22*	47.2	82.9

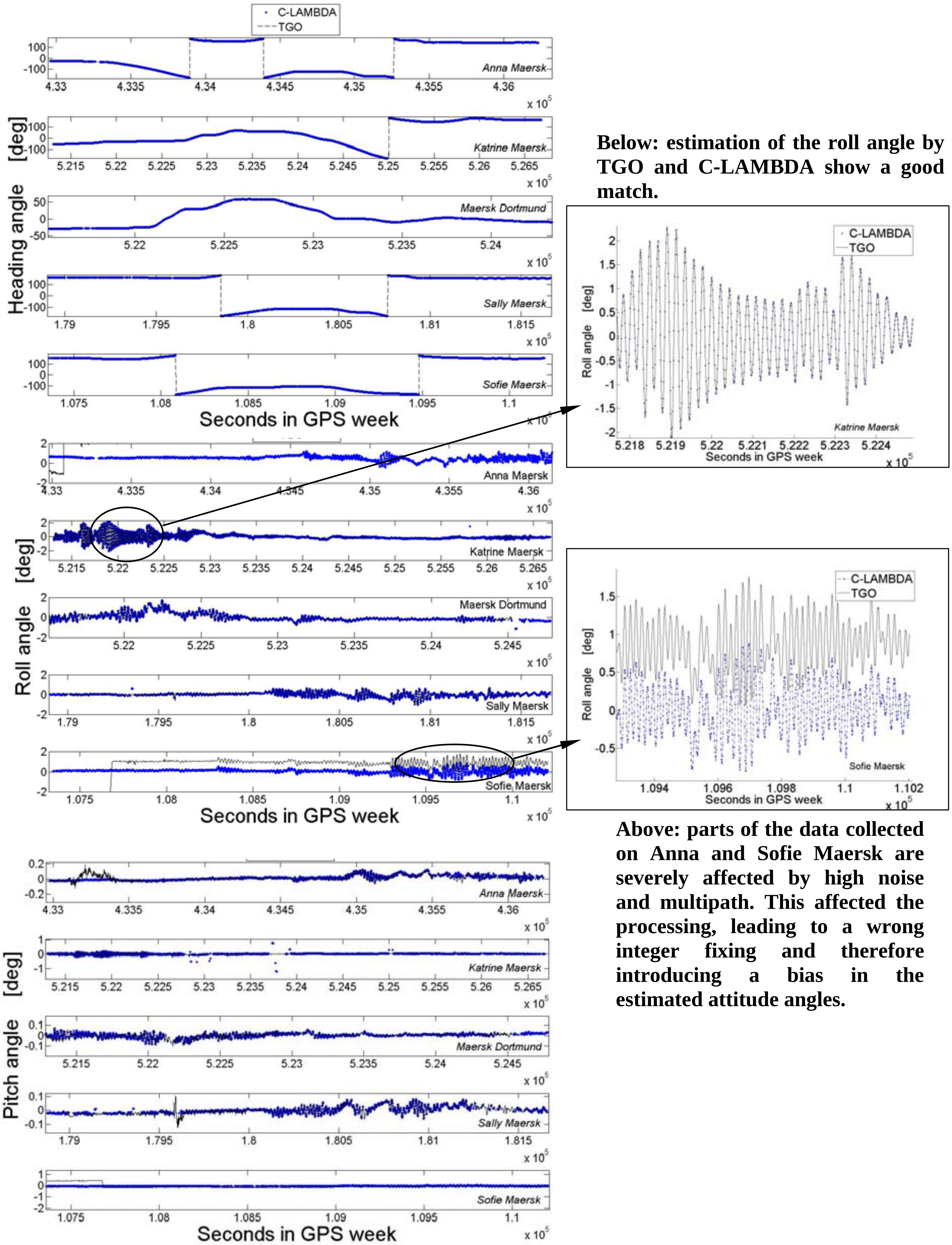

Figure 4 Time series of the attitude angles (Heading, Roll and Pitch) computed with the classical RTK approach using theTGO software (multi-epoch/dual-frequency) or applying the C-LAMBDA method (single-epoch/single-frequency) to the baselines formed by the onboard antennas.

