Brief history of Radionavigation
Lecture Notes(*)

(*) Mostly based on
"Global Positioning System; Signals, Measurements, and Performance",
P. Misra and P. Enge, Ganga-Jamnua Press, 2004

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• https://scholar.google.es/citations?user=Tm-DcsMAAAAJ&hl=en

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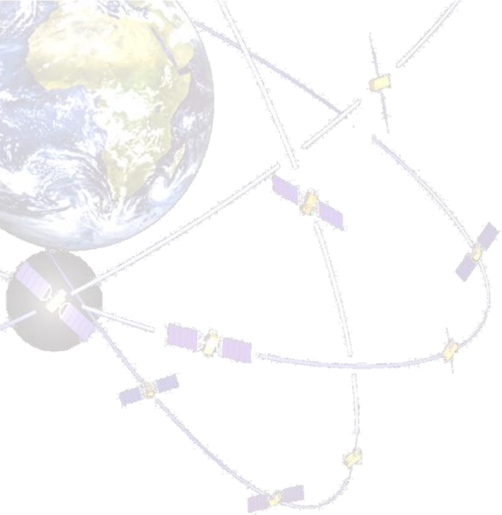

Lesson 1

Introduction to Radionavigation

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1. Introduction

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Magallan, in 1519, performed his voyage to cirumnavigate the globe equipped with sea charts, a terrestrial globe, theodolites, quadrants, compasses, magnetic needles…. He could estimate the ship's speed, direction and latitude, but not the longitude. Now position, velocity and time (pvt) can be estimated instantaneously, continuously, inexpensively and effortlessly with GPS.

It took another 250 years for the sailors to be able to determine their longitude at sea.

And it took 200 years more to get GPS, which is the fruit of several technologies, which matured in the second half of XX century: artificial satellites, ultra-stable atomic clocks, spread spectrum signaling, microelectronics.

In this way GPS implements the trilateration, or position determination by measuring distances from known points.

1.1 A Brief History of Navigation

The ancient and modern positioning and navegation systems are based on three fields:

Geodesy: the study of the size and shape of the earth and mapping of its surface.

Timekeeping (horology, the technique of measuring time).

Astronomy, and in the XX Century the Astronautics (space flight).

The early navigators & mapmakers relied on celestial observations to determine both time and positions on earth, providing in this way the impetus for study the basic laws governing the stars and planets movements.

Navigation provided the impetus for development of accurate clocks in the seventeenth and eighteenth centuries.

The roles reversed in the XX century: the advances in timeskeeping (demanded by telecommunication industry) led to the development of a new class of radionavigation systems (such as GPS).

