Utilizing Digital Celestial Navigation in GNSS-denied open-sea environments

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Global Navigation Satellite Systems (GNSS) have become the cornerstone of modern navigation, providing accurate and continuous positioning across various domains, including maritime traffic. However, GNSS interference has been increasing, which poses significant risks for maritime safety.

The increase of GNSS disruptions has been accelerating in the last five years. The importance of researching alternative or complementary navigation methods has been recognized worldwide. The feasibility of solutions vary according to the operational domain and vehicle type. This thesis examines these differences and aims to identify the specific characteristics that apply to marine environments, particularly open-sea environments where external infrastructure is limited.

As a potential solution, the thesis explores digital celestial navigation, a modernized version of traditional sextant-based navigation. A prototype using computer vision, astronomical datasets, and low-cost computing is proposed. The proposed system detects stars in images captured of the night sky, and estimates the observer's position by comparing the detections to astronomical star charts.

The software component of the prototype is evaluated through a simulation. The results indicate that positioning of kilometre-level accuracy can be achieved, and that celestial navigation has potential as an independent and self-contained backup navigation method.

Keywords: celestial navigation, GNSS-denied environments, maritime navigation, autonomous systems

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Maailmanlaajuiset satelliittipaikannusjärjestelmät (GNSS) muodostavat nykyaikaisen navigoinnin perustan. Järjestelmät mahdollistavat tarkan ja jatkuvan paikantamisen useilla sovellusalueilla meriliikenne mukaan lukien. GNSS-signaalit ovat kuitenkin alttiita häiriöille, joiden viimeaikainen yleistyminen uhkaa meriliikenteen turvallisuutta.

GNSS-häirintä on viimeisen viiden vuoden aikana lisääntynyt erityisen voimakkaasti, ja tarve vaihtoehtoisten navigointimenetelmien kehittamiselle on tunnistettu maailmanlaajuisesti. Tutkimuksissa nousee esille, että ratkaisujen toteutuskelpoisuus vaihtelee huomattavasti sovellusalueen mukaan, ja merellinen ympäristö asettaa navigoinnille omat haasteensa. Tässä työssä tarkastelen eri ratkaisujen eroja ja erityisesti mitkä ominaisuudet ovat relevantteja meriympäristössä.

Mahdollisena ratkaisuna työssä tutkitaan digitaalista tähtinavigointia, joka perustuu samoille menetelmille kuin perinteinen sekstanttipohjainen navigointi. Työssä hahmotellaan prototyyppi joka hyödyntää konenäköä, astronomisia tietoaineistoja ja edullisia kaupallisia komponentteja. Esitetty ratkaisu tunnistaa yötaivaasta otetuista kuvista tähtiä ja arvioi havaintipaikan sijaintia vertaamalla havaintoja tähtiaineistoihin.

Prototyypin ohjelmistokomponentin toimintaa arvioidaan simulaation avulla. Tulokset osoittavat, että kilometriluokan tarkkuus on saavutettavissa tähtipaikannuksella, ja että tähtinavigoinnilla on potentiaalia itsenäisenä varanavigointimenetelmänä GNSS-signaalien puuttuessa.

Asiasanat: tähtinavigointi, GNSS-häirityt ympäristöt, merenkulku, autonomiset järjestelmät

Contents

Glossary

Azimuth A horizontal angle measured clockwise from a cardinal direction.

Cardinal directions The four main compass directions North, East, South and West.

Dead reckoning Determining a predicted position, using the last known point, speed and direction.

Inertial navigation Using sensors, including gyros and accelerometers, to compute position, velocity and attitude.

Latitude A coordinate that specifies the north-south location of a point on the surface of the earth, given as an angle from 90 degrees (north pole) to -90 degrees (south pole).

Local apparent noon The moment when the sun is at its highest position. Solar noon.

Loxodrome A line that is a curved line on a sphere and a straight line on a Mercator chart, that intersects all meridians at a constant angle.

Prime meridian A chosen meridian at which longitude is defined to be 0°. Earth's current international standard prime meridian passes through Greenwich, in London, England.

Rhumb A fixed direction used as a compass source. A mathematical curve on the Earth's surface that maintains a constant compass bearing.

Solar azimuth angle The azimuth of the sun's position.

Solar noon The moment when the sun is at its highest position. Local apparent noon.

Solar zenith angle Angle between the sun's rays and the zenith of a specific point.

Urban canyon A canyon-like environment created in cities by dense blocks of tall structures that line a street.

Zenith An imaginary point in the celestial sphere directly above a particular point, or the vertical direction from that point up.

Acronyms

AGV Autonomous Ground Vehicle.

AIS Automatic Identification System.

CN Celestial Navigation.

DR Dead Reckoning.

EDCIS Electronic Chart Display and Information System.

EP Estimated Position.

GLONASS Global'naya Navigatsionnaya Sputnikovaya Sistema.

GNSS Global Navigation Satellite Systems.

GPS Global Positioning System.

IMU Inertial Measurement Unit.

INS Inertial Navigation System.

LAN Local Apparent Noon.

MAV Manned Aerial Vehicle.

PNT Position, Navigation and Timing.

SLAM Simultaneous Localization and Mapping.

STCW Standards of Training, Certification and Watchkeeping for Seafarers.

TAN Terrain-Aided Navigation.

UAV Unmanned Aerial Vehicle.

UGV Unmanned Ground Vehicle.

USV Unmanned Subsurface Vehicle.

List of Figures

List of Tables

1 Introduction

This thesis examines the applicability of celestial navigation as an alternative in environments where Global Navigation Satellite Systems (GNSS) are unavailable, also known as GNSS-denied environments, focusing on maritime traffic. While GNSS has become the most widely used navigational asset in the world, the weakness of the signals make it vulnerable to both natural and man-made disruptions. This exposes vessels without other reliable navigation systems to various risks.

The motivation for this research stems from my own interest in maritime navigation and from concerns regarding the vulnerability of solely GNSS-based navigation. The current geopolitical tensions coupled with increased reports of GNSS disturbances highlight the need for increased redundancy in navigation systems.

In Finland alone, GNSS interference has increased notably in the last few years [1], [2], and alternative solutions are being adopted both in aviation [3] and marine traffic [4]. In Sweden, a plan was made in 2025 to install radar beacons in ten lighthouses along the southeastern coast to provide an alternative positioning method to mitigate the increasing GNSS disruptions [5]. In January 2026, 14 coastal states of the Baltic Sea and the North Sea published a letter to the International Maritime Community on the safety and security risks caused by GNSS interference, stating that the development of alternative navigation systems is of great importance [6].

Worldwide, the situation is every bit as alarming. The UK Royal Institute of Navigation released in January 2026 a report on GNSS-interference and its impact on the maritime sector, stating that the widespread and deeply-integrated reliance the maritime industry has on GNSS poses serious risks for maritime safety and needs to be addressed and managed [7]. The Federal Aviation Administration in the US has reacted to the increasing interference by releasing a GNSS disruption safety alert in 2024 [8], and GNSS interference resource guide for 2026 where they state that GNSS interference started rapidly increasing in fall of 2023 [9]. The need to find alternative navigation methods is urgent.

Before the age of GNSS, celestial navigation was the cornerstone of navigation in ocean-going vessels for centuries. No jamming signal can move the stars, and the most basic instruments needed for practising celestial navigation can be available for almost anyone. When combined with modern sensors and digital processing, it has the potential to offer a low-cost and robust complement or alternative for GNSS systems.

1.1 Research questions

Based on the above motivation, the thesis addresses the following research questions:

RQ1: What navigation methods are currently employed in GNSS-denied environments, and how do their strengths and limitations compare?

The first research question has a broad focus. The aim of this question is to construct a basic understanding of the contemporary methods most commonly used in GNSS-denied environments, and to investigate the advantages and disadvantages associated

with them. In this thesis, this question is answered through a structured literature review, the methodology of which is explained in Section 1.2.

The result provides important context for understanding celestial navigation in the broader scope of GNSS-less solutions and provides a basis for the second research question of this thesis.

RQ2: Can celestial navigation be considered a viable alternative for ocean navigation when GNSS integrity is compromised?

The second question focuses on the viability of celestial navigation specifically for modern maritime context. Many variables such as accuracy, cost effectiveness and practicality influence the applicability of celestial navigation in actual scenarios. Maritime environments present unique challenges and the attributes of ships relevant to navigation differ from other vessels.

The aim of the question is to find out what potential celestial navigation has as an alternative or supplement to GNSS in ships. This in turn provides the basis for the third and final research question.

RQ3: What would be a cost-efficient and practical way to implement celestial navigation in a modern maritime vessel?

The final question explores the practicalities of implementing a robust, low-cost solution for celestial navigation. This includes considerations of component costs, computational aspects and similar restrictions. The aim of the question is to identify a simple yet effective solution for GNSS-denied environments.

1.2 Methodology

For this thesis, the research was conducted in three phases. To gain the necessary knowledge for performing the literature review, I first familiarized myself with the history of navigational methods. The purpose of this preliminary study was to form a better understanding of the development and usage of navigational methods from introduction of satellite systems. A second, equally important purpose was to deepen my understanding of celestial navigation. In this historical study I used both classical and modern sources. A comprehensive encyclopedia of navigation by Nathaniel Bowditch, *The American Practical Navigator* [10], [11], provided me with insight of practical navigation spanning three centuries. Pike [12] and Williams [13] offered a complementary perspective of the evolution of navigational methods from early seafaring to the satellite age, while Hofmann-Wellenhof et al. [14] also provided the technical basis of navigational principles.

The second phase of the research involved conducting the systematic literature review. The scope of the review was on navigation methods applicable in different types of vehicles in GNSS-denied environments. This phase focused on identifying and analyzing peer-reviewed research that discuss alternative and supplementary navigation methods.

Literature searches were performed in two databases; one in IEEE Xplore and another in ScienceDirect. They were chosen due to their coverage of engineering and navigation technologies. Phrase **("GNSS denied" OR "no GNSS" OR "GNSS-less") AND navigation** in both databases for the search.

The selection process followed a three-stage filtering approach illustrated in Figure 1.1. In the first stage, the titles of all unique publications were screened for relevance. In the second stage, the publications were filtered by abstract relevance. In the third and final stage, the remaining articles were reviewed by full-text to assess their suitability for inclusion.

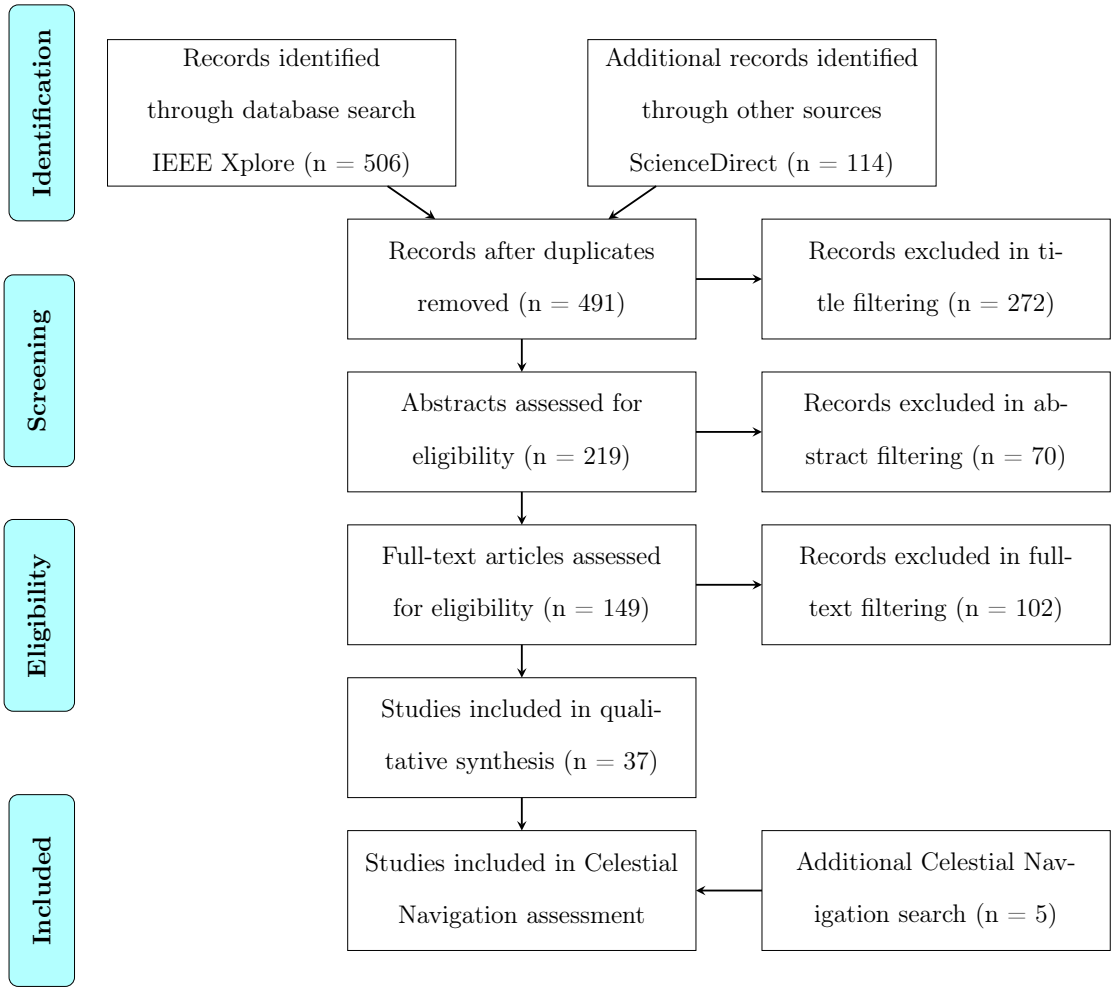

Figure 1.1: Literature review process

At every stage, evaluation was done through assessing if the publication matched the inclusion or exclusion criteria. A publication was included if it met all of the following criteria:

- It was a peer-reviewed scientific article or conference paper,
- It was written in English,
- Its main focus was navigation or positioning of a vehicle in GNSS-denied environments.

