MEASURING SHIP CONTROLLABILITY

GNSS for Sea Trials

The effective seakeeping performance of any watercraft is vital for safe navigation. Due to the long maritime tradition in Greece, the National Technical University of Athens (NTUA) has been a key player in developing tools and practices for conducting sea trials in open water. Since the introduction of the Mini-Ranger many years ago through to the recent introduction of the modern GNSS sensors, a number of new-built and commissioned surface ships of various sizes have been tested either in the interests of the shipbuilder or the owner. Currently, new navigation tools and techniques are being set in place to fulfil the demand for increased accuracy and reliability measures.

Ship controllability includes all aspects of regulating vessel kinematics (trajectory, speed and attitude). Sea trials are essential in the verification of critical course keeping and course changing capabilities, as well as emergency manoeuvrability characteristics, while others are intended to demonstrate the performance of vital machinery and regulatory requirements. With regard to the testing of the navigation capabilities of a ship, three distinct areas are involved; i.e. course keeping or steering, manoeuvring and speed changing trials. The first category aims to check the ship's ability to maintain a straight path in a predetermined course direction. Typical testing involves the execution of the Z-manoeuvre and direct / reverse spiral trials (Figure 1). Course changing or turning tests assess the manoeuvrability features of a boat. In this case, the turning circle and Z-manoeuvre are used to characterise the turning and yaw-checking potential of a vessel. Finally, speed changing tests demonstrate the ability to control vessel speed including emergency / inertia slowing, stopping and backing. Here, critical manoeuvre parameters relate to the ease, rapidity and travelled distance associated with a change. In addition, speed tests that characterise ship performance in relation to engine horsepower and propeller capacity are required.

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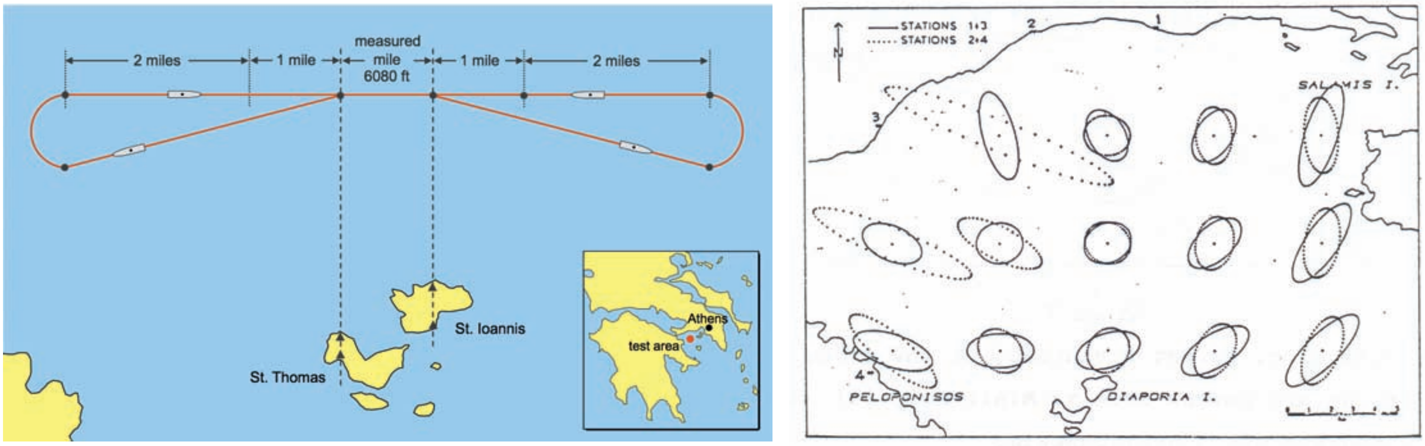
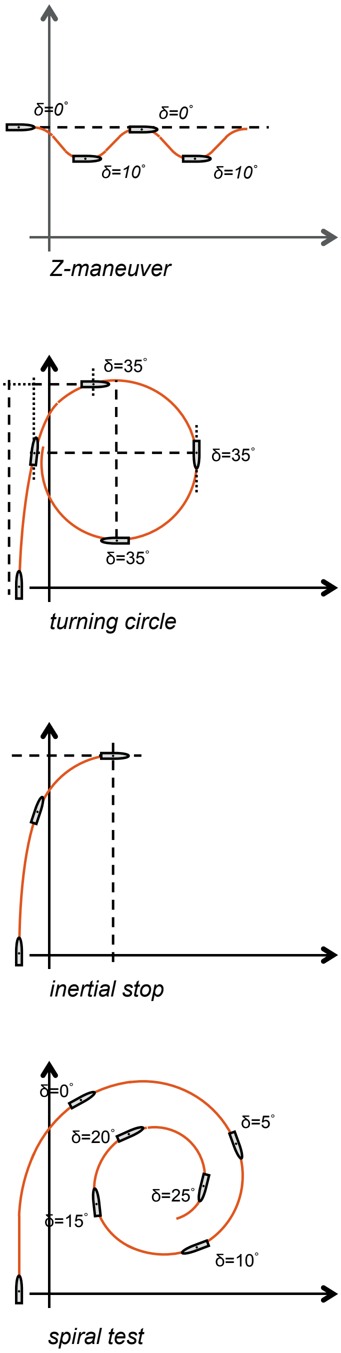