1.1 A Brief History of Navigation (Contd').

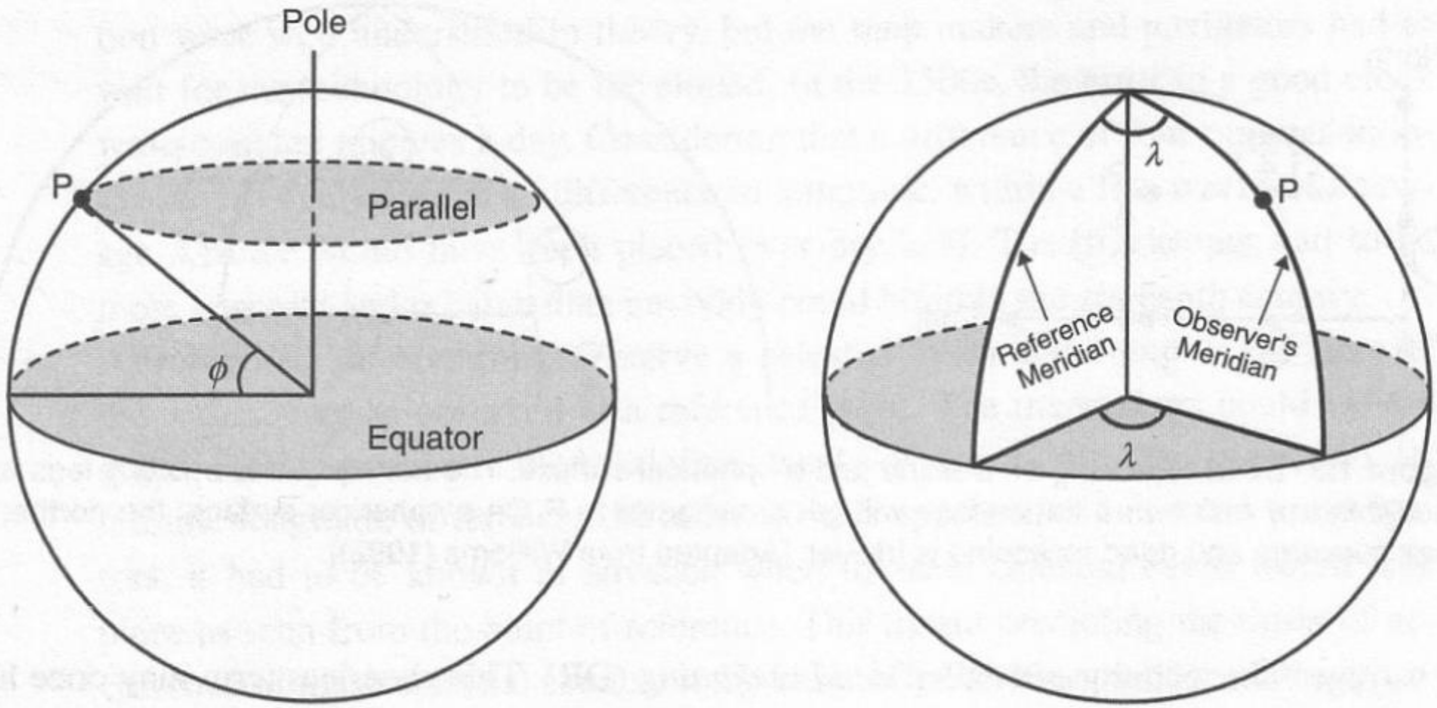

Figure 1.1 Geocentric latitude (ϕ) and longitude (λ).

2000 years ago: the Greeks knew the earth to be spherical, and that a point could represented by latitude (northern or southern angle to the equator) and longitude (western or eastern angle to a chosen meridian). A similar coordinate system is still in use.

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1.1 A Brief History of Navigation (Contd').