A publication was excluded if it met some of the following criteria:

- It was not accessible in full text,
- It only addressed collaborative or inter-vehicle positioning where the location was not in relation to the environment.

Finally, the findings were combined with additional sources to assess if celestial navigation is a viable solution for GNSS-less environments on the open sea. As publications specifically about celestial navigation were hard to come by, additional targeted searches were performed to provide supplemental information. In phase 3, based on the findings from the previous phases, a prototype of a celestial navigation system was designed. The algorithm developed for the system was tested in a simulation where a series of generated sky images were used as an input.

1.3 Structure

The structure of this thesis is as follows. Chapter 2 describes the historical progress in navigation from prehistoric methods to celestial navigation and satellite systems. This introduces important concepts needed for a full understanding of modern navigational principles.

Chapter 3 is a structured literature review, examining trends in navigation methods used in GNSS-denied environments. In Chapter 4, I assess whether celestial navigation can be implemented in modern maritime navigation as a reliable and cost-effective navigation method in GNSS-denied environments and present a low-cost prototype that is assessed via a simulation. In Chapter 5, I discuss the feasibility of celestial navigation as an alternative navigation system, while Chapter 6 concludes the thesis.

2 Navigation through the ages

Throughout history, navigation has been an essential discipline. It has enabled exploring new lands and enhanced the speed and capacity of travel and transport, leading to more effective trade and other types of connections across vast distances. The techniques used have evolved from simply recognizing familiar landmarks while piloting along the coast or along a river to automatically acquiring ones position via signals received from satellites sent to the skies by 20th century humans.

The word navigation is derived from the Latin navis (ship) and agere (to drive). Though the word is applicable to many sorts of vessels, its history began with boats and ships. This waterway navigation can be divided in four different phases according to where the ship is driven - Inland Waterway Phase, Harbor Phase, Coastal Phase and Ocean Phase (Table 2.1) [11]. The earliest navigators were confined mainly to inland, harbour and coastal phases. The methods they used were landmark-based, where the land remained in sight and familiar landmarks were the main method of knowing the position of the vessel [12].

Table 2.1: Phases of navigation

Inland Waterway Phase	Piloting in narrow canals, channels, rivers, and estuaries.
Harbor/Harbor Approach Phase	Navigating to a harbour entrance through bays and sounds, and negotiating harbour approach channels.
Coastal Phase	Navigating within 50 miles of the coast or inshore of the 200 meter depth contour.
Ocean Phase	Navigating outside the coastal area in the open sea.

Research on ancient navigation methods has been mostly based on archaeological and evidence, as they predate written language [14]. However, there is evidence

of ancient waterway navigation from all over the world. Different environments shaped the development in different ways, from small river crossings to the vast ocean journeys required for discovering distant pacific islands [12], [14].

2.1 The development of navigational methods

Polynesians, finding their way in the Pacific Ocean during the Polynesian expansion between 1500 BCE and 1500 CE, were probably the first open-ocean navigators. Instead of navigational equipment, their techniques were based on acquiring a vast knowledge of how to read the environment, passed down via oral tradition, apprenticeship and songs. While on the ocean visibility is not restricted by forests, hills or mountains, the islands are so far apart that they could not be found simply by looking. Several techniques could be used to extend the navigator's observational range beyond the horizon. One of these methods was based on clouds forming on top of the islands – while the islands themselves could not be seen, the rising air on top of the sun-warmed islands create clouds that due to their altitude are visible from greater distances [12].

Islands could also be found by observing migratory birds or releasing caged birds from the vessel. Frigate birds native to the area cannot land on water, and when released would rise higher up to sight land, and could then be followed. When the course had been found with birds, it could be kept using the stars. While the northern hemisphere has the Pole star that provides a fixed reference point for north, the Polynesian triangle is mostly located close to and south of the equator. Navigating by the stars included remembering the sequences of rising stars and taking the bearing form them [12].

In China, the pole star Polaris is visible. This shaped the development of navigation in ancient China as it provided a reference for both finding north and for calculating the latitude, which is discussed more in Section 2.1.1. The Chinese do

not have lots of records of their longer seafaring voyages, but there exists archaeological evidence that they developed one of the earliest compasses; a water compass with a magnetic mineral floating on a cork [12], [13]. It was adopted to maritime usage during the Song dynasty around the 10th century. This kind of compass worked best on bigger, steadier vessels, what might have played a part in why the Chinese began using quite large vessels [12]. On these larger vessels they measured the speed of the vessel by throwing a floating object in the water from the bow and measuring how long it took for it to pass the stern [12].

In Europe, the conditions for navigational development were best in the Mediterranean sea. The sea is sheltered by enclosing lands, providing milder and more predictable weather. The coasts were always relatively close, reducing the length of open-sea voyages and providing attractive possibilities for trade routes by sea. [12] From the late Bronze age, the Phoenicians were at the forefront of development; their methods evolved from travelling along the coast using landmarks to using seasonal winds and later celestial bodies to determine and maintain direction. [13]

In the Atlantic, the rough sea presented challenges that discouraged travel further from the coast. While in the Mediterranean, Phoenicians, Greeks and later Romans could measure the speed of their ships by throwing floating objects in the water, in the Atlantic the tidal currents were stronger than early sailing speeds, making dead reckoning unreliable. The skies were often overcast which made navigating with any celestial bodies difficult. [12] It has been hypothesized that Vikings, who still managed to make impressive voyages to the islands in the northern Atlantic, used crystalline minerals to determine the position of the hidden sun by polarization [15]. It is also speculated that some of the discoveries they made were due getting lost at the sea [12].

During the medieval era, navigation technologies that had emerged in certain parts of the world spread to others and maritime science began to gradually take

more systematic forms. The magnetic compass was adopted first in the Middle East and then Europe, and became an indispensable navigational tool, coupled with marine charts [13]. The earliest surviving European marine chart is the *Carta Pisana*. The navigator laid a ruler on the chart in the required direction and chose a rhumb parallel to it. A compass then aided in keeping the heading, progress was measured by dead reckoning and logged with traverse boards. Pilot books like *Compasso da navegare* complemented the charts, giving rhumbs and distances from port to port and describing landmarks, hazards and depths of the routes it covered [13].

The measuring of ship speed in knots comes from this era. Speed measurements were done by throwing a *chip log* overboard, attached to a line knotted at fixed intervals. The number of knots that passed through the hands of a sailor letting the line run freely for a defined time was the measurement. [13]

For several centuries, navigation was based on marine charts, magnetic compass bearings and dead reckoning. All of the measurements could be made by illiterate sailors, and there was next to no knowledge exchange between sailors and scholars. The concept of latitude had existed and studied by scholars, but not used in navigation outside medieval China, where the altitude of the Pole star was matched to its altitude at known locations in an early form of latitudinal navigation. The adoption and refinement of declination charts and latitudinal measurements by the Portuguese in the Age of Discovery revolutionized navigation. [13]

2.1.1 Finding latitude

Latitude can be calculated from several celestial bodies with varying difficulties. The most straightforward method can be used in the northern hemisphere where the Northern star Polaris is visible. As the position of Polaris is very close to the celestial north pole, an approximate latitude can be found by measuring its altitude.

The altitude of Polaris translates directly to Northern longitude. At the north pole, the altitude of Polaris is almost exactly 90°, while at the equator it is 0°.

The difference between Polaris and the celestial north is approximately 0.7°, which translates to a maximal error of approximately 144 kilometres in estimated location. To mitigate the error, two measurements of the altitude of Polaris can be taken exactly 12 hours apart, at dusk and dawn, and their average used to get the true celestial north.

In the southern hemisphere, latitude can be found in a similar manner from the constellation Southern Cross and the two Southern Pointer stars Alpha Centauri and Beta Centauri. An alternative that works in both hemispheres is to use the altitude of the sun. This approach requires usage of solar declination charts, one example of which can be found in Appendix A. While the pole stars appear fixed to the celestial sphere in human time frames, altitude of the sun is in a constant seasonal change. The declination changes of the Sun and the planets in the solar system can be seen in Figure 2.1.

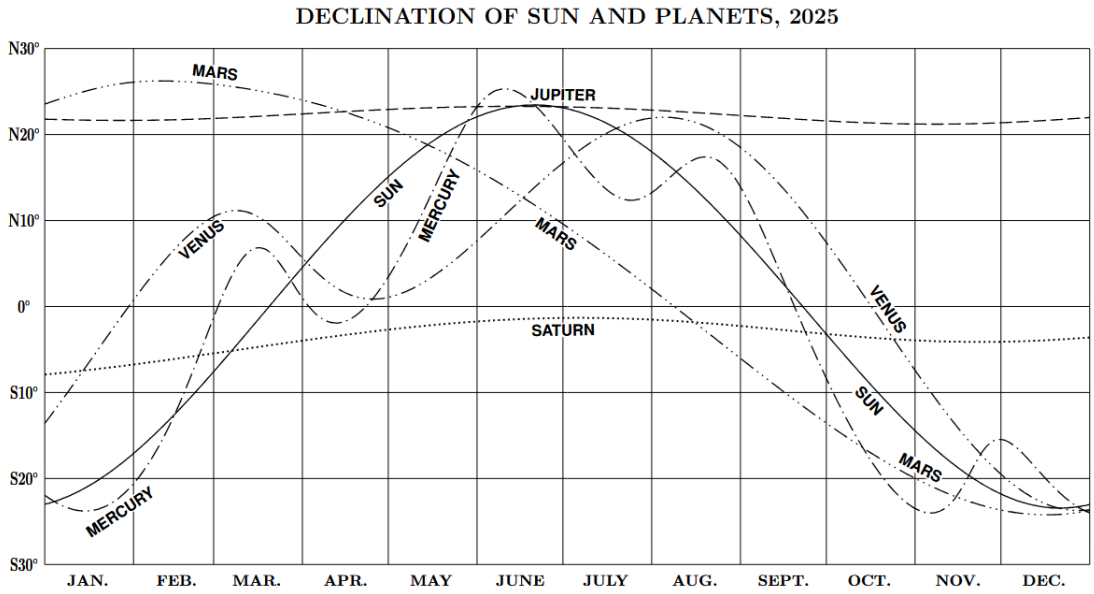

Figure 2.1: Declinations. Image source: [16]

The formula used for calculating latitude from the sun depends on which hemispheres the location and declination are in, as well as which one of them is greater. The zenith distance ZD of the sun is calculated by subtracting its altitude *Ho* from 90°.

$$ZD = (90° - Ho)$$

If latitude and declination are in the same hemisphere and latitude is greater than declination:

$$LAT = DEC + ZD \tag{2.1}$$

If latitude and declination are in the same hemisphere and declination greater than latitude:

$$LAT = DEC - ZD \tag{2.2}$$

If latitude and declination are in different hemispheres:

$$LAT = ZD - DEC \tag{2.3}$$

As an example the latitude of London in August 29th 2025 at local apparent noon can be calculated. From the declination table in Appendix A can be seen that the solar declination is North 9.16°. At the chosen date the altitude of the sun at local apparent noon (LAN) in London is 47.66°[1]. Since both the location and the declination are in the northern hemisphere, the Formula 2.1 is used:

$$LAT = 9.16° + (90° - 47.66°) = 51.5°$$

[1]https://gml.noaa.gov/grad/solcalc/

2.1.2 Altitude measurement instruments

Throughout the ages, there have been several different instruments for measuring the altitudes of celestial bodies. There are two basic approaches to making the measurement; measuring the angle between the observer's zenith and the body, or the angle between the horizon and the body. Both kinds evolved from those used by astronomers on land, but adapted to marine usage [13], [14].

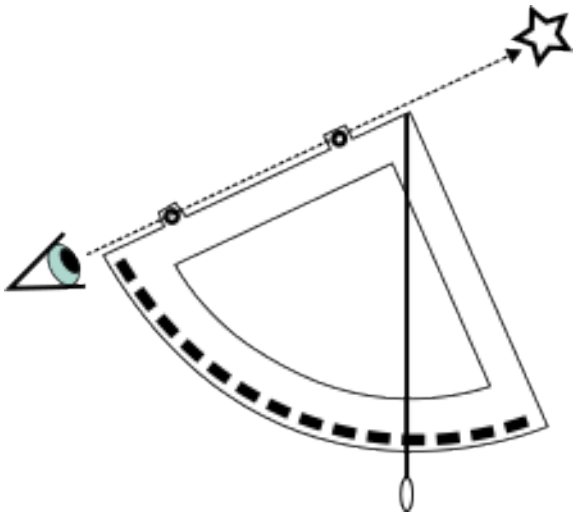

Figure 2.2: Usage of the mariner's quadrant. The user aligns the top edge of the instrument with their eye and the examined celestial body. A weighted thread shows the angle on the side of the instrument.

An astrolabe and a mariner's quadrant both use gravity to acquire the zenith angle. The astrolabe is suspended from top and an *alidade*, resembling a clock arm, is aligned towards a celestial body. The angle is then read from the scale on the edge of the astrolabe. In a mariner's quadrant, the upper edge of the instrument is aligned with the celestial body and a weighed thread hanging straight down marks the angle [13] (Figure 2.2).

As the conditions on a ship floating on water are never as stable as on solid land, gravity-based methods have a disadvantage. The cross-staff and back-staff function better in marine environments since they measure the angle of the sun from the horizon instead of the zenith. The cross-staff is used by sliding a cross-piece called

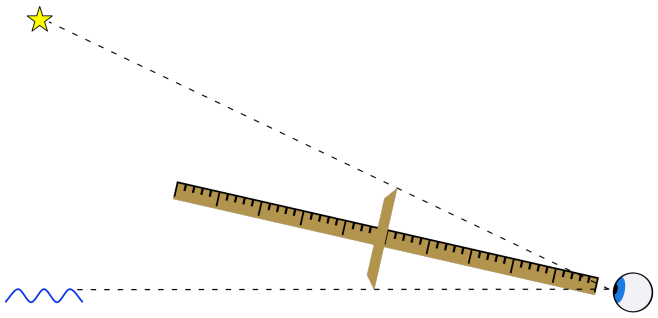

Figure 2.3: Cross-staff, also known as Jacob's staff. The user slides the cross-piece until its ends align with the horizon and the celestial body. The angle is then read from the scale along the staff. "Use of Jacob's staff" by Majo statt Senf is licensed under CC BY 4.0.

transom until it's ends align with the horizon and the sun. The angle is then read from the scale inscribed along the staff [13] (Figure 2.3).