Table 2 reports the single-frequency, single-epoch success rates (i.e., the ratio of epochs where the ambiguities have been correctly fixed) for each of the baselines between the onboard antennas. All the baselines formed by the three antennas on the ship have been processed with the LAMBDA and C-LAMBDA methods, to compare the performance.
The improvement in fixing rate is rather large for all the cases, showing that the inclusion of the baseline length as a constraint in the ambiguity resolution process leads to a striking improvement in the capacity of resolving the correct set of carrier phase ambiguities.
The correct set of integer ambiguities provides the precise baseline coordinates vector. The full attitude of the ship can be easily extracted from the vector observations [14].
Figure 4 shows the three attitude angles for each ship: Heading (with respect to the North direction), Roll and Pitch. The angles have been derived with the two approaches described earlier: the first one using the TGO software, the second one using the C-LAMBDA method. The performances of the C-LAMBDA method match the one of the TGO software, with small deviations between the different estimations. Table 3 gives the mean and standard deviations of the differences between the angle estimations provided by the two methods. Only the three tests where the TGO could resolve the ambiguities for the whole data set have been derived. The differences are mostly contained within 0.05 degree (1 σ), with the exception of the roll angle in the Maersk Dortmund test.

It can be observed that the TGO software provides some incorrect solutions for the first and the last data sets (Anna Maersk and Sofie Maersk): this is probably due to the proximity of the ship to the berth, which causes strong multipath due to the presence of numerous metallic structures. The C-LAMBDA method, instead, provides the correct solution for most part of the trials, making available precise attitude estimations on an epoch by epoch base. It is less sensitive to higher noise levels and multipath due to the higher strength of the underlying model, as given by the inclusion of the geometrical constraints.
It is stressed that the results of the C-LAMBDA method are based on a single-epoch of data, to determine whether the algorithm can provide a correct solution within one epoch. The inclusion of few more epochs (often only two or three) would be sufficient to achieve close to 100% success rate [21].

Table 3 Mean and standard deviations of the differences between the attitude angles provided by TGO and C-LAMBDA processing. Only the three tests where TGO could resolve the ambiguities are given.

Ship		*Heading*	*Roll*	*Pitch*
Katrine Maersk	*Mean [deg]*	0.004	0.001	0.001
(inbound)	*Std dev [deg]*	0.076	0.040	0.055
Maersk Dortmund	*Mean [deg]*	0.005	0.004	0.0004
(inbound)	*Std dev [deg]*	0.079	0.221	0.023
Sally Maersk	*Mean [deg]*	0.001	0.012	0.001
(outbound)	*Std dev [deg]*	0.064	0.036	0.047