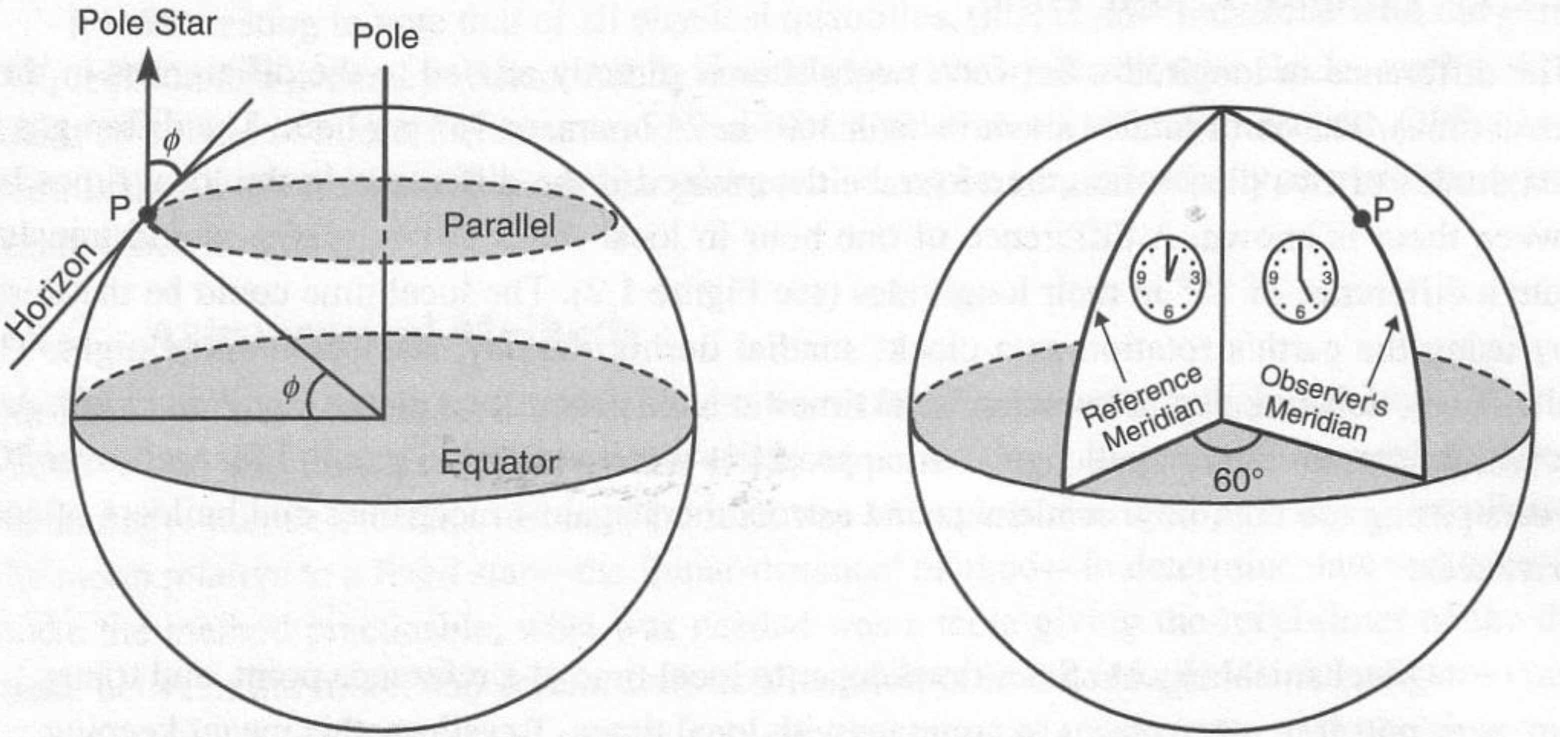


Figure 1.2 Measurement of latitude and longitude.

The latitude is easy to measure (elevation of Polar Star, or from Sun culmination).

The longitude is a much trickier concept: its refers to an arbitrarily reference meridian (Greenwich). Its measurement was a challenge for scientists and craftsmen of XVII and XVIII cent. Its determination waited until 1650s (land) and 1770s (sea).

1.1 A Brief History of Navigation (Contd').

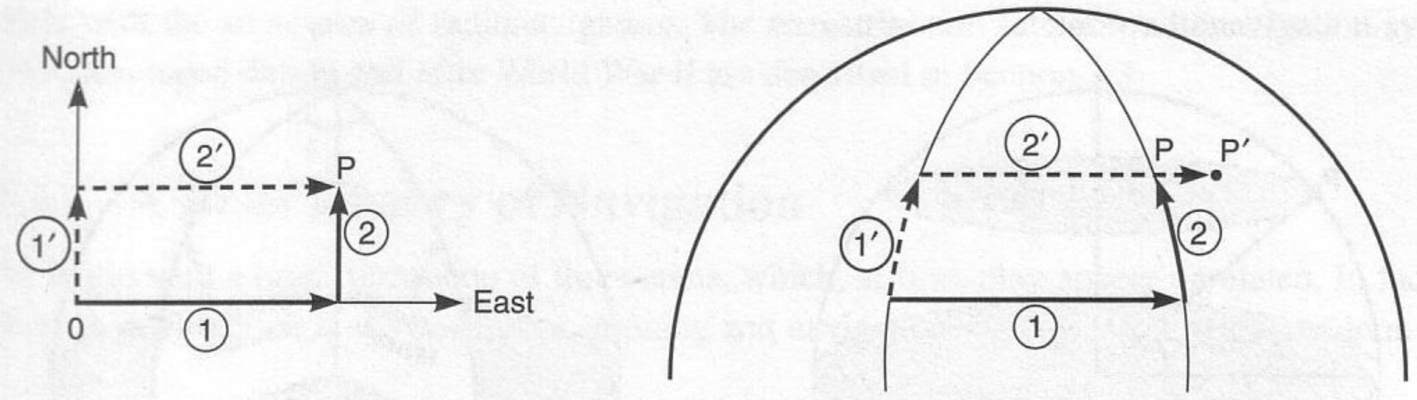


Figure 1.3 Dead reckoning on a plane and a spherical surface. The northerly and easterly legs executed in any order on a flat surface will get a navigator to P. On a spherical surface, the northerly lines converge and dead reckoning is trickier. [Adapted from Williams (1992)]

Columbus, like many early sailors, knew of latitude, but not of longitude. How did these early explorers manage to cross oceans and return to their home ports?

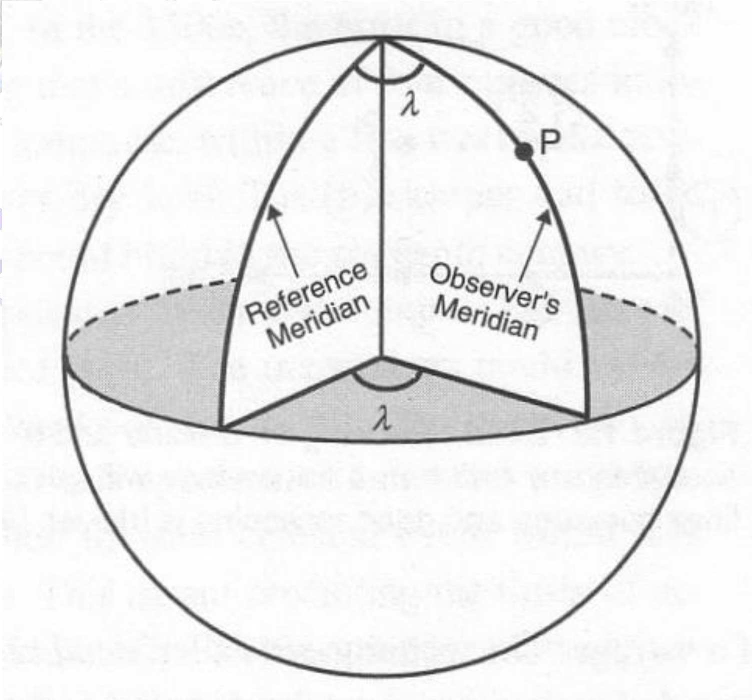
By dead reckoning, by keeping track of the direction and distance traveled on each leg of a voyage (or by seamanship…).