The accuracy of altitude measurement was highly improved by the invention of the octant in the early 18th century, and its evolution to the sextant [13], [14]. Both instruments use mirrors that enable viewing the measured celestial object at the same level as the horizon. When the mirror arm is positioned so that the object aligns with the horizon, the angle can be read from the scale in the instrument [10], illustrated in Figure 2.4.

The design of a sextant reduces the need to steady aim, as the relative location of the horizon and the celestial object remains steady when viewed through the instrument. This made it an optimal tool for marine celestial measurements [10].

2.1.3 Longitude

While the latitude of a point can be calculated by measuring the altitude of the sun at solar noon and referencing the declination of the sun from an almanac, longitude is a more complicated matter. Latitude has, due to the properties of the Earth and its rotation, natural reference points at the equator and poles, making it directly observable through celestial measurements.

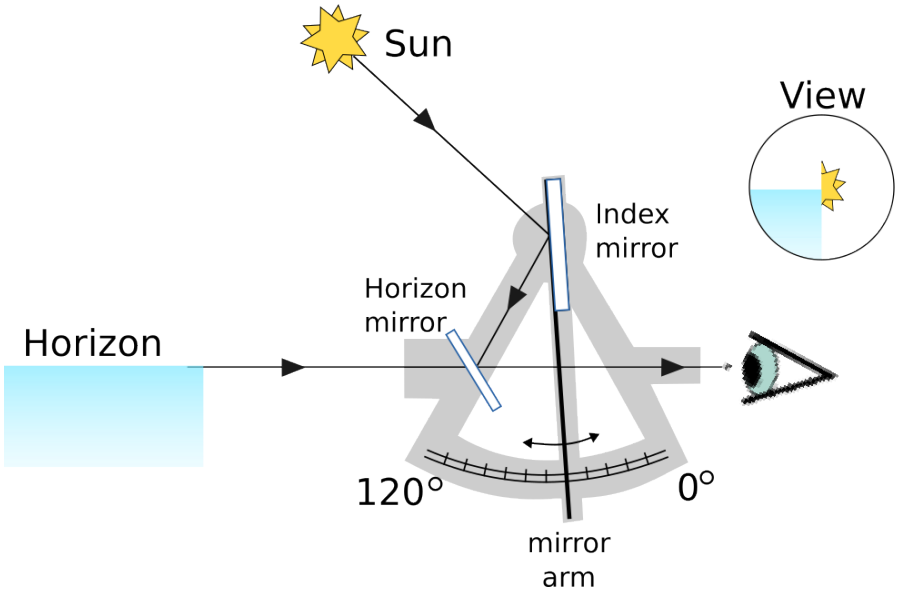

Figure 2.4: Sextant. The user views the horizon through the instrument and adjusts the mirror arm so that the attached index mirror reflects the celestial body to the eye via the horizon mirror. The position of the mirror arm on the scale of the bottom of the instrument shows the angle.

In contrast, there is no physical feature that would mark one longitude different from others. Round the globe, at the same latitude, the celestial bodies appear identical in any longitude at the local apparent noon. In Figure 2.5, LAN is seen in both London, England and Vavenby, Calgary, Canada. Because the apparent motion of the celestial bodies is identical along any given circle of latitude, longitude cannot be measured solely from celestial observations. Any differences in the sky at LAN are due to latitude.

Longitude is calculated east or west from an arbitrarily chosen meridian, called a Prime Meridian. At the Prime Meridian, longitude is 0°. In 1884, Greenwich meridian was chosen to the standard Prime Meridian by the International Meridian Conference [14]. The longitudes westward are negative, and eastward positive, until they meet at the Antimeridian at −180° and 180° respectively.

Longitude calculation is based on the relation of rotational degrees to time. The Earth, having a 24-hour day, rotates a full 360° at 15° per hour. Thereby every

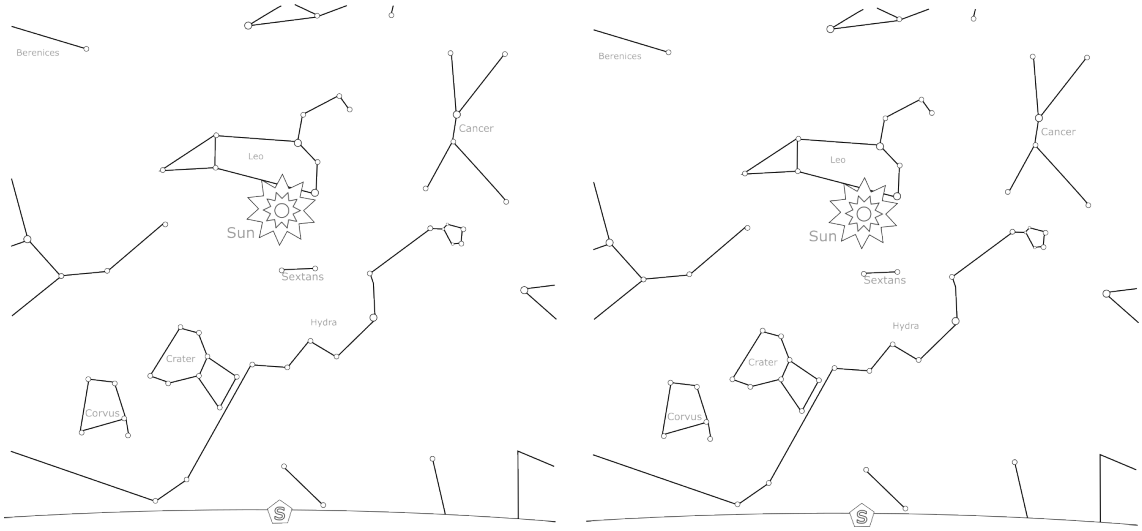

Figure 2.5: Similarity of celestial noon at different longitudes. Left: celestial bodies while looking south in London at solar noon. Right: celestial bodies while looking south in Vavenby mountain at solar noon. [17]

hour of difference directly translates to a 15° difference in longitude. As illustrated in Figure 2.6, longitude as difference from Pride Meridian can be calculated by subtracting the Local Solar time from Prime Meridian Time and multiplying it with 15°:

$$LON = (Ta - Tb) \times 15^\circ$$

Since Greenwich meridian is used as the Prime Meridian, Greenwich Time is used to calculate longitude.

$$LON = (\text{Local Solar Time - Greenwich Time}) \times 15^\circ$$

At the example location Vavenby mountain, LAN happens 11:58 local time (PST)[2]. At the same time, the Greenwich time is 19:58. For the exact measurement, local solar time (12:00) is used instead of PST:

[2]Calculated using Mean Solar Time. Exact time varies by the Equation of Time.

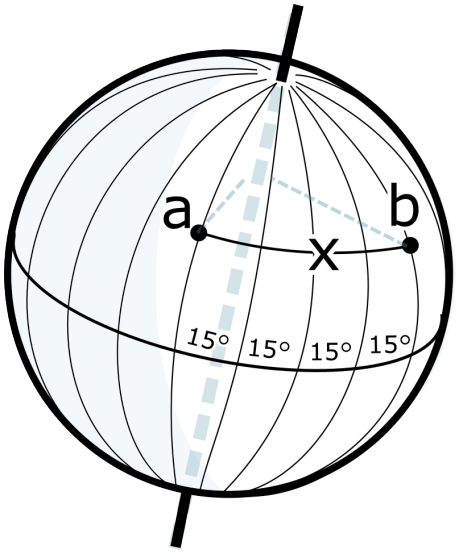

Figure 2.6: Calculating longitude. Longitude difference between locations a and b can be calculated from the time difference between local times of both places. Every 1 hour of difference equals to 15° of longitudinal distance. If time at Prime Meridian (b) is 12 and time at unknown location (a) is 16, the difference is 4 hours, and therefore the longitudinal distance (x) is 60°.

$$LON = (12:00 - 19:58) \times 15^\circ \approx -119.5^\circ$$

Calculating longitude using modern tools is simpler than calculating latitude, as no declination information is needed and one only needs a way of observing LAN and a clock that shows the Prime Meridian Time. However, before the invention of the chronometer by John Harrison in 1730, there were no instruments that could reliably keep the time on a ship [14]. Therefore, navigating using longitude at sea was only a theoretical possibility.

2.1.4 Changes in navigation methods the 20th century

Although the etymology of the word *navigation* originates from the Latin *navis* referring to seafaring, its meaning has expanded to encompass movement on land, at sea, in the air or in space. As technological advances accelerated during the

twentieth century, new methods emerged, some of which were more domain-specific, while some saw usage across domains [14].

Well into the twentieth century, celestial navigation remained a fundamental component of navigation, especially in the maritime domain. Ships moved relatively slowly and could afford longer position-fixing intervals and provided sufficient space and working conditions for the use of charts and almanacs and other celestial navigation equipment. In contrast, the emerging navigational domain of aviation imposed stricter constraints and required more frequent position updates. As a result, aviation became a primary driver in the development and refinement of alternative methods. Two of these methods that persist to today are inertial and radio navigation systems. [13].

Inertial navigation systems (INS) determine position by the aid of inertial measurement units (IMU) that use accelerometers and gyroscopes to measure the acceleration and velocity of a body. When the original location of the vessel is known, INS can calculate the new location based on the speed and direction, functioning as an automated version of traditional dead reckoning. INS do not require external input like radio signals or celestial body sightings, making them self-contained. This self-containment made INS particularly attractive for military usage as well as domains where outside signals are hard or impossible to obtain, like submarine navigation. The main weakness of INS is that when used for longer periods, small errors accumulate and the difference of the calculated and actual location grows over time and distance. This can be mitigated by providing periodical location fixes with parallel systems, like celestial or radio positioning [13], [14].

Radio-based navigation systems use electromagnetic signals transmitted from known locations to provide bearing and position information [14]. While radio navigation functions in all weather conditions, its weaknesses include the reliance on external transmitters. This makes the accuracy and availability of radio navigation

dependent on the coverage and integrity of transmitter infrastructure. Radio systems like LORAN and Omega were adopted even to maritime usage [13]. Radio was used especially in coastal waters and in poor visibility conditions. Ocean-going vessels still continued to carry sextants and nautical almanacs which were essential when operating outside the coverage areas of radio systems. This coexistence of traditional and electronic navigation methods persisted until the widespread adoption of satellite navigation systems in the late twentieth century [13].

The history of satellite navigation systems began with the launch of *Sputnik 1* in 1957. Researchers Guier and Weiffenbach at the John Hopkins University Applied Physics Laboratory (APL) studied the transmissions received from the satellite. They realized that when the location of the observer is known, the Doppler shift of the transmissions could be used to determine the position of the satellite [18]. The research to solve the inverse problem, i.e., determining the location of the receiver when knowing the location of the satellite, began the next year at APL and led to the development of the first satellite navigation system TRANSIT [18], [19].

TRANSIT consisted of a constellation of five satellites and a similar number of backup satellites. As there were so few satellites, usually only one was visible at a time. TRANSIT was initially developed by the US army to provide a position reference for US Naval submarines and missile systems. The receiver location was calculated from one satellite by Doppler effect measurements [19], [20].

TRANSIT started the age of satellite navigation and prompted the development of more sophisticated systems, like the US Global Positioning System (GPS) and the Soviet GLONASS (*Global'naya Navigatsionnaya Sputnikovaya Sistema*, Global Navigation Satellite System), both of which entered development in the 1970s [19]. Unlike TRANSIT, these newer systems provided constant coverage of several satellites at all times. GPS was declared fully operational in 1995, and the satellite

constellation of GLONASS was also completed the same year [21]. Of these two systems, GPS became the more widely adapted [19].

GPS is accurate an an easy to use system, and it was quickly adopted by both private persons and commercial operators globally. To reduce the reliance of a system provided by controlled and operated by the military authorities of one nation state, China and the European Union developed their own systems, BeiDou and Galileo respectively. The generic term used for all similar systems that provide a global satellite coverage is Global Satellite Navigation Systems (GNSS) [19].

2.2 Contemporary navigation

GNSS has become the most widely used means of navigation across almost all navigational domains, providing accurate and continuous positioning globally [19]. The devices needed for GNSS navigation are affordable compared to its predecessors, making it inexpensive to use [13], [19]. Despite the prevalence of GNSS, navigation is not uniform across all domains, as different operational environments impose different kinds of constraints.

In modern marine traffic, GNSS is generally used as the primary system [21]. In coastal areas, mariners can also rely on traditional visual landmarks like buoys and lighthouses, using marine charts to determine the position of the vessel. Depending on the type and size of the vessel, different rules can apply, mandating the usage of certain systems. The widely used Electronic Chart Display and Information System (ECDIS) integrates GNSS, radar, Automatic Identification Systems (AIS), and weather overlays. In open-sea contexts, where visual landmarks are unavailable and radio coverage is lacking, navigation is even more reliant on GNSS. For increased safety at sea, the usage of celestial navigation is maintained by many marine actors, as its independence of external systems makes it a reliable backup method [22].

Submarine navigation differs fundamentally from surface navigation in what navigational means can be used. As GNSS signals do not penetrate water, it is one of the domains where GNSS cannot provide near-continuous positioning. The subsurface environment is also devoid of the traditional marine landmarks such as lighthouses and buoys. As the sky is not visible either, celestial navigation is not of use. Alternative navigational strategies have therefore been researched since the mid-20th century, particularly during the Cold War. INS are widely used in submarines, along with radar and sonar, and position fixes are provided via GNSS or radio during surfacing [13].