▲ *Figure 2, NTUA test-site (left), and accuracy pre-analysis for MiniRanger III (right).*



▲ *Figure 1, Ship trajectory for main sea trials (δ: rudder angle).*

The procedures applied (in many cases adopted by flag states as national requirements) for conducting sea trials primarily rely on guidelines and standards produced by the Society of Naval Architects (SNAME) and the International Maritime Organisation (IMO). The last one provides (interim) standards for the planning, conducting and reporting of sea trials, as well as a set of parameter criteria used to assess seakeeping performance. Critical parameters for the turning circle of large ships require the "advance" (distance travelled along the direction of the initial course) at 90o change of heading and "tactical diameter" (transfer) at 180o change of heading to be less than 5 and 4.5 ship lengths respectively. A key parameter to assess the stopping ability of a vessel is the "track reach" (the distance travelled along a path until ahead speed changes sign) which should not exceed 15 ship lengths. Similarly, the "overshoot angle" (the exceeding angle of the ship's heading between the point the rudder is deflected and the point the ship's change of heading reverses) is used to assess the yaw-checking ability.

PAST PRACTICES

The first sea trials conducted by the NTUA go back to the early 80s. The test area is located in Saronikos Gulf, some 30km west of Athens, Greece. The area has been a test site for NTUA since 1978, when the officially measured nautical mile was established nearby Diaporia islands (Figure 2). The site was carefully selected due to its adequate water depths, low current strength, proximity and the generally good weather conditions. The limited accuracy of long-range, hyperbolic positioning systems at that time (such as Loran-C) could not match the precision requirements for the tests. Instead, the MiniRanger III short-range, pulse navigation system was used. The system employed four reference stations on shore (Figure 2 and 3), from which the distances from the shipboard station were measured via interrogation-to-reply time delay. The ranges were recorded in real time with final positions calculated at a later time. The on-board section consisted of the receiver / transmitter, a range console and a digital printer. The system operated in the 5.6 GHz frequency band producing ranges of about ±3m accuracy over ranges of up to 30km. If more than two ranges were available, final positions were computed using least squares adjustment, resulting in absolute position uncertainties less than 10-12 m (95% confidence level). Part of this error could be attributed to the time delay involved in multiple ranging, given that simultaneous observations could not be precisely taken. In effect, as shown in Figure 2, final navigational accuracy was also subject to the number and relative geometry of the reference

▲ *Figure 3, MiniRanger III shore station configuration.*

◀ *Figure 4, Turning circle path of a cargo vessel.*

stations used. Besides, shore stations had to be periodically calibrated for signal strength loss by measuring the turn-around delay for each beacon from a number of known locations.