Dead reckoning is performed by vector addition from measurements of direction (magnetic compass introduced in China in XII c.), speed (ship estimation procedures) and time.

But the problem arises in 2-D reckoning of distances on a spherical surface (east-west mov. cannot be repeated at different latitudes).

In 1569 Gerardus Mercator devised a projection of the spherical earth onto a cylindrical surface (shapes retained –not the size-, constant bearing appear as straight lines)

1.1.1 Longitud and Time



The difference in longitudes between two places is directly given by the difference of local times during simultaneous events (the earth rotates 360º in 24 hours, 15º per hour).

Such knowledge of local times at an instant at two places simultaneously was an extraordinary challenge during 200 years, competing scientists and mechanics, with two different approaches:

Mechanical clocks: Set a timekeeper to local time at a reference point (sailor home port), and transport it to other places to compare with local times. Problem: clock error (~1500: ~10 minutes/day, in few weeks the sailor could got dry land coordinates!). Mechanical development : John Harrison clock at ~1760 (40 sec. after 46 days).

Astronomical observations: Celestial events with expected occurrence time at a reference point, observed from the sailor at sea. Problem: prediction accuracy, celestial mechanics development needed.

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1.1.2 Astronomical Methods

Lunar distance to starts (and star occultation events): The first idea was developed by Isaac Newton (1642-1727) and Edmond Halley (1656-1742), tied to lunar orbits. Improvement in prediction of lunar orbits for their use in navigation had influence in the founding of Paris Observatory (1667) and Greenwich Observatory (1675).

But the Newton's theory of 2 body motion gave an error of 5', an unacceptable level. The lunar problem deserved a three-body motion approach, developed by Leonhard Euler (1707-1783). This idea was never practical in the sea, but tried to compete with the chronometers (and later telegraphs).

Galilean satellites occultation behind Jupiter's shadow: The development of the telescope at the beginning of the XVII century allows to compare the local times during such events with the predicted ones at the reference site (Galileo proposed this method to the Spanish Crown, without success; the French crown adopted it as official at the end of XVIII cen.).

Many practical instruments were available at the end of XVIII cen.: a sextant measuring the celestial body elevation (by overimposing the celestial body image to the horizon), an accurate clock to get an the observation time, an almanac to find the predicted position of the body, and a magnetic compass to determine azimuth.

1.1.3 XX Century Developments: Inertial Navigation and Radio

Two early 20th century events determined its technological direction:

The bridging of Atlantic Ocean in 1901 by radio signal transmitting the letter “S” in Morse code across the Atlantic (Marconi was responsible).

The first airplane flew in 1903 (Wright Brothers).

Nowadays jetliners loaded with hundreds of passengers were flying around the world navigating with radio navigation aids (navaids) and inertial navigation systems, and being guided to land on narrow strips of lands shrouded in fog.

Nuclear-powered submarines were using inertial navigation not only to navigate but to initialize missile position, velocity, and azimuth.

The navigation systems can be classified as follows:

Dead reckoning system (such as the inertial navigation).

Guidance systems, which provides the user a course to steer by toward a destination without necessarily knowing his position (radio guidence systems such as: Instrument Landing System, ILS, Microwave Landing System, MLS, both used by aircraft under poor visibility conditions), heat sensors…

Position finding systems, which determines the position of the user in a well-defined coordinate frame (Loran, Omega, Transit, and GPS which provides as well time and velocity).

1.1.3 XX Century Developments: Inertial Navigation

A gyroscope is simply a spinning mass, usally mounted on gimbals so that the rotation axis is free to turn in any direction. It points continuously to the same direction (e.g. an star) thanks to the conservation of the angular momentum.

A gyrocompas is a gyroscope pointing to the North (quite useful in metallic (modern) ships).

An inertial navigation system (INS) consists of three accelerometers (a knife one would be a pendulum) and three gyroscopes.

Integrating two times, we get the trajectory regarding to an initial position and velocity. PROS: Independent of external signals. CONS: the positioning errors accumulates.