Modern aerial navigation uses an integrated set of systems intended to provide reliable and continuous positioning throughout all phases of flight. GNSS is generally the primary location source. However, as GNSS can be vulnerable to disturbances, it is never used in isolation due to security regulations, but always complemented by INS, different kinds of radio navigation and barometric systems [23].

In terrestrial navigation, GNSS is the most prevalent navigational method. It is supplemented by cellular fixes, wifi positioning systems (WPS), radio beacons and data from sensors like odometers and INS, depending on the vehicle and application. In areas where roads are adequately marked and landmarks recognizable, drivers can use maps, but the prevalence and ease of use of GNSS-based navigational tools have led to an increased reliance on satellite positioning in everyday situations. One of the most fundamentally different navigational domains is space. Being extra-terrestrial, space navigation places unique restrictions on the used navigation methods. As there are no terrestrial landmarks in space, space vessels must rely on celestial navigation, radio-based measurements, and INS [12]. Radio ranging from Earth provides distance measurements and INS provides attitude and velocity. Space is the domain of celestial navigation, as celestial bodies provide the only relevant framework for a vessel to position itself in [12].

2.3 Conclusion

Navigation has developed over millennia through contributions and breakthroughs made all over the world, gradually progressing from simple methods like measuring the speed of a floating log to measuring the angles of stars to radio, inertial and satellite-based systems. Modern navigation is heavily reliant on electronic systems, with GNSS providing accurate and continuous positioning across most operational domains and being supplemented by parallel systems like radio and INS.

Despite the technical advancements, the historical methods remain relevant as backup systems even today. As it is stated in the 2024 edition of the Practical Navigator [11]:

> The mariner is constantly tempted to rely solely on electronic systems. But electronic navigation systems are always subject to failure, and the professional mariner must never forget that the safety of his ship and crew may depend on skills that differ little from those practised generations ago. Proficiency in conventional piloting and celestial navigation remains essential.

In the next chapter, I examine what kinds of failure GNSS can be subject to and why.

3 The GNSS problem

GNSS-based navigation has unparalleled ease of use and accuracy under normal conditions. However, there are many threats to the integrity of GNSS signals. In this chapter, I describe the main threats to GNSS integrity and present findings from a structured literature review that investigates how these vulnerabilities are mitigated across different types of vehicles.

For the literature review, 37 articles were selected for analysis. As shown in Table 3.1, the majority of the reviewed research focuses on unmanned aerial vehicles (UAVs) and automotives, reflecting their widespread use and importance of reliable navigation in these domains. Other vehicle categories, such as trains and marine vehicles are less frequently studied, indicating opportunities for future research.

Table 3.1: Included publications categorized by type of vehicle

Unmanned aerial vehicles (UAV)	[24] [25] [26] [27] [28] [29] [30] [31] [32] [33] [34] [35] [36] [37]
Manned aerial vehicles	[38] [39]
Unmanned underwater vehicles	[40]
Manned underwater vehicles	
Unmanned surface vehicles	[41]
Manned surface vehicles	[42]
Unmanned automotives	[43] [44]
Manned automotives	[45] [46] [47] [48] [49] [50] [51] [52] [53] [54] [55] [56]
Trains	[57] [58] [59] [60]

3.1 Reasons for GNSS disruptions

The signals transmitted by the satellites from the orbit are inherently weak by the time they reach Earth, and can be easily overpowered by stronger transmissions within the same frequency bands [61]. Additionally, receiving GNSS signals requires line-of-sight (LOS) to the orbital satellites to function properly [62], [63]. These properties make GNSS vulnerable to several types of intentional and unintentional disruptions. Unintentional disruptions can be caused both by natural environmental features, man-made environmental features, as well as unrelated stronger signals accidentally disturbing the reception [64].

Natural disruptions of environmental causes are mostly the result of failing to meet the LOS requirements due to foliage or terrain blocking the signal. In forests, dense canopies block satellite visibility [58]. Steep mountain walls or other natural formations can also restrict the LOS of signals and reduce accuracy even if parts of the sky are visible [31]. In subterranean environments GNSS signals are blocked by earth, and in underwater environments the signals are blocked by water [41], [54].

In addition to signal blockage, the environment can also give rise to positioning errors due to GNSS signals reflecting from cliffs or foliage. Examples of signal reflection and blockage are pictured in Figure 3.1.

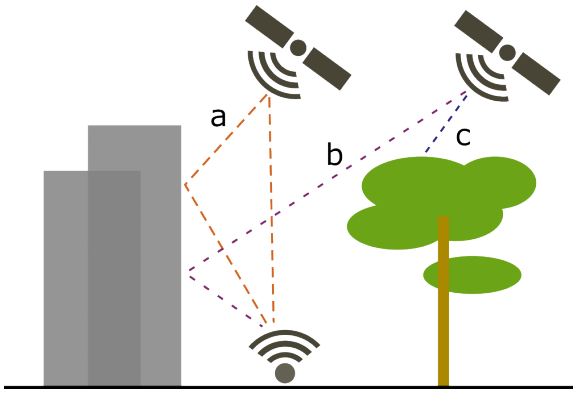

Figure 3.1: Environmental GNSS signal disruptions. a) Multipath interference. b) Non-line-of-sight reception. c) Blocked signal.

Multipath interference is when the transmission is received both directly from the satellite and a reflection. Via the direct and reflected paths, the receiver receives multiple copies of the same signal at different times, making it harder to determine the actual distance to the satellite [52]. The situation when the signal is only received via reflection, and the receiver has a non line-of-sight to the satellite, is called NLOS reception [52].

Man-made environmental disruptions work in a similar way to natural disruptions, but are arise from human-built infrastructure. In densely built urban areas with tall buildings, satellite signals are often blocked by or reflected from the buildings. These kinds of environments are commonly referred to as **urban canyons** [46], [50], and are the most prominent reason for signal disruptions mentioned in car-related studies in the examined literature, as seen in Figure 3.2.

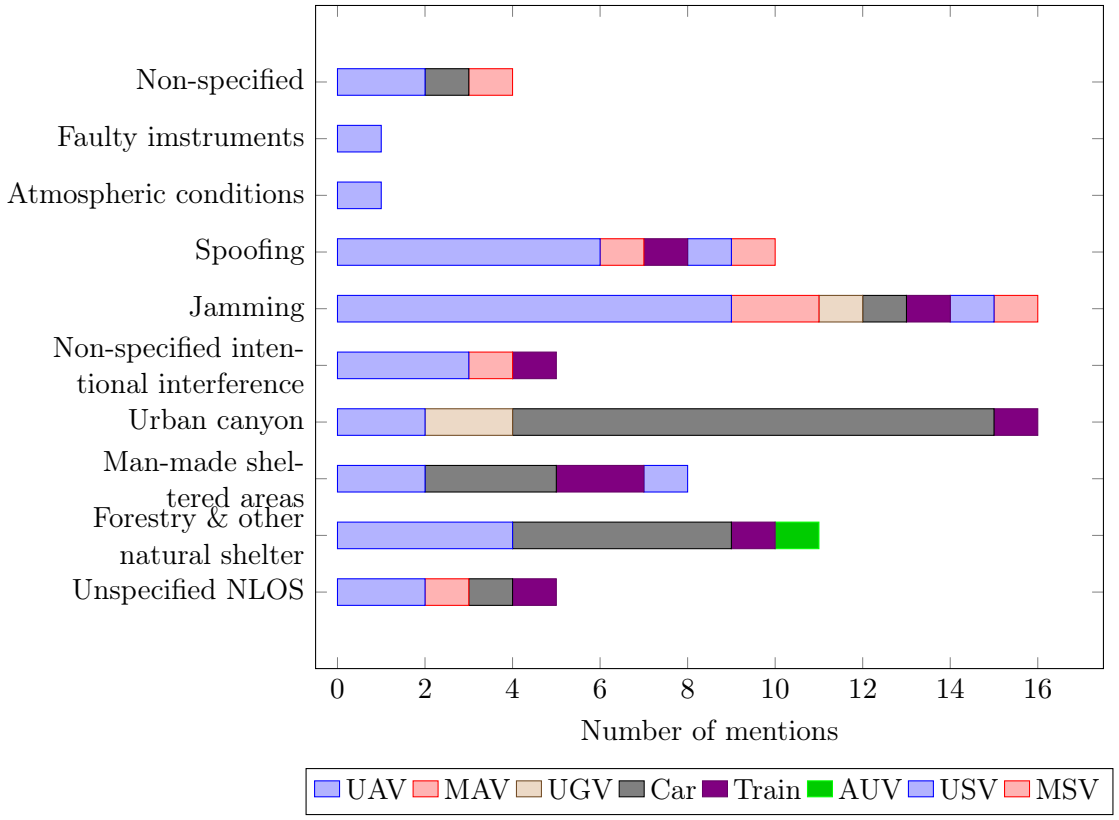

Figure 3.2: Reasons for reduced GNSS integrity mentioned in the literature.

In addition, car navigation is affected by tunnels and parking garages, where the signals are blocked i a similar manner to natural subterranean environments [37], [50], [54].

Other terrestrial systems face similar challenges. The most frequently mentioned threats to GNSS integrity in trains are environmental reasons like sheltered areas and urban canyon effects. Cao et al. [57] also mention intentional interference like jamming and spoofing. Notably, only a small number of car related studies mention jamming or spoofing as potential threats to GNSS signal integrity. This contrasts most notably with the aerial and marine domains, where they are the most frequently discussed threats.

Jamming refers to broadcasting a signal at or near the GNSS frequencies, obscuring the authentic satellite signal [61], [65], pictured in Figure 3.3. Because of the weakness of the satellite signals at their arrival to the surface of the Earth, even a low-intensity interfering signal can successfully overpower the authentic signal [66]. Different kinds of jamming signals can be used, like simple pure white noise or chirping patterns in simpler forms of jamming. These kinds of signals can be identified by a receiver, and while the authentic signal might be unobtainable due to it being overpowered, a warning can be issued. An example of more sophisticated jamming is the usage of so-called Pseudorandom Noise codes that are used in authentic satellite signals for identification purposes. As they follow an expected pattern, they can be used in malicious signals to bypass some jamming filters in so called "smart jamming" [61], [66].

In addition to denying an authentic satellite signal from a receiver, a more sophisticated malicious signal can be sent, posing as a satellite and providing false information [61]. This kind of interference is usually called **spoofing**, and it results in the receiver miscalculating its location. It can be harder to detect than simpler

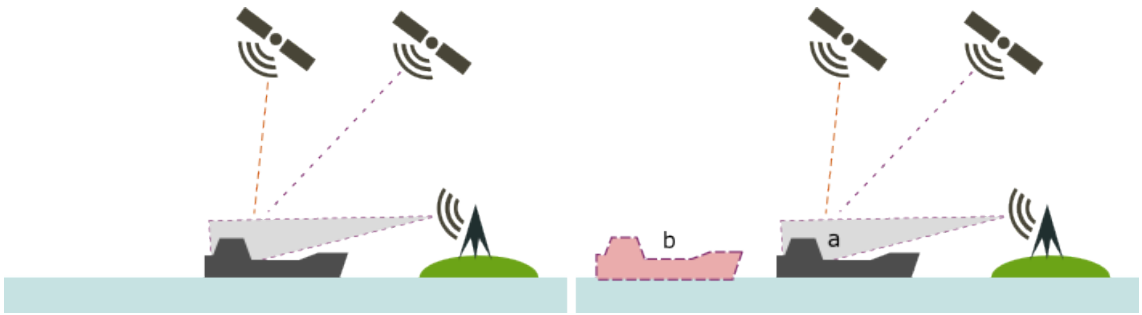

Figure 3.3: Jamming and spoofing. Left: Jamming. The ship is prevented of receiving GNSS signals by a stronger signal and cannot determine its position. Right: Spoofing. The ship receives a signal with false information, resulting it locating itself in the false position (b) instead of the correct (a).

jamming, since it can be difficult to determine that the location and time received from the signal are false if it is otherwise believable [67].

As seen in Figure 3.2, different types of intentional interference constituting of jamming, spoofing and non-specified intentional interference emerge as the most prominent category of identified threats to GNSS integrity in the included literature. However, while interference is frequently identified as a major threat, in most literature it is mentioned only at a general level, and the possible reasons or actors behind it are rarely elaborated on. Concrete examples of attacks are mentioned by Han et al. [41], Kassas et al. [39] and Liubarets [67], including malicious jamming in Korean coastal waters, disruptions in NATO exercises in Scandinavia caused by Russian GNSS jamming, hijacking UAVs and oil tankers in the Persian Gulf, and disturbing aircraft operations around the world. Kassas et al. [39] and Naus et al. [42] mention that intentional GNSS interference has traditionally been seen as a military problem, but as jamming equipment has become more affordable, there has been an increase of independent actors using personal jammers.

In conclusion, the emphasis of different types of GNSS vulnerabilities in the literature differs between the navigational domains. The differences reflect the operational conditions that are common for the respective domains. Terrestrial ve-

hicles frequently operate in environments where environmental signal obstructions are common. In contrast, aerial and maritime navigation takes place in more open environments where there are less disruptions to satellite visibility. Additionally, terrestrial vehicles are more often confined to predefined infrastructure, such as roads and railways, which provide positional context. In contrast, aircraft and marine vessels typically navigate in more open environments that do not have similar spatial constraints that could aid in verifying their position. As a result, they often rely more on GNSS navigation, making them a more susceptible target for intentional interference. In the next section, I analyze how the signal loss is mitigated in the different domains.

3.2 Solutions

Navigation generally depends on extracting positional information from either motion measurements (dead reckoning) or observations of external reference points with known positions (piloting) [36], [45]. Most navigation methods can be categorized in one of these two approaches.