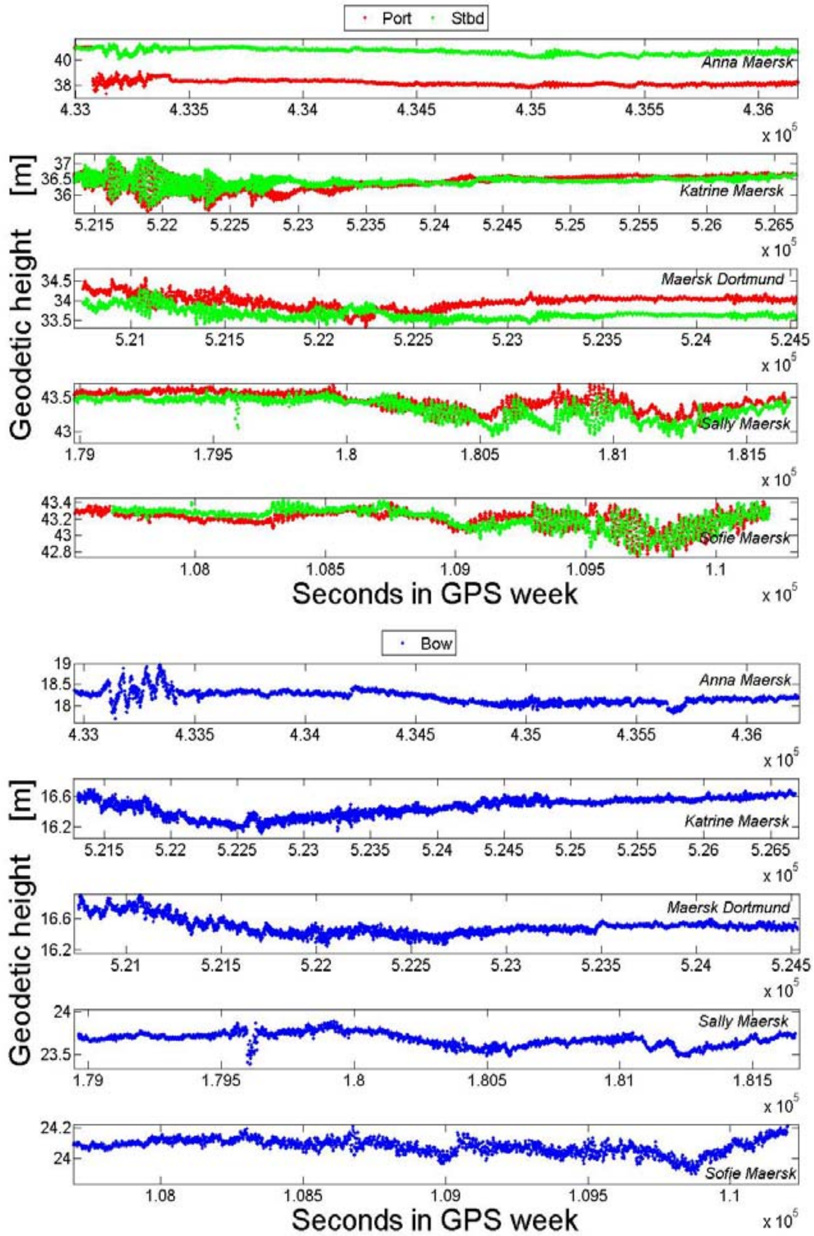

Figure 5 Geodetic height (with respect to the standard ellipsoid WGS84) for the three antennas (Port, Starboard and Bow) on each ship

3.4 Ship UKC estimation

For large ships in shallow water, under-keel clearance (UKC) must be accurately predicted and allowed for, to avoid ship grounding. Part of the difficulty in achieving this is that ships tend to "squat", or sink lower in the water as their speed increases. This effect varies from ship to ship, so extensive research has gone into developing squat allowances for each ship and speed (see [22] for an overview). Heeling of the ship due to turning or wind, and wave-induced ship motions, all act to change the UKC, and must be understood and allowed for.

In order to validate squat prediction methods, GNSS has previously been used to measure ships' vertical elevation changes relative to the undisturbed water level [2,16]. Such validations are an integral part of developing squat prediction formulae, which are then used to plan safe transits through shallow areas. The UKC is generally predicted by combining charted bathymetry, measured or predicted tide heights, and pre-determined allowances for squat, heel and wave-induced motions.

A proposed new application of GNSS to shipping is real-time monitoring and short-term prediction of UKC [1]. This idea makes use of the absolute nature of GNSS elevation measurements. By accurately measuring the positions of the shipboard receivers relative to the ship's frame of reference, the absolute positions of the keel extremities can be found, and compared to the charted local bathymetry to determine UKC. This method bypasses the need for tide height estimation in the calculation of UKC. As discussed in [1], this method is also preferable to the use of depth sounders for assessing UKC of merchant ships, as it promises higher accuracy, gives a complete breakdown of the factors affecting UKC, and allows prediction of UKC over the upcoming bathymetry, so that warnings can be given of impending grounding risk.

Figure 5 shows the time series of the geodetic height estimation for the three antennas on each ship. The geodetic height changes of each antenna are influenced by the vertical movement of the ship's centre of gravity (primarily due to the squat effect with increasing speed) as well as the roll and pitch changes shown in Figure 4.

By using the fixed antenna positions relative to the ship's frame of reference, antenna geodetic heights such as in Figure 5 can be used to determine the keel geodetic heights and hence clearance from the seabed.

4. CONCLUSIONS

This contribution reports field-test results of a newly developed method for GNSS carrier phase ambiguity resolution. The process of resolving the ambiguities inherent to the GNSS phase observables is the key towards very precise (up to cm-level) positioning products. The LAMBDA method is an optimal algorithm to resolve the integer ambiguities, and it is widely used for its computational efficiency. The algorithm has been extended with the C-LAMBDA method to tackle those configurations where the relative distances between the antennas are known. This is the case of frames of antennas firmly mounted onboard moving platforms for attitude determination purposes. The a-priori information is embedded into the ambiguity resolution process, via a modification of the cost function to be minimized by the search algorithm. The strengthening of the observation model reflects into an improved capacity of fixing the correct set of integer ambiguities, if compared to the classical unconstrained algorithms. This allows the user to match the performance usually obtainable only with dual-frequency equipment by using only single-frequency receivers/antennas.

The application subject of this paper is the estimation of ship's attitude and UKC (Under Keel Clearance). To estimate the distance between a ship's hull and the seabed, it is necessary to first resolve for the absolute position of one point on the ship, in order to locate the ship on a nautical chart datum. Then, the attitude of the ship is necessary to detect the deepest point of the hull and avoid collisions with any of the seabed features.

The method presented in this work makes use of only two dual-frequency receivers (one onboard, one onshore) to precisely estimate the ship's position. Then, a set of two or more single-frequency receivers/antennas onboard is required to estimate the hull's attitude. The

use of lower grade equipment is compensated by the higher strength of the functional model if the set of geometrical constraints posed on the baselines are embedded into the ambiguity resolution algorithm.
Test results showed that the C-LAMBDA method matches the performance obtainable with classical RTK multi-frequency configurations, allowing a fast, reliable and precise estimation of the ship's attitude with reduced costs.
Numerous maritime applications could benefit from the algorithm described in this work, ranging from the automatic port navigation to precise docking assistance.

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