Solution: synergy with other systems such as GPS, which is used to calibrate the INS systems (lower rate), and at the same time provides to GPS higher sampling rate and availability in places without satellite measurements (obstructions, indoor).

Recently the availability of very small inertial sensors as microelectromechanical systems (MEMS), opens the door for future very cheap integrations with GPS (nowadays is being applied to ABS, video-camera stabilization,...)

1.1.3 XX Cen. Developments: Radionavigation

Table 1.1 Classification of radio frequencies

Band	*Frequency*	*Wavelength*
Very Low Frequency (VLF)	< 30 kHz	> 10 km
Low Frequency (LF)	30–300 kHz	1–10 km
Medium Frequency (MF)	300 kHz–3 MHz	100 m–1 km
High Frequency (HF)	3–30 MHz	10–100 m
Very High Frequency (VHF)	30–300 MHz	1–10 m
Ultra High Frequency (UHF)	300 MHz–3 GHz	10 cm–1 m
Super High Frequency (SHF)	3–30 GHz	1–10 cm

Frequency bands, following the International Telecommunication Union (ITU, U.N. agency for the allocation of radio frequencies to different user groups to prevent mutual interference).

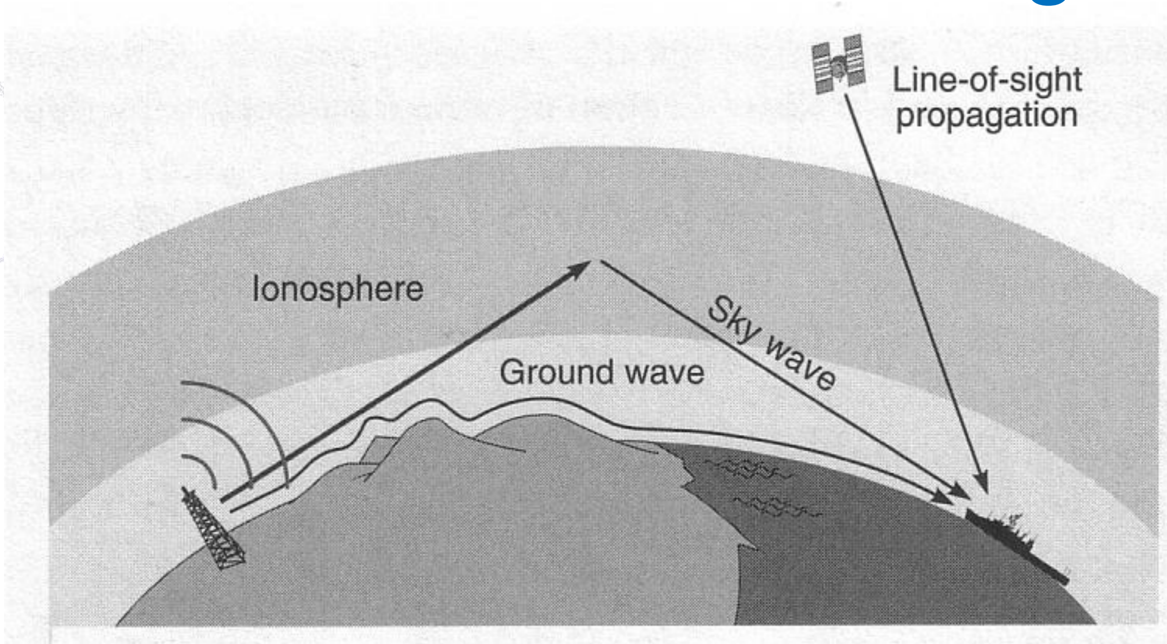
Radio signals, since the light, reflects, refracts, diffracts (interfering between them) and attenuates with the atmosphere, among other effects.

Ground waves: the radio signals below HF range, which travel around the curvature of the earth, but with propagation velocity stable and moderate propagation losts: useful for navigation (Loran, Omega, Decca, in VLF and LF bands).

Sky waves: Such HF and below radio signals also reflects on the ionosphere, being able to reach long distances, but there is a certain uncertainty of the ionospheric height: not so useful for navigation.

Line-of-sight propagation: Satellite navigation systems have used VHF and UHF bands (Transit, GPS).