Dead reckoning estimates a vehicle's position by interpreting motion measurements and propagating the position estimate from a previous known location [47]. Some widely used solutions are inertial measurement units (IMUs) [44], [47], [50], [57], [58] and different odometry solutions where motion is inferred from various sources, such as wheel movement (wheel odometry) [44], [47], [50] or image sequences from a camera feed (visual odometry) [32], [47], [49] or LiDAR [68]. Dead reckoning solutions are highly self-contained and do not rely on external signal availability, making them resistant to interference [36], [57]. However, they are inherently susceptible to error accumulation. Over time, small errors accumulate into growing position uncertainty, resulting to a need of periodic location check from external sources.

Using external reference points, also called anchor points or simply anchors, is commonly referred to as **piloting** [45]. Anchors are known points, or landmarks, from which the vehicle location can be determined from if the distance and direction to an anchor point is known [45]. Examples of traditional anchors are lighthouses and buoys, in principle any recognizable object or signal with a known position can be used as an anchor. Modern navigation systems can use a great variety of techniques to utilize their surroundings for piloting. For example, coastline features can be recognized with radar [41] or mobile access points found with radio receivers [45]. The satellites in GNSS constellations can also be considered anchors, as their position is known and the position of a receiver can be calculated relative to them [45].

3.2.1 Overview of techniques

Like ancient Phoenicians, many contemporary navigational systems use a pairing of dead reckoning and piloting. A commonly used dead reckoning tool is an inertial measurement unit (IMU), which forms the basis of an inertial navigation system (INS). They are often paired with GNSS - **integrated GNSS/INS systems** are widely considered a standard foundation for reliable positioning [39], [43], [52].

The combination effectively mitigates the problems of both techniques: GNSS provides accurate positioning but might suffer from signal loss or interference, while INS are self-contained and do not suffer from outside interference but accumulate errors over time. In an integrated system, INS can provide accurate enough continuous positioning under short GNSS outages, and GNSS can provide accurate position updates for the INS to correct the accumulated drift [37].

The integration of GNSS and INS is typically achieved by using sensor fusion techniques. Kalman filter is the most widely used optimal estimator for this purpose [32], [43]. It is used for combining measurements from multiple sources and to

minimize errors and drift, as it can be used to predict how the vehicle state should evolve [37].

Table 3.2: Proposed solution technologies in included publications by platform

Solution	Aerial	Ground	Marine
INS	[24], [26], [27]	[43], [44], [46], [49], [50], [51], [52], [54], [57], [58], [60]	
Reducing INS drift by AI	[37]		
Visual map/feature recognition	[25], [27], [29], [30], [33], [34], [35], [38]	[53]	[40]
Visual odometry	[24], [28], [30], [31]	[49], [50]	
Wheel odometry		[44], [48], [50], [57], [60]	
Radar odometry		[54]	
Sonar			[40]
LiDAR		[51], [52]	
Ultrasonic odometry		[43]	
Dedicated radio Frequency (RF) localization		[46], [54]	
Radio, signals of opportunity	[26], [39]	[55], [56]	
Non-visual maps		[45], [46], [48], [57], [60]	
Radar feature recognition		[45]	[41], [42]
Magnetic matching		[48], [59]	
Review paper	[32], [36]	[47]	

A considerable part of the literature approach the GNSS problem by developing the INS part of GNSS/INS (Table 3.2) by sensor fusion. The aim of the approaches is to minimize the INS drift and thereby extend the duration during which reliable positioning can be maintained under GNSS outages.

However, contemporary GNSS/INS integrations alone do not fully resolve the challenges associated with GNSS integrity. Advanced INS systems provide accurate position for short periods, but the accumulation of small inaccuracies is still a problem during longer outages [57]. Additionally, the periodic checks from GNSS are still vulnerable for disruptions, resulting in the INS possibly calculating from a false position [33], [55], [57]. Furthermore, high-performance INS can also be costly [38], limiting their applicability, while low-end IMUs tend to suffer more from drift [50].

In the literature, the inability to trust the initial GNSS location is particularly associated with environments of low GNSS signal visibility. For example, in urban areas where multipath interference and NLOS and similar accuracy issues are prevalent and lane-level accuracy might be needed, the accuracy of GNSS is not enough even in non-interfered conditions [51], [52]. Autonomous cars require higher accuracy and integrity than current GNSS can provide in urban environments [47]. When the acquired GNSS position cannot be guaranteed to be accurate, INS that is location-checked from it cannot be trusted either, marking urban vehicles as a prominent example of GNSS/INS challenges [43], [50], [58].

Visual odometry (VO) provides an alternative self-contained approach for dead reckoning. VO estimates vehicle motion by tracking visual features in the environment across consecutive images from an onboard camera feed [32], [49]. By analyzing the amount of displacement, the relative movement of the vehicle can be calculated [33], [34]. VO can be combined with inertial measurements to from **visual-inertial odometry** (VIO), improving accuracy in situations where the camera feed is blurry or otherwise difficult to interpret. The combination can in turn also help mitigate the INS drift, as investigated in [32], [49].

Visual observations can also be used for **landmark recognition**. It is a piloting-based approach, where identifiable features in the environment, like buildings, road markings or other structures, are matched to known references. These references have been georeferenced, meaning that their absolute location has been saved so that they can be used as anchors [25], [34]. Closely related to landmark recognition is **map matching**, where sensor observations are used to determine the vehicle's position within the constraints of a pre-defined map [47]. This is particularly useful for determining the location of a vehicle moving in a constrained system, like a rail or road network [57].

Piloting is not restricted only to the visible domain. Anomalies in the Earth's magnetic field can also be used as anchors in **magnetic navigation**. Distortions caused by materials like steel rails and reinforced concrete create "fingerprints" than can be recognized and used for loop closure detection [48], [59]. Dedicated magnetic markers can also be created and installed as infrastructure elements [43]. However, reliance on magnetic fingerprints introduces sensitivity to changes in the magnetic environment. Disturbances can be caused by large vehicles or electromagnetic interference [48], [59]. Despite this, studies indicate that apart from temporary disruptions the magnetic waveforms can remain stable over extended periods [48].

Sound waves can also be used for navigation. Sound Navigation and Ranging (**sonar**) is commonly used in subsurface environments to determine distance to seafloor features and surroundings [40]. It can be used for feature recognition or odometry, and operates often in the audible range since lower frequencies can travel long distances underwater. **Ultrasonic** sensors can be used for shorter-range proximity detection [43].

Another solution sensing the environment are Light Detection and Ranging (**LiDAR**) sensors. They are used to provide high-frequency and high-precision distance measurements. LiDAR can be used as a quick and accurate tool to create point maps of the surrounds of the vehicle. The information acquired from LiDAR can be used both for piloting and for dead reckoning. For example, the observations can be compared to a previously created georeferenced map to estimate the vehicle's absolute position. Alternatively, consecutive scans can be compared to estimate the velocity of the vehicle by the difference between the scans. The main advantages of LiDAR are its high accuracy and independence from lighting conditions. However, they can be expensive, relatively heavy, and require significant amounts of power.

Similarly to LiDAR, **radar** sensors provide proximity information and can be used to measure the distance and relative velocity of surrounding objects. Like

LiDAR, radar is largely insensitive to lighting conditions and perform well in harsh weather. Radar measurements can also be used both for odometry [36], [54], [57] and map-matching [38], [41], [42], [45]. Radar typically offers greater detection ranges than LiDAR, the former reaching ranges from a couple of meters up to hundreds of kilometers depending on the application [42], [45] and the latter up to 90 meter ranges [36], [68].

Since both LiDAR and radar depend on the presence of relatively close-range features in the environment, they are more suited to feature-rich environments like cities or shallow coastal waters [39], [40]. In feature-sparse environments such as open sea, LiDAR is practically unusable, and radar requires the vessel to stay relatively close to coasts or other landmarks [39], [40].

In contrast to these local sensing methods, **radio**-based techniques enable positioning over much larger distances. They do not rely on nearby physical features, but instead use signals transmitted from distant sources. The most prominent example of radio signals used for localization are GNSS, utilizing satellites that transmit their orbital position and timestamps, allowing the receiver to calculate distances from the signal delay. Historically, terrestrial navigational radio systems like LORAN have been used, particularly in maritime environments [67].

The usage of radio can be extended beyond dedicated navigation systems through the usage of **Signals of opportunity** (SOPs). SOPs are existing radio-frequency signals that are not originally designed to be used for navigational purposes. Communication like cellular signals and TV or radio broadcasts can be exploited for positioning, navigation and timing [39]. They can be used as a reference for dead reckoning, or when the positions of the transmitters are known, absolute position information can be extracted from SOPs [39].

The advantages of using SOPs are many: they are abundant in many locations and as their sources already exist, therefore no extra infrastructure is needed to

be installed [39]. The signals are usually quite strong and are not particularly affected by weather or cloud coverage. Kassas et al. [39] state that Cellular SOPs in particular possess attractive attributes for navigation, as their carrier-to-noise ratio is 20–30 dBs higher than that of GNSS. Additionally, SOPs do not require a dedicated navigation infrastructure, and are often harder to deny simultaneously when a range of different sources are used [56].

While SOPs are more resistent to jamming due to their higher signal strength, they still have a vulnerability to interference [56]. Another disadvantage is the scarcity of SOPs in rural areas. As navigaton methods using SOPs exploit existing insfrastructure, they fare best in built-up areas, but fail in areas where SOPs are sparse [39]. For example, Kassas and Abdallah [55] note that the furthest distance they could have to a cellular base station and still be able to utilize it as a source of SOPs was 25 km.

3.2.2 Comparison of terrestrial, aerial and marine solutions

Of the different vehicle types, UAVs tend to exhibit the most restrictive requirements for equipment [31]. The payload capacity of an UAV is limited, and an increase in weight directly impacts its flight time. Additionally, the UAV sensors require battery power to run, using up the same batteries used for flight. The more energy is needed to keep the UAV in the air due to its weight or to run its sensors, the shorter the flight time. [29], [31]

One of the differences of UAVs compared to other vehicle types is that they can employ downwards-facing sensors to capture data over large surface areas. The scale of coverage is affected by the altitude of the UAV, allowing higher-altitude UAVs to cover vast areas. Examples of sensors used are monocular cameras, stereo cameras and rangefinders [25], [31], [32], [33]. These sensors enable UAVs to gather information from the ground below and use it for ground-based odometry solutions [32] and

different kinds of map-matching. The used maps can be visual [31] or be based on other features, like terrain elevation data for terrain aided navigation (TAN) [38].

The usability of map-matching relies heavily on the availability of reference data of a usable quality, as well as that the reference data and the real-time observation are similar enough. In the case of visual map-matching, environmental conditions such as weather, seasons and time of day affect the real-time observation and can make it difficult to match with the original map [30]. Gurgu et al. [34] note that map-matching is generally easier in urban areas, because they have more recognizable features. If an UAV flies over featureless areas like large fields or forests, there is a greatly increased risk of a match to an incorrect map section [34].

In UAV map-matching, the maps are often based on ortophotos; aerial images that have been processed so that they have an uniform scale and a perspective perpendicular to the ground [33]. The images can be collected with drones, using the drone GNSS sensor to georeference the collected data. An alternative solution is using satellite images, as they have similar properties. This removes the need to map the areas with a drone before being able to use the data for GNSS-less flight [34]. Using satellite imagery also has its drawbacks, as the data might be out of date or be collected in a different season, making recognition more difficult. Using large datasets also requires more processing power, and even with satellite maps the flight area must be approximately known in beforehand so that the extent of the needed map can be selected, pre-built and uploaded to the drone for offline usage before flight [34].

Strictly downwards-facing cameras are usually not sufficient for the drone to accomplish other tasks than navigation, as the orientation limits its usability for other purposes [33]. They are ideal for providing imagery that is easier to match with previously acquired orthophotos or satellite images due to having similar proportions. This often leads to the drone needing two cameras, one facing forward and one

down. However, according to Kinnari et al. [33], using another camera orientation and transforming the frame from an arbitrarily positioned camera to have orthorectified proportions is also possible and might have the advantage of simplifying the camera setup of the UAV [33].

LiDAR rangefinders can help improve UAV navigation by providing accurate vertical position [24]. Nodding or rotating LiDARs can also be used for generating point clouds for SLAM or feature matching [36] The main drawback when using LiDAR is the weight of the sensor, and another a relatively high cost compared to cameras [28].

In solutions that need data from strictly downwards-pointing sensors, the attitude of a UAV can be another source of error. Pitch and roll variations can distort the observation, making it more difficult to match with the reference data. These variations can be mitigated by gimbaling the sensor, which enhances stability and ensures that it is always pointing to the desired direction [31]. The drawback of gimbaling is added weight as well as increased energy consumption, again reducing the flight time of the UAV.

When examining terrestrial navigation in the included literature, two types of environments are present. Most of the studies focus on urban environments. Rural environments, further divided to on-road and off-road contexts, are less frequently addressed. Both urban and rural environments pose their own challenges. The literature includes both automotive systems and railway trains, though the volume of automotive-related research is notably higher, as seen in table 3.1.

Autonomous driving has been a major driver of navigational research in the automotive domain [47]. Human-oriented navigation is more robust because the driver and passengers can flexibly adapt to use additional navigational aids like physical maps, road signs and local environmental knowledge, mitigating GNSS

failures. In contrast, autonomous driving requires continuous positioning with lane-level accuracy, as opposed to road-level accuracy sufficient for human use [52].

Apart from off-road contexts, a key characteristic of automotive navigation is that the vehicles spend most of their time within constrained infrastructure, as they operate within road systems [47]. Another characteristic constraint that applies to ground vehicles is their limited lateral movement, as they usually only move forward and backwards [45]. Additionally, unlike aerial and marine vehicles. ground vehicles by default remain stationary relative to the earth while not actively moving [43], [47]. In both automotive and train navigation, these constraints can be used to reduce error accumulation in inertial and odometry-based systems. Movement to a false direction can be filtered out from an IMU, including all movement when other sensors, like wheel speed, indicate that the vehicle is not moving [43], [45], [52].