MiniRanger III provided only a single point location at a time (the ship's bridge). In addition, given its low (0.25 Hz) sampling frequency, it was unrealistic to compute the ship's heading using subsequent point fixes. The ship's orientation was therefore obtained via time matching of vessel location with gyro information.
In this process, inaccurate data synchronisation could induce errors of 5-10m in certain parameters, such as the "advance" and "tactical diameter" for a turning circle.

Apart from the limited positioning accuracy, sea trial operations at this time faced a great number of practical difficulties. It was, therefore, necessary to repeat a large number of test runs before final approval was attained, rendering a trial campaign costly and hard to complete in time. Temporal loss in ranging signal strength could result in data collection delays. Communication between the ship segment and shore stations was also hard, and it was therefore difficult to report problems and potential alterations in the testing schedule. Regarding the shore stations, instrumentation was heavy to carry, required high power needs, and therefore heavy charging units. Critical sea trial controllability parameter computation and graphical representation was done mostly through hand computations, whereas the use of computers was largely confined to vessel location calculations.

PRESENT STATUS

Today, sea trials are conducted in the same test area in accordance with IMO interim standards and its explanatory notes published thereafter. However, depending on client requirements, small-scale modifications may apply to the execution process according to shipyard guidelines or national organisation recommendations. Generally, care is taken to conduct trials in a calm sea state to eliminate excessive vessel crab angles (angular difference between heading and track) and in full load / even keel conditions. Also, specific engine power control and propeller revolution settings, approach run and test speed conditions apply depending on individual tests. Navigation data acquisition is typically undertaken employing Differential pseudorange GNSS techniques at sub-metre accuracy. Until the late 90s, the base station was temporarily installed ashore at a secure site nearby. Nowadays, correction data is taken from multiple permanently operating GNSS stations, established by NTUA in the broader area for geophysical monitoring purposes with an update rate of 1 sec. Several receivers have been used over the years, such as Trimble 4000 SSI and Javad Triumph. Depending on weather conditions and specific requirements, tests can last a few hours or several days.

Computation of ship turning and steering parameters (such as the "advance", "tactical diameter" and "overshooting angle" respectively) depends on the ship's heading.
In the past, in order to study the impact of error in the ship's heading on manoeuvring parameters, we performed a limited number of tests based on heading values obtained in different ways, namely: gyrocompass measurements, successive point fixes of the ship's location obtained from a single GNSS device, and pairs of receiver locations retrieved simultaneously from GNSS units placed at the bridge and stern of the vessel. Cross-comparisons between the gyrocompass and GNSS-derived headings verified the total (dynamic and follow-up) gyrocompass uncertainty; for CMZ900 being about 1o at 40o latitude. For a turning test of a long boat, such delays induce an error in "advance" and "transfer" parameters in the order of up to 3m. Similarly, the differences observed in the turning parameters computed using a single GNSS unit from those derived based on two receivers were, in the worst case (high speed vessels), less than 2.5m. These differences are nevertheless acceptable (especially for large ships) and despite the ▶

fact that many shipborne gyros do not facilitate easy synchronisation with external devices in the field, an effort is made to record gyrocompass measurements for redundancy.