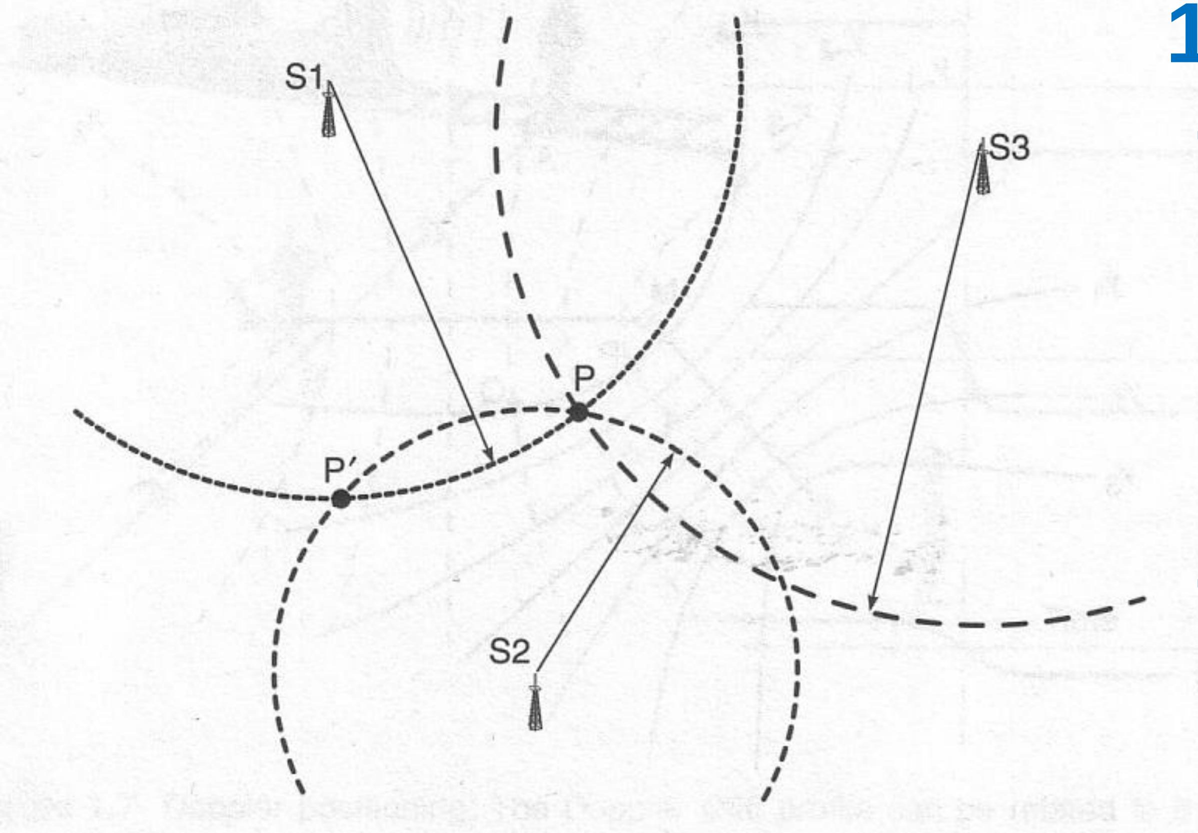
1.2 Methods of Radionavigation



The first radio navaids determined the position of an aircraft by bearing two directional antennas. After the second World War aviation: the VHF omnidirectional radio range (VOR), Tactical Air Navigation (TACAN), Instrument Landing System (ILS), Microwave Landing System (MLS). They are ground-based, short-range, line-of-sight systems. We will focus to long-range, global radionavigation systems, and in particular in GPS.

Navigators in land are typically satisfied with 2D navigation. However surveyors, geodesists and aviators needs altitude (these in real-time).

In the past horizontal and vertical coordinates were determined separately, with different methods. Nowadays 3D and time with the satellite navigation systems.



1.2.1 Trilateration

Trilateration: Given distances to three transmitters at known locations, the user can compute its 2D position unambiguously (2 tr., depending on the distance).