Urban environments are often rich in features that can be used for different kinds of navigation. These include objects like buildings, traffic signs, and road markings that can be observed by onboard cameras, radar, od LiDAR. Additionally, both SOPs and dadicated radio signals can be used for navigation [45]. In addition to the density of environmental detail and signals, urban environments often also have a high automotive density. The density enables possibilities for collaborative map building via Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication [47]. As the distances are relatively short, V2V communication can happen via short-range methods, like dedicated Short-range communication (DSRC) or based on the IEEE 802.11 WiFi standard [45], [46]. In urban environments, integrating dedicated roadside units to engage in the communication to act as a source of truth or mitigate lack of vehicles to communicate with is also a possibility [46].

Although trains are constrained to railway tracks, simplifying the potential positioning space even more than in automotives, accurate positioning remains desirable for safety and operational efficiency. Systems like the European Railway Traffic

Management System (ERTMS) require meter-level accuracy to support higher track capacity and effective train control system functions [58].

In trains, navigation solutions can exploit the strict physical constraints of rails, utilizing virtual sensors for transverse Zero Velocity Updates (ZUPT) to correct sensor bias [58]. Another advantage of trains being constrained to rails is that infrastructure providing anchor points can be installed along the tracks [57], [58]. The rail environment provides also good possibilities for using magnetic matching to identify vehicle position [59].

As terrain vehicles have much less payload restrictions than UAVs, sensor fusion with a much greater number of sensors is available. Automobiles often already have many sensors that can be used for additional navigation solutions that can be read via the Controller Area Network (CAN) bus without installing additional hardware, like wheel speed sensors [50]. Another difference is the utilization of the horizontal level; compared to UAVs that mostly utilize downward data, ground vehicles operate in environments that are feature-rich even sideways and around. [52]

The third type of environment in the included literature is the marine domain. As noted by Han et al., while literature of GNSS disruptions in UAVs and terrestrial vehicles is extensive, studies addressing similar challenges and alternative solutions in marine traffic are comparatively sparse [41]. The imbalance does not seem to have changed in the last decade. While the reasons for the discrepancy have not been explicitly stated in the literature, several contributing factors can be identified.

In subsurface navigation, the inability to use GNSS while submerged has most likely influenced navigational design and research from the beginning, leading it not to be seen as a major problem contemporarily, as submarines already rely on other solutions [40]. In surface vessels, the relative lack of research attention may be a result of ships having less pressure to solve short-term GNSS disruption problems compared to other domains. As ships typically move more slowly and often operate

in open environments where continuous, high-precision positioning is not required, marine vessels can afford to wait out GNSS disruptions better than UAVs for example. In coastal and harbour areas, visual landmarks and supplementary navigation methods like radar can provide sufficient positional awareness.

Even if marine vessels have not had similar pressure for alternatives to GNSS as the other types of vehicles discussed in this chapter, the threat of intentional GNSS disruption is growing even at sea [42]. Han et al. [41] identify increased jamming and spoofing in coastal waters in South Korea as an increasing problem already in 2016, Naus et al. [42] assess it as a serious safety risk for all human activity at sea in 2020, and Liubarets [67] discusses the increased risks of GNSS disruptions concerning marine navigation in 2024.

In coastal areas, several positioning methods can be used instead or in addition to GNSS. Visual landmarks and dedicated navigation marks as well as coastal features can be used for piloting, either through direct observation or with radar systems [41], [42]. Radar enables positioning by detecting reflections from coastlines, buoys, and other fixed structures. These observations can be compared to premade digital maps to estimate the position of the vessel [41], [42].

As GNSS signals do not penetrate water, subsurface vehicles like AUVs primarily rely on INS supported by acoustic-based positioning methods [40]. Sonar can be used for SLAM as well as TAN using the seafloor and pre-identified features [40], [41]. GNSS fixes can be acquired while surfacing, but as the window for acquiring the position from GNSS is shorter than for surface vessels, there is less time to notice a faulty reading.

The marine environment provides extra challenges for some dead reckoning methods. Naus et al. [42] point out that vessel velocity is often measured in relation to the water, adding drift to the readings. In open-sea environments, additional challenges arise from the lack of features in the environment and the limited availability

of terrestrial signals. Historically, long-range radio navigation aids such as LORAN have been used, highlighting the possibility of using terrestrial radio signals as an alternative to GNSS. However, such systems have been decommissioned, leaving open-sea navigation reliant on GNSS [67].

With the increasing development of autonomous marine systems the need for reliable alternatives to GNSS becomes even more critical. While in manned vessels, navigators trained in celestial navigation can look for the stars, providing an independent backup for GNSS, autonomous vessels lack a robust and trustworthy alternative.

3.3 Conclusion

The reviewed literature indicates that research for alternative navigation systems in GNSS-denied environments is heavily focused on unmanned aerial vehicles (UAVs), with ground vehicles like cars being the second most researched application area. While marine vessels have in the past faced less pressure for development of alternate solutions, the rising frequency of GNSS interference is affecting all domains, and research for alternatives could be expected to expand.

At the moment, there is no single complete substitute for GNSS. Navigation relies heavily on complementary sensor fusion where the used sensors vary by domain and vehicle purpose. Supplementing INS with another type of odometry is the most widely used strategy in mitigating GNSS disruptions. In Automotives, the usage of different types of sensors is most varied, while in the aerial domain solutions are mostly based in visual camera feed.

The usability of most solutions heavily relies of the feature-richness of the environment. In feature-rich environments, like urban streets, a wide range of techniques can be effectively employed, while in feature-sparse environments the possibilities are more limited. This applies to the open-sea environments, where no coastlines,

other environmental features, or human infrastructure are available, and the only navigation methods to consistently rely on are based on GNSS. This reveals a need for a robust, non-jammable navigation alternative.

4 Celestial navigation as a solution to the GNSS problem

Celestial navigation (CN) was once a cornerstone of long-distance navigation. Its was an essential method in the 1970's, when the evolution of portable calculators opened up new possibilities for computing. Research on how to automatize the calculations needed for CN began [69], [70] and continued long into the end of the 20th century [71]. After GPS was declared fully functional in 1995, interest in marine CN research waned [21]. However, the increasing vulnerability of GNSS has reignited the search for navigational alternatives.

Unlike GNSS, celestial navigation is independent of external signals and infrastructure, relying only on onboard instruments and the positions of celestial bodies. This independence makes it very resistant to external interference and an attractive alternative for modern navigation systems. CN has often been overlooked because of its perceived obsolescence, manual instruments and laborious mathematical equations [72]. However, with technological advancements like electronic sextants, star trackers and automated calculation software, CN has the potential to enter a new era as a robust navigational tool.

This chapter explores the potential of using digital celestial navigation to address the GNSS problem in open-sea environments. I examine the contemporary scope of

usage of CN, instruments and techniques involved, advantages and limitations, and feasibility of implementing CN in modern maritime vessels.

4.1 Celestial navigation in use today

Celestial navigation is widely taught in maritime institutions despite not being as frequently used in practice as before the adoption of GNSS. The International Maritime Organization (IMO) recognizes the importance of CN in their conventions. Teaching of CN is mandated by the international convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW), which requires deck officers to have "Ability to use celestial bodies to determine the ship's position and compass errors" [22], [73].

The requirement of proficiency in CN is not present in all international maritime conventions. It is missing from the international convention for the Safety of Life at Sea (SOLAS) and some countries have proposed to remove the requirement even from STCW. Arguments for the removal include notions of it being an outdated practice requiring difficult mathematics that are challenging to teach, while the main argument against removal is its reliability as a backup navigation in GNSS-denied situations [21], [22].

However, some authorities that have removed the requirements have since brought them back. The US Navy resigned teaching CN in the early 2000s, but have reinstated it into the navigation curriculum in 2016 and it has since then been a requirement in the US Navy Officer Professional Core Competencies Manual [74]. This reversal reflects the recognition of the growing vulnerability of GNSS and the importance of an independent position validation method.

When CN is used in maritime context, it is typically utilized as a means of verification and redundancy instead of a primary navigational method [21], [67]. The extent of its usage also varies significantly depending on sector, geographic

region of operation, and authorative body [21]. CN is mostly restricted to detecting GNSS anomalies and determining compass errors [22].

In modern bridge systems, GNSS is well integrated and connected to virtually all navigation equipment, including EDCIS, AIS, and GMDSS (Global Maritime Distress and Safety System) [21]. When working correctly, it provides automated, efficient and accurate positioning with minimal effort required from the crew. In comparison, the perceived usability and ease of use of CN is probably significantly affected by how much manual work is required compared to GNSS. Dachev and Panov [72] identify three types of CN used today:

- Traditional, manual methods with handheld sextant and manual.
- Traditional, computer based methods using handheld sextant for measurement but software for sight planning and reduction.
- Fully automated with electronic sextant or star tracker, coupled with celestial calculation software.

The importance of CN can be seen in the reinstation of requirements, but its practical revival is probably mostly slowed down by lack of adequate automation and integration with modern bridge systems. Even with specialized celestial fix software, navigators need to use a separate computer for the calculation and feed the result manually in the navigation system slowing down the process [67].

4.2 Instrumentation and techniques

While interest in maritime celestial navigation declined following the full functionality of GPS, technological advancement has continued in other sectors. GNSS usage is restricted to Earth, and other navigation solutions are required in space, where CN is used to determine attitude and position of spacecrafts [75]. Additionally, CN

is used in intercontinental ballistic missiles to provide additional jam-proof positioning [76], as well as in some high-altitude aircraft [77].

While there has been technical advancements both in instrumentation and algorithms, the fundamental strategy of CN remains unchanged. Swaszek et al. [78] describe the basic workings of CN as a four-step process:

> The general strategy in celestial navigation is to (1) choose a set of reasonable celestial bodies for measurement, based on visibility, azimuth, and altitude, (2) measure observed altitudes of that set of celestial bodies at known time(s), (3) correct altitude measurements for effects such as refraction, height of eye, or parallax, and (4) determine each celestial body's location on the celestial sphere at the observation time.

The core instruments of maritime CN have evolved from manual tools to digital equivalents. Traditionally, a sextant has been used to measure the angles of celestial bodies. A modern version of the tool is a digital sextant, which provides electronic assistance for angle reading [22]. Marine chronometers have been used for timekeeping, but have largely been replaced by time readings from GNSS satellites [67]. Printed nautical almanacs and tables have been replaced by digital versions, nautical calculators and specialized software [67].

The shift from manual to digital calculation has influenced the preferred algorithms for position reduction. Traditionally, methods requiring less calculation and relying more on sight reduction tables were more feasible, as calculation was done without electric assistance [67]. An example is the haversine formula [22] that can be relatively quickly calculated by hand. While it used to be a standard method, the ubiquity of handheld calculators have made more complicated algorithms feasible [67]. These methods include the fundamental spherical cosine formula [79] and the intercept method, also known as the Marcq St. Hilaire method [79].

With today's computing power and devices, position reduction can be automatized even further. As computers can perform complex calculations in seconds, even more complex algorithms that yield more precise results can be used without adding to the workload of the navigator. The ubiquity of computers enables even further automatization where the star identification and angle measuring is done directly by a dedicated system, and filtering can be applied to take into account changes in ship steering and speed [80].

Traditionally when navigating with CN, celestial bodies have been identified by humans. Automated star tracking systems that needed to be locked to a specific star were researched since the early 1960's for spacecraft, satellites and missiles [20], [72]. In the 1990's, facilitated by Charge-Coupled Device (CCD) technology and low-power microcomputers, these star trackers evolved to more adaptable second-generation star imagers that are able to recognize constellations in their field of vision using internal star catalogs and pattern recognition [81]. Based on the identified stars, the tracker can calculate its attitude and rotation [81]. For maritime use, this data would be compared to horizon measurement and time to derive the latitude and longitude.

Another approach to star tracking is the usage of fisheye lenses or wide-angle cameras. They require more processing power due to image distortion and having more data to use for matching. On the other hand, the larger Field of View (FOV) improves star identification as it allows capturing a larger number of stars simultaneously [80].

Daytime star tracking remains a problem for CN, although Shortwave Infrared (SWIR) filters can be used to filter out sunlight scattering [20]. This allows star tracers to operate day and night with the drawback if SWIR cameras having lower signal-to-noise ratios than visible spectrum cameras, resulting in more erroneous measurements [82]. While SWIR cameras also suffer from the same visibility

blockage in cloudy weather as visible spectrum cameras, they could provide a daytime CN alternative. Alternatively, a system utilizing primary the position of the Sun during daytime can be developed.

4.3 Advantages and challenges of celestial navigation

Celestial navigation has many advantages that make it a robust alternative in hostile environments, as presented in Table 4.1. It does not rely on knowledge of a previous position or integrity of external signals. An absolute position can be acquired with tools kept in the vessel, without the threat of a jammed signal or accumulation errors [82]. Another advantage is that using CN does not require sending outward signals, enhancing stealth that can be essential in military applications.

Table 4.1: Strengths, Weaknesses and Opportunities of autonomous Celestial Navigation

Strengths	Weaknesses	Opportunities
• Independent and reliable positioning • No accumulation of errors over time • No infrastructure maintenance • Simplified use using electronic aids • Non-emissive (stealth)	• Low position accuracy compared to GNSS • Limited by time of day and visible horizon • Dependence on weather and sky cover	• Improvement of system integration • Development of military and commercial technologies due to increased interest • Application of new technology from other domains • Capacity of ships do not restrict system size or weight substantially

When the celestial charts, calculations and even star identification are solved with computers, it resolves the requirements of knowledge of complicated mathematics

and need of extensive data tables and proficiency to read them. This automatization provides ease of use as another advantage. Additionally, there is no need for constructing and maintaining infrastructure, as stars do not need maintenance but remain in the sky for anyone to look at.

While celestial bodies cannot be jammed in the technical sense, a kind of natural jamming hinders the usage of celestial navigation. Traditionally, it is highly susceptible to weather conditions. Clouds or fog block the view to the sky and can render a sextant useless. The problem persists in automated systems. In partly cloudy conditions, it can be mitigated to a degree by having star trackers with a wide FOV that can identify stars from a partly visible sky.