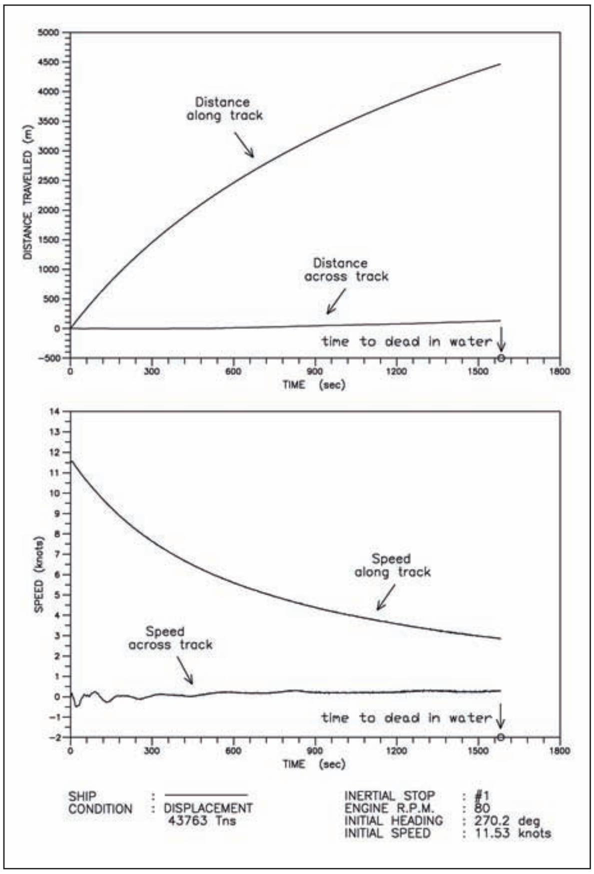
Using GNSS data and ship dimensional and operational (rudder angle, engine power and propeller revolution) information plots for the ship's trajectory, kinematics (speed, acceleration) and yaw / yaw-rate are produced. Data analysis relies on in-house software to compute critical parameters according to IMO standards, such as: the "advance", "transfer", "mean turning rate", "tactical / final diameter" for the turning circle; "overshooting angles" at predefined steering and engine power events for the Z-manoeuvre; "track reach", "head reach" and "lateral deviation" for the stopping tests; and "rate of turn" for the spiral test. The software can accommodate multiple receiver inputs and facilitates additional tools; for instance, least squares analysis for computing the turning circle radius. Figures 4 and 5 show typical screen plots for the turning circle and inertial stop tests for a large (225 m long) cargo vessel.

In recent years, in order to enhance the navigational accuracies, the Doppler shift (the apparent change in the wavelength of GPS signal due to relative motion between satellites and ship) on the GPS carrier frequency is measured. The GPS-Doppler observables urge a direct method of speed measurement that is largely insensitive to atmospheric disturbances. Using this method we found an overall improvement in ship kinematics of more than 50% (from 0.46o / 0.10 knots to 0.16o / 0.04 knots in heading and speed error respectively).

FUTURE PERSPECTIVES AND CONCLUSION

Currently applied navigation techniques and practices in most cases meet standing sea trial requirements and standards. In special cases that require increased navigational accuracies, such as small size, highly manoeuvrable and specific purpose vessels (patrol ships and hovercrafts); dual frequency GNSS receivers can be used in real-time kinematic mode. Future advancements include the use of multiple, collocated GNSS antennas operated at fixed lever-arm geometry to allow the capture of the six degrees of freedom of a ship's motion. These systems are currently used in various applications such as those in hydrographic surveys to correct bathymetric measurements for ship attitude. The use of four-antenna GNSS configurations in combination with inertial systems for sea trials will provide yaw, roll and pitch observations from which the ship's trajectory can be reconstructed as a solid body moving in 3D space. This will increase redundancy and improve reliability of test results, provide source information for theoretical studies and pave the way to draft procedures and guidelines for conducting sea trials under non-standard sea-state and water depth operating conditions.

In addition to full-scale trials in the open sea, current geo-technologies can prove particularly useful for use in restricted areas or laboratory ship model trials. Experimental results obtained with self-propelled model ships can provide source data for computing hydrodynamic coefficients to assist in the prediction of ship manoeuvrability at a design stage. Modern OEM GNSS / MEMS IMU configurations are very promising solutions, due to their small size and weight and sub-decimetre accuracy. Furthermore, in small scale laboratory conditions, other non-contact technologies can be used in addition to inertial measurements. This category includes video recording systems employing digital photogrammetry algorithms that can produce vessel trajectory at sub-centimetre accuracy. ◂



▲ *Figure 5, Travelled distance / speed change diagrams for inertial stopping.*

FURTHER READING

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