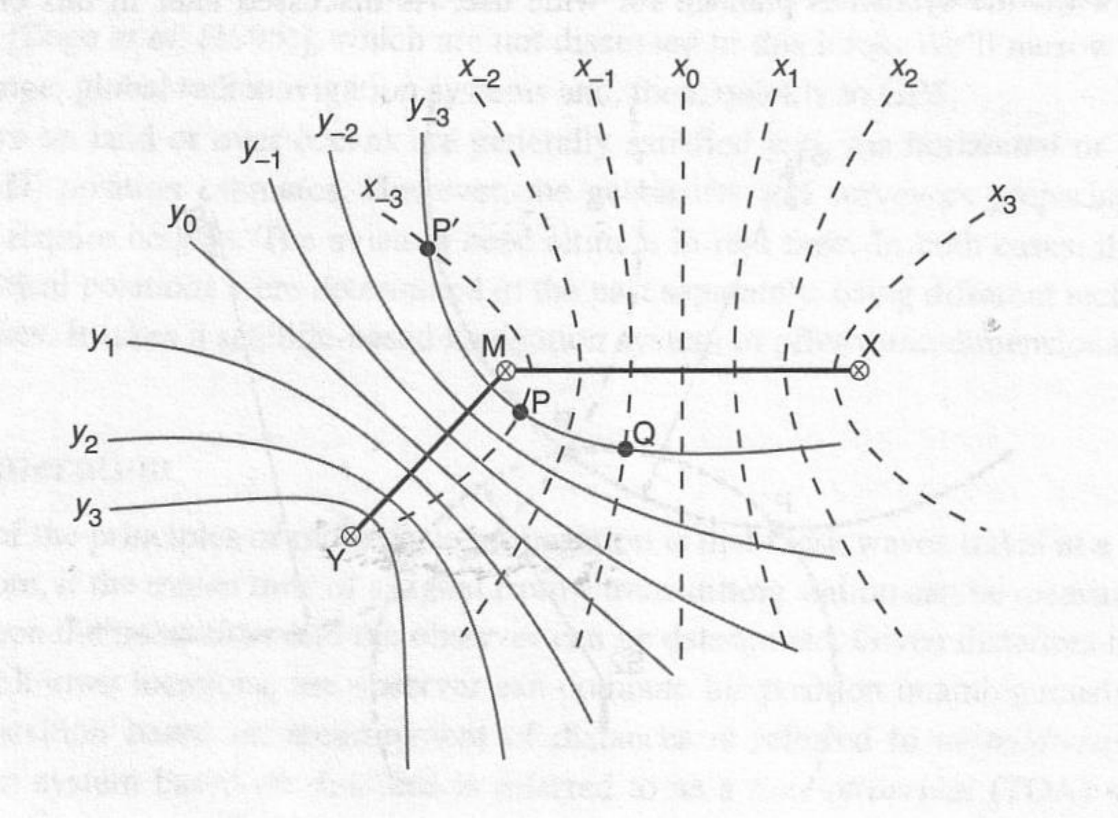
Time-of-arrival (TOA) system is a radionavigation system based on trilateration (such as GPS).

To determine 3D position, transmitter at different heights: limited to spatial systems.

The clocks of the transmitter and receiver should be synchronized.

GPS minimized demands on receiver clock at the expense of increased computational complexity in the receiver (not a problem with the actual CPUs). But in the early radionavigation age this was not the case and the following approaches were more feasible.

1.2.2 Hyperbolic Positioning



These systems are based on the difference in the times of arrival of signals (TDOA) from two (or three) transmitting stations: intersection of hiperbolas.

Only the transmitters should be syncronized, in TDOA the user clock should not be syncronized.

1.2.3 Doppler Positioning

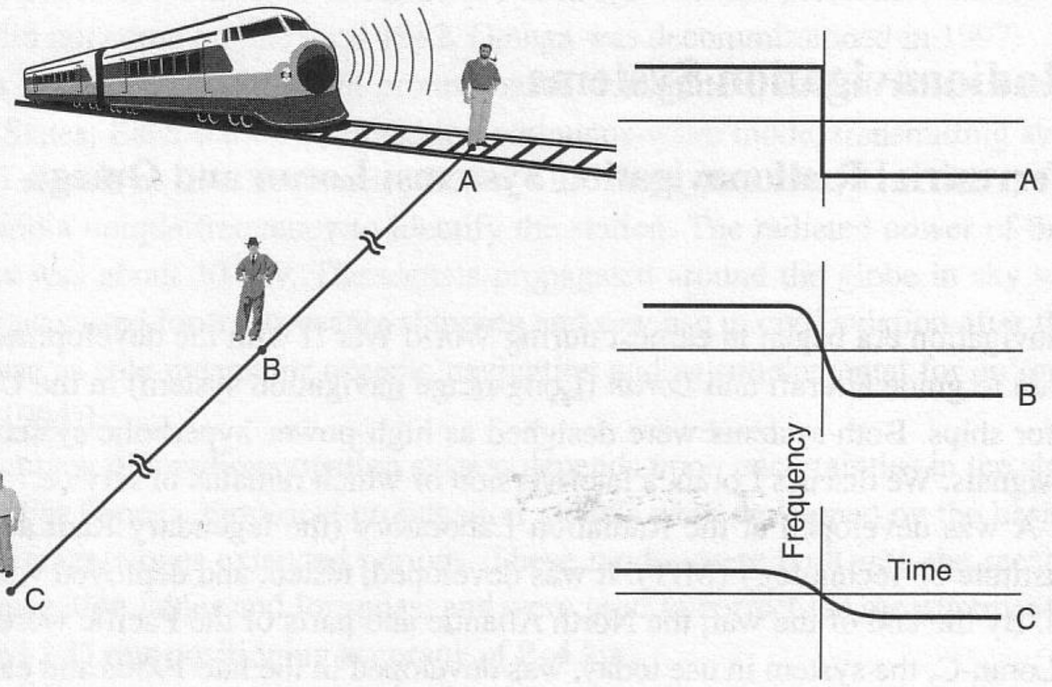


Figure 1.7 Doppler positioning: The Doppler shift profile can be related to the observer's distance from the track.