Time of day can provide another disadvantage. Traditionally, daytime celestial navigation has been restricted to observing the sun and moon, while other celestial bodies are not visible due to sunlight scattering in the atmosphere. While many star sensors are primarily developed for use in space, where the atmosphere is not a problem, there have been development even in star tracking technology that is usable from the surface of the earth in daytime. Optical filters, especially shortwave infrared filters, have been found to enhance the visibility of stars in daytime [83].

Time is the source of another problem. While latitude can be acquired from celestial bodies without knowing the exact time, longitude cannot. GNSS provide an accurate time via satellite signals, but it is of no use during outages. However, computers can fulfill the role of the traditional chronometers. Modern real-time clocks have a clock drift of about 3 ppm (0.3 s per 24 h) [82]. If the drift is allowed to accumulate for longer times, navigation accuracy can be degraded. As the Earth rotates 15 arcseconds by second of time, a daily drift of 0.3 seconds results to a 4.5 arcsecond error, equal to 0.075 nautical miles, or approximately 139 meters, per day at the equator. In practice, a short-term timing error is typically smaller than other sources of uncertainty, but can accumulate if left unchecked.

The accuracy of GNSS is still hard to achieve with celestial navigation. With their solution, Critchley-Marrows and Mortari [20] have reached a positioning accuracy under 100 m in the horizontal plane. They conclude that for ships, GNSS is still the most accurate source of navigation reference when fully functional, but that celestial navigation is a viable backup technique or can be used to check the approximate correctness of the GNSS-derived position to detect anomalies.

In UAV navigation, Teague and Chahl [82] identify weight to be one of the main problems of utilizing celestial navigation systems. The problem stems from the need to reduce the weight of an airborne vessel mentioned in Section 3.2.2. For example, hardware used for stabilizing a sensor receiving the visual of the celestial bodies can weigh several kilograms rendering it unusable for smaller aircrafts [82]. In ships, the size and weight are not a problem as the capacity of the vessel is multitudes larger.

4.4 Proposed low-cost automated celestial navigation system

To assess the feasibility of low-cost celestial navigation, I propose a prototype for autonomous nighttime CN. The system is designed to provide GNSS-independent position fixes using low-cost, commercially available components combined with open star libraries, modern computer vision and astronomical computation methods.

The proposed components, data sources and software libraries are seen in Table 4.2. The hardware consists of a Raspberry Pi 5 microcomputer with dual camera support, a camera module equipped with a fisheye lens, and a secondary camera dedicated to horizon detection. The star camera periodically captures images of the sky, while the horizon camera provides information about the orientation of the system relative to the horizontal plane. The horizon camera can be exchanged for an IMU for a computationally less expensive solution to provide orientation. A consumer-

grade IMU can be a less expensive component, but accumulates error in the long run and requires correction.

Table 4.2: Components and data sources of the proposed system

Main processing system	Raspberry Pi 5 microcomputer
Star camera	Raspberry Pi HQ Camera module
Fisheye lens	Arducam 180 Degree Fisheye Lens
Horizon camera	Raspberry Pi HQ Camera module
Star catalog	Hipparcos main catalog
Planetary and lunar catalog	Jet Propulsion Laboratory Ephemerides
Time handling and coordinate transfer	Skyfield Python library
Computer vision	OpenCV Python library

Astronomical reference data is downloaded from the following established sources. The Hipparcos main catalog [84] is used for the basis for star positions. To reduce computational load while preserving sufficient coverage of the sky, the dataset is filtered to stars brighter than magnitude 5, resulting in approximately 1600 stars. Planetary and lunar positions are obtained from Jet Propulsion Laboratory Ephemerides [85]. Time handling and coordinate transfer tools necessary for celestial navigation are provided by the Skyfield library [86]. Image processing is done with OpenCV, while NumPy and Scipy provide vector arithmetic and the nonlinear least-squares solver.

The system operates by detecting stars in the images captured by the fisheye camera. The centroid position of each detected star is converted into a direction vector, and the stars are identified by matching pairwise angular distances to the same distances calculated from the brightest stars in the catalog. Once enough stars are identified, the latitude and longitude of the observer along with the camera rotation are solved by projecting positions of the catalog stars and finding the best matching parameter sets from a grid of different latitudes and longitudes.

4.5 Simulation

The observation processing flow (shown in Figure 4.1) was evaluated against synthetic fisheye images of the sky generated with the Stellarium planetarium software [87]. Stellarium was chosen as the image provider because every render has an exactly known latitude, longitude, altitude as well as UTC timestamp, providing ground truth against which to evaluate the accuracy of the algorithm. The images were generated without atmospheric disturbances, clouds or other noise. The test set consisted of fifteen images at five distinct ground truth locations, most of which shared the same UTC timestamp. Four of the images were generated with different timestamps to verify behaviour across seasonal changes.

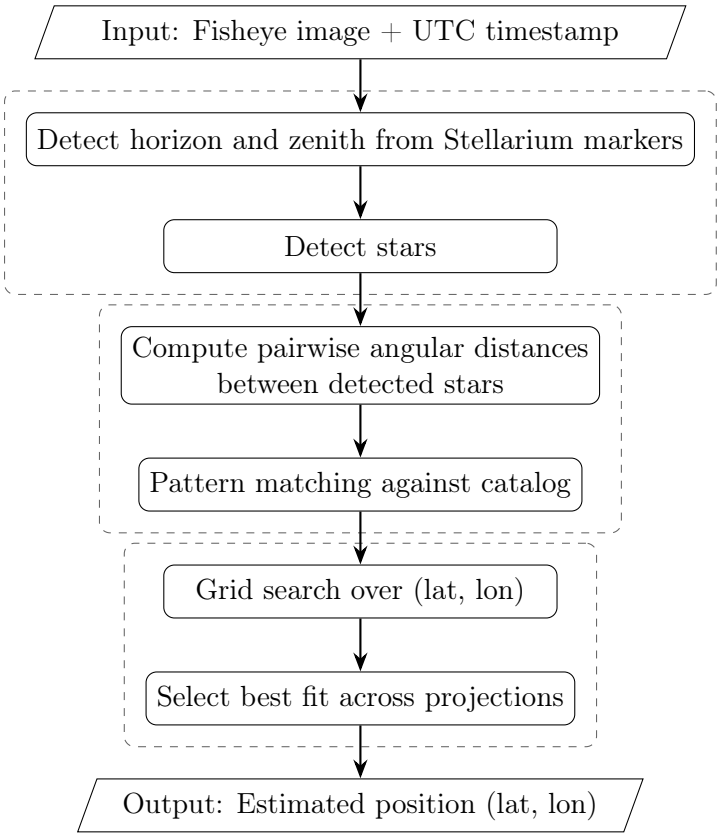

Figure 4.1: Flowchart of the algorithm used in the simulation. Detection extracts the attitude of the observation from Stellarium markers and positions of the brightest stars. Identification matches the stars against the catalog and postitioning calculates the observer's position by joint nonlinear least-squares.

The simulation was implemented on a desktop computer using the software stack listed in Table 4.2. The algorithm takes as its input the rendered image and its UTC timestamp, mirroring the information available to the prototype at runtime. Instead of determining orientation from a horizon camera, the horizon and zenith are provided via Stellarium markers visible in the rendered images. OpenCV was used to load each image, detect the Stellarium markers and the stars using binary thresholding. Skyfield provided the Hipparcos catalog data and astronomical computations. Star positions and angular distances were calculated with NumPy and pattern-matched against the star catalog (as shown in Listing 1).

Listing 1 Star identification by triangle-pattern voting.

```
  def identify(blobs, lens, catalog, *,
               n_obs=20, n_cat=80, tol_deg=0.5,
               min_distance=3.0, max_distance=80.0, min_spread=0.6,
               min_votes=3):
      """Identify the brightest detected blobs against the brightest
      catalog stars by triangle-pattern voting."""
      blobs = blobs[:n_obs]
      if len(blobs) < 3:
          return []

      # Catalog data: brightest n_cat stars with their pairwise distances.
      cat_entries = catalog.entries[:n_cat]
      cat_ras  = np.array([e.ra_deg  for e in cat_entries])
      cat_decs = np.array([e.dec_deg for e in cat_entries])
      cat_D    = _great_circle_matrix(cat_ras, cat_decs)

      # Pairwise distances between detected stars under an initial lens.
      obs_D = _observed_distance_matrix(blobs, lens)

      # Hash table of catalog triangles, keyed by sorted-distance bucket.
      cat_triangles = _build_catalog_triangle_hash(
          cat_D, tol_deg=tol_deg,
          min_distance=min_distance, max_distance=max_distance,
          min_spread=min_spread,
      )

      # Triangle-pattern voting + greedy 1-to-1 resolution.
      votes = _collect_votes(
          obs_D, cat_D, cat_triangles,
          tol_deg=tol_deg, min_distance=min_distance,
          max_distance=max_distance, min_spread=min_spread,
      )
      return _greedy_assign(votes, cat_entries, min_votes=min_votes)
```

The position and rotation of the observer were determined by a two-dimensional search over latitude and longitude. As Stellarium's projection model of the render was not known a priori, the fit was repeated under four standard fisheye projection

models (equidistant, stereographic, equal-area, and orthographic), and the lowest-residual result was kept. The estimated positions were written to a CSV file and then compared to the ground truths using the Haversine formula.

The algorithm solved each of the fifteen images successfully and recovered the observer position with a median error of 5.2 km and a maximum error of 22.2 km (Table 4.3).

Table 4.3: Per-image simulation results across five ground-truth locations. Three images were rendered at each location at different dates and times to verify behaviour across seasonal changes.

Location	Ground truth		Solved		Absolute difference		Error
	lat (°)	lon (°)	lat (°)	lon (°)	lat (°)	lon (°)	(km)
Arctic Ocean	+75.185	+47.407	+75.191	+47.226	0.006	0.181	5.2
Arctic Ocean	+75.185	+47.407	+75.192	+47.304	0.007	0.103	3.0
Arctic Ocean	+75.185	+47.407	+75.192	+47.221	0.007	0.186	5.4
Baltic Sea	+58.889	+19.259	+58.893	+19.270	0.004	0.011	0.8
Baltic Sea	+58.889	+19.259	+58.897	+19.243	0.008	0.016	1.3
Baltic Sea	+58.889	+19.259	+58.892	+19.238	0.003	0.021	1.3
North Atlantic	+35.185	−35.556	+35.175	−35.527	0.010	0.029	2.8
North Atlantic	+35.185	−35.556	+35.194	−35.502	0.009	0.054	5.0
North Atlantic	+35.185	−35.556	+35.193	−35.520	0.008	0.036	3.4
Indian Ocean	−24.074	+84.444	−24.094	+84.255	0.020	0.189	19.3
Indian Ocean	−24.074	+84.444	−24.075	+84.225	0.001	0.219	22.2
Indian Ocean	−24.074	+84.444	−24.084	+84.230	0.010	0.214	21.8
South Pacific	−35.926	−104.444	−35.918	−104.264	0.008	0.180	16.2
South Pacific	−35.926	−104.444	−35.912	−104.253	0.014	0.191	17.3
South Pacific	−35.926	−104.444	−35.923	−104.232	0.003	0.212	19.2
				Median error	0.008	0.180	5.2
				Maximum error	0.020	0.219	22.2

Longitude errors were consistently larger than latitude errors. The error can be explained by the differences in obtaining latitude and longitude as discussed in Chapter 2. While latitude is derived from altitude observations, determining longitude is dependent on accurate timing. As mentioned in Section 4.3, sub-second time inaccuracies result in errors of several arcseconds, and the timestamps used in the simulation were limited to one-second accuracy.

A second, probably more impactful contributor is the lack of a bright pole star in the southern celestial hemisphere. In northern observations, Polaris provides a north reference within 0.7° of the celestial pole, providing and anchor for the rotational

angle of the sky in the image. Observations where Polaris is below the horizon lack this constraint, leaving the rotational angle to be inferred from the larger stellar pattern. However, as seen in the Arctic Ocean observations, the anchoring effect of Polaris weakens as its zenith angle decreases. A small zenith angle places Polaris close to the image center, where its position contributes less weight to the rotation fix.

Additionally, image resolution sets a structural ceiling on the positioning accuracy, as the pixel-to-arcminute ratio limits the precision of the angular separations that can be extracted from the images. Higher-resolution sky images would relax this ceiling, enhancing precision.

A trend can also be seen where high-latitude observations generally have a smaller overall positioning error, even when the angular longitude error is similar to that at lower latitudes. This can be explained by the convergence of the longitude lines towards the poles, causing a given longitude error to result in a smaller physical distance. The positioning error remained between 3.0 and 5.4 kilometres for the three Arctic Ocean observations, as shown in Table 4.3, while the South Pacific observations with comparable angular longitude errors produced considerably larger physical errors of 16.2 to 19.2 km.

For open-ocean navigation, an accuracy of a few kilometres is usually sufficient. Kaplan [88] reports that traditional sextant fixes are "rarely more accurate than several nautical miles", translating to an accuracy of roughly 5-10 km. The prototype's median error of 5.2 km is in the same range, and the best northern hemisphere fixes with a lower than 1.5 km error, obtained without requiring manual sight reduction, are promising. While the accuracy of CN is far from that of GNSS, the system could provide a sufficient position for a fallback solution at sea.

4.6 Potential field prototype

The simulation evaluates the algorithm against generated images that reflect ideal conditions, while in the real life scenario several practical factors influence the accuracy of the system. Longer exposure times improve star visibility but increase motion blur due to vessel movement. At sea, the roll and pitch are in constant change, presenting a major challenge that can be mitigated either with gimbaling or advanced image processing. Gimbaling reduces motion at the source and simplifies processing, but introduces an additional cost as well as mechanical and maintenance requirements. For a low-cost system, software-based stabilization provides an affordable alternative.

The quality of the cameras and lenses also affect observation precision. A low-cost fisheye lens can introduce severe optical aberrations and generate measurement errors, especially nearer to the edges of the image. Higher-quality components can provide better sharpness, light sensitivity and more predictable distortion characteristics, but can also significantly increase the total cost of the system. The optical systems also need to be suited for obtaining nighttime images, as the proposed system is intended for nighttime position verification. To develop a system for daytime usage, a sun camera or alternatively a star camera with SWIR filtering could be used.

For algorithmic upgrades, two design choices can help in accuracy. The Hipparcos catalog could be replaced with Gaia Data release 3 [89], a star catalog with a reference epoch closer to current observations than Hipparcos'. It can provide more precise astrometrics, and it's larger catalog could help in partly cloudy conditions. Another upgrade would be using the classical circles-of-position (COP) approach for positioning. While the pairwise angular pattern matching method used in the simulation can incorporate the calibration of the fisheye lens type in each positioning cycle, COP could, when calibrated, provide a computationally lighter and easier

to debug method in field conditions. The COP method only needs three stars to calculate their COPs and to find their approximate intersection with least-square fitting.

5 Discussion

Reports of GNSS disturbances have increased in recent years, followed by concerns for navigation safety [7], [8]. This has led to an increased demand for alternative and parallel navigation methods, voiced by several countries worldwide [6]. Despite its vulnerability, GNSS remains the the dominant positioning system across domains (excluding vessels operating in natively GNSS-denied environments, like submarines). This popularity is due to its unparalleled accuracy under nominal conditions as well as ease of use and widespread integration to existing systems [19].

Reasons for GNSS disruptions vary. Some environments, like cities or tunnels, can cause unintended blockage or reflection of satellite signals. In marine environments, these kinds of environmental features are nonexistent, and GNSS disruption seems to be caused almost exclusively by intentional interference like jamming and spoofing. While ships might not be severely affected by short-term disturbances due to their relatively slow speeds, heightened global tensions and the increased availability of low-cost jamming equipment affect even marine traffic.

In my literature review, a clear trend across domains was the adoption of multi-sensor navigation systems to mitigate GNSS disturbances. The single most popular approach was combining GNSS with an odometry solution. In ground vehicles, INS was the most commonly implemented technology, while in aerial vehicles visual odometry was most common. GNSS-odometry integration improves robustness, but remains reliant on accurate GNSS updates to prevent error accumulation of the

odometry solution, making it vulnerable to prolonged outages and sustained interference. In the marine domain, only one paper (Bayat and Aguiar [40]) describing an UAV proposed an odometry solution using visual SLAM.

All the three papers discussing marine solutions included in the literature review use feature recognition. In addition to odometry, Bayat and Aguiar [40] also utilize sonar to recognize seafloor features for navigational purposes, whereas Han et al. [41] use radar for coastal feature recognition and Naus et al. [42] use radar for identifying navigational infrastructure. From the literature, it is apparent that the suitability of methods is highly reliant on the environment. In feature-rich environments and environments where navigational infrastructure exists or can be built, absolute position can be derived without GNSS. The drawback of these kinds of solutions is that they require collecting and georeferencing large amounts of data or building extensive navigational infrastructure. In marine environments, the sparsity of features provides an additional challenge as it greatly reduces techniques that navigating can be based on. In a relatively small scale, sonar or radar can be used to match the seafloor to previously collected, georeferenced data, but producing these seafloor maps for vast areas would not be feasible. Similarly, building and maintaining navigational infrastructure to cover large parts of the ocean is not possible.

In coastal waters, ships can use landmarks or potentially SOPs to navigate, but in open-sea environments only GNSS, INS and celestial navigation remain usable. As relying solely in GNSS/INS leaves the vessel vulnerable to sustained interference and INS drift, implementing a complementary CN system would increase navigational safety. Due to its great accuracy in normal conditions GNSS will probably not be replaced, but a method to receive an independent position to check the integrity of the GNSS signal would provide much needed robustness.

In the past, utilizing CN has required manual tool usage, knowledge of complicated mathematics and advanced navigational competence. This combined with the

ubiquity of GNSS has resulted in it being perceived as an outdated and laborous practice [21]. Modern advancements can automate all the required steps from star detection to position determination, increasing the attractiveness and potential of CN and making it a feasible method for GNSS-less navigation.

The greatest advantages of celestial navigation are its independence and self-containment. It does not require infrastructure to be built, and cannot be jammed or spoofed like radio-based solutions. No outward signals that can be detected by a potential adversary are produced, increasing the usefulness of CN for operations where stealth is required.

The main limitations of CN are its sensitivity to weather conditions and clear sky visibility. Approximately 70 % of Earth's surface is cloud-covered at any given time, with substantial regional variation [90]. Its accuracy is also not comparable to GNSS in normal conditions, but for open-sea environments an approximate location is sufficient. Traditional celestial navigation with a hand-held sextant typically produces a fix with an accuracy of roughly 5–10 km [88].

In the simulation, the prototype achieved a median position error of 5.2 km, with the best position fix at an error of 0.8 km, comparable or even better than the traditional method. While the accuracy of the prototype was diminished in the southern hemisphere by the lack of a pole star, using a larger catalog that captures the dimmer Octantis near the southern celestial pole could mitigate the error. Furthermore, when the used star catalog is large enough, capturing only sections of the skies in partially cloudy conditions is sufficient. To further increase accuracy, higher-end components can be used to enhance image quality, and more advanced filtering algorithms can be used for processing.

Only three marine solutions and no studies on celestial navigation were identified in the initial literature search, which necessitated supplemental targeted searches to obtain relevant information. This indicates that the original search scope might

have been too narrow, and a broader approach could improve coverage. Limiting the search terms to only cover "GNSS" instead of including the named implementations GPS, GLONASS, BeiDou and Galileo might have reduced the number of search results. The search could also be extended to other databases. Furthermore, the literature was restricted by fulltext availability, filtering results from some possibly relevant journals. However, even the supplemental results were few, revealing a research gap for maritime digital celestial navigation. The search was conducted in March 2025, and given the rapidly increasing relevance of GNSS resilience, it is likely that additional relevant research has since been published. Future work should therefore include an updated and expanded review, as well as the implementation and testing of a field version of the proposed prototype to assess its practical performance and limitations.

6 Conclusion

The growing frequency of GNSS interference, combined with geopolitical tensions and the widespread dependency on satellite-based positioning, has raised concerns regarding maritime safety and navigation robustness. As several countries and maritime authorities have expressed concerns over GNSS reliability, the need for independent and reliable navigation methods that allow vessels to operate in GNSS-denied environments has become more apparent. Against this background, this thesis examined navigation systems in the context of increased GNSS vulnerability, and addressed the following research questions:

RQ1: What navigation methods are currently employed in GNSS-denied environments, and how do their strengths and limitations compare?

RQ2: Can celestial navigation be considered a viable alternative for ocean navigation when GNSS integrity is compromised?

RQ3: What would be a cost-efficient and practical way to implement celestial navigation in a modern maritime vessel?

In relation to RQ1, the literature review shows that current navigation methods in GNSS-denied environments include inertial navigation systems, other dead reckoning solutions such as visual or radar odometry, feature recognition, and various infrastructure-dependent alternatives. The solutions vary in cost, accuracy and

independence, and their usability is often highly dependent on the surrounding environment and its features.

Despite the increasing reports on GNSS interference, marine solutions for mitigating their effects remain underresearched. Due to the feature-sparseness of the ocean, solutions applicable to aerial and terrestrial domains are not suitable for the marine environment. Regarding RQ2, celestial navigation has the potential to offer a fully independent positioning method that does not rely on external infrastructure, radio signals, or previously gathered geographical knowledge, making it a viable alternative in GNSS-denied environments. While previously limited by manual operations, traditional equipment and decreased perceived relevance, modern CN can be fully automated by modern technology, greatly increasing its potential.

In response to RQ3, a practical and low-cost system utilizing CN can be implemented with a single-board computer combined with a wide-field camera system and pre-downloaded astronomical datasets. The results suggest that a lightweight implementation can in optimal conditions achieve kilometre-level positioning accuracy, which is at a sufficient level for backup positioning at sea.

While the accuracy of GNSS ensures it continues as the primary method of navigation, CN can provide fully independent and self-contained positioning with sufficient accuracy for open sea navigation. Cloud coverage and weather conditions remain a challenge for CN, but filtering technology can mitigate daylight scattering. Furthermore, the additional size, weight and cost of a CN system are small and do not present a problem for marine vessels.

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Appendix A Solar declination table

Day	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	S22.96°	S16.95°	S7.38°	N4.75°	N15.24°	N22.13°	N23.07°	N17.87°	N8.08°	S3.40°	S14.60°	S21.88°
2	S22.87°	S16.66°	S7.00°	N5.13°	N15.54°	N22.26°	N22.99°	N17.62°	N7.71°	S3.79°	S14.92°	S22.03°
3	S22.77°	S16.36°	S6.62°	N5.51°	N15.83°	N22.38°	N22.91°	N17.36°	N7.35°	S4.17°	S15.23°	S22.17°
4	S22.66°	S16.06°	S6.23°	N5.90°	N16.12°	N22.49°	N22.82°	N17.09°	N6.98°	S4.56°	S15.53°	S22.30°
5	S22.55°	S15.76°	S5.85°	N6.28°	N16.41°	N22.60°	N22.73°	N16.82°	N6.61°	S4.94°	S15.84°	S22.43°
6	S22.43°	S15.45°	S5.46°	N6.65°	N16.69°	N22.71°	N22.63°	N16.54°	N6.23°	S5.33°	S16.14°	S22.55°
7	S22.30°	S15.14°	S5.07°	N7.03°	N16.96°	N22.80°	N22.52°	N16.26°	N5.86°	S5.71°	S16.43°	S22.66°
8	S22.17°	S14.82°	S4.68°	N7.40°	N17.23°	N22.89°	N22.41°	N15.98°	N5.48°	S6.09°	S16.72°	S22.77°
9	S22.02°	S14.50°	S4.29°	N7.78°	N17.50°	N22.97°	N22.29°	N15.69°	N5.11°	S6.47°	S17.01°	S22.87°
10	S21.87°	S14.18°	S3.90°	N8.15°	N17.76°	N23.05°	N22.16°	N15.40°	N4.73°	S6.85°	S17.29°	S22.96°
11	S21.72°	S13.85°	S3.50°	N8.51°	N18.02°	N23.12°	N22.03°	N15.10°	N4.35°	S7.22°	S17.56°	S23.04°
12	S21.55°	S13.51°	S3.11°	N8.88°	N18.27°	N23.18°	N21.89°	N14.80°	N3.97°	S7.60°	S17.83°	S23.11°
13	S21.38°	S13.18°	S2.72°	N9.24°	N18.52°	N23.24°	N21.74°	N14.50°	N3.58°	S7.97°	S18.10°	S23.18°
14	S21.21°	S12.84°	S2.32°	N9.60°	N18.76°	N23.29°	N21.59°	N14.19°	N3.20°	S8.34°	S18.36°	S23.24°
15	S21.02°	S12.49°	S1.93°	N9.96°	N18.99°	N23.33°	N21.43°	N13.88°	N2.82°	S8.71°	S18.62°	S23.29°
16	S20.83°	S12.15°	S1.53°	N10.31°	N19.22°	N23.36°	N21.27°	N13.56°	N2.43°	S9.08°	S18.87°	S23.34°
17	S20.64°	S11.80°	S1.14°	N10.66°	N19.45°	N23.39°	N21.10°	N13.24°	N2.04°	S9.45°	S19.11°	S23.37°
18	S20.43°	S11.44°	S0.74°	N11.01°	N19.67°	N23.41°	N20.92°	N12.92°	N1.66°	S9.81°	S19.35°	S23.40°
19	S20.22°	S11.09°	S0.35°	N11.36°	N19.88°	N23.43°	N20.74°	N12.59°	N1.27°	S10.17°	S19.58°	S23.42°
20	S20.00°	S10.73°	N0.05°	N11.70°	N20.09°	N23.44°	N20.55°	N12.26°	N0.88°	S10.53°	S19.81°	S23.43°
21	S19.78°	S10.37°	N0.44°	N12.04°	N20.29°	N23.44°	N20.36°	N11.93°	N0.49°	S10.89°	S20.03°	S23.44°
22	S19.55°	S10.00°	N0.84°	N12.38°	N20.49°	N23.43°	N20.16°	N11.59°	N0.10°	S11.24°	S20.24°	S23.44°
23	S19.32°	S9.63°	N1.23°	N12.71°	N20.68°	N23.42°	N19.96°	N11.25°	S0.29°	S11.59°	S20.45°	S23.42°
24	S19.08°	S9.26°	N1.63°	N13.04°	N20.87°	N23.40°	N19.75°	N10.91°	S0.68°	S11.94°	S20.65°	S23.41°
25	S18.83°	S8.89°	N2.02°	N13.36°	N21.05°	N23.37°	N19.53°	N10.57°	S1.07°	S12.28°	S20.85°	S23.38°
26	S18.58°	S8.52°	N2.41°	N13.69°	N21.22°	N23.34°	N19.31°	N10.22°	S1.46°	S12.62°	S21.04°	S23.34°
27	S18.32°	S8.14°	N2.80°	N14.01°	N21.39°	N23.30°	N19.08°	N9.87°	S1.84°	S12.96°	S21.22°	S23.30°
28	S18.06°	S7.76°	N3.20°	N14.32°	N21.55°	N23.25°	N18.85°	N9.51°	S2.23°	S13.30°	S21.39°	S23.25°
29	S17.79°		N3.58°	N14.63°	N21.70°	N23.20°	N18.61°	N9.16°	S2.62°	S13.63°	S21.56°	S23.20°
30	S17.51°		N3.97°	N14.94°	N21.85°	N23.14°	N18.37°	N8.80°	S3.01°	S13.96°	S21.73°	S23.13°
31	S17.23°		N4.36°		N21.99°		N18.13°	N8.44°		S14.28°		S23.06°