The change of apparent frequency of a signal is proportional to the velocity between the source and the user. From here it can be integrated giving the corresponding range variation.

The change of frequency profile is depending on the distance to the source track (cross-track). And knowing the source trajectory, the long-track coordinate can be deduced from the user timing.

This is the basis of Transit system.

1.3.1 Terrestrial Radionavigation Systems: Loran

Loran was designed by MIT, USA (as Gee in UK) as high-power hyperbolic systems transmiting pulse signals, and is still in service. After 1974 it became a civil system.

It operates in the LF band at 90-110 kHz, comprising a set of chains of transmitters (one chain typically consists of a master and 2-3 secondary transmitting stations, separated by about 1000 km.

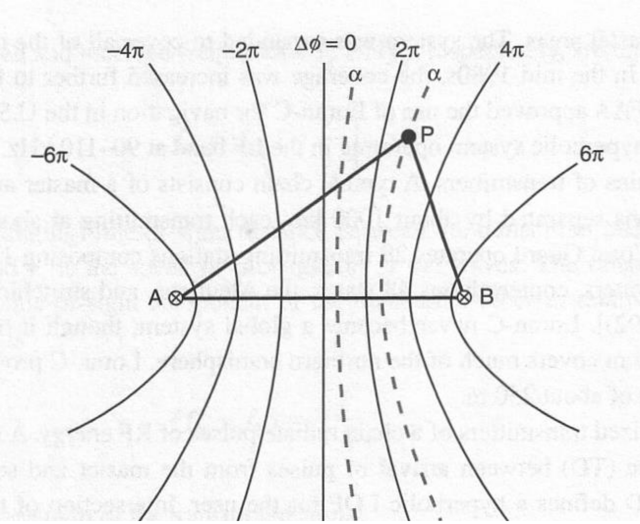
Loran-C provides 2-D rms positioning accuracy of about 250 m.

Loran-C signal has both ground and sky components, being the first one the more suitable for navigation (not under the uncertainties of the ionospheric height).

The initial decision of decommission Loran in 2000 were reversed, and nowadays it can serve as a complement to GPS.

A similar Russian system exists called Chayka.

1.3.1 Terrestrial Radionav. Systems: Omega



Omega was the first worldwide, continuously available system. It was developped in the early sixties by the U.S. Navy and Coast Guard and six international partners. It became operational in 1970s and was decommissioned in 1997.

Omega was based on eight ground-based transmitters, transmitting at five frequencies in the VLF band (10.2, 11.05, 11.333, 13.6 kHz and an unique frequency for each station).

The signals propagates worldwide in sky wave mode, with the uncertainty of the ionospheric height.

It was declared as sole-mean for oceanic navigation (FAA, 1994). Accuracy: 2-4 km horizontally.

Omega instead of TDOA, measures phase differences between the sinusoidal signals: widelaning as a way to reduce / fix the carrier phase ambiguity (see figure).

Also calibrating the error (from a known position receiver) and broadcasting it, allows to correct part of the error: Differential mode.

1.3.2 Satellite Navigation Systems: Transit.

Transit was the results of a brilliant discovery (pattern of Sputnik's Doppler shifts obtained from an station of known coordinates were enough to compute its Orbit) followed by a brilliant deduction (reversal: from known Orbit and Doppler shift, the station coordinates could be deduced).

The U.S. Navy developped the Navy Navigation Satellite System (NNSS or Transit, by the APL of the John Hopkins Univ.) for launching Polaris tactical weapons from the submarines.

Transit was realized with 4-7 Low Earth Orbiting satellites (~1100 km) within in almost pefect polar orbits, emitting two carriers at 150 and 400 MHz for ionospheric cancellation purposes.

2D rms accuracy was ~25 m. At a fixed site ~5 m, reaching to ~1m in differential mode.

The corresponding soviet system was Tsikada.

The Doppler shift based navigation worked well for ships at sea requiring infrequent position updates, and could track a signal during the 10-20 minutes satellite pass, but not for air

Table 1.2 A performance summary of radionavigation systems

System	*Coverage*		*Fix dimensions*	*Positioning accuracy (rms)*
	Worldwide	*Continuous*		
Loran-C	No	Yes	2-D	250 m
Omega	Yes	Yes	2-D	2–4 km
Transit	Yes	No	2-D	25 m
GPS	Yes	Yes	3-D plus time	Horizontal: 5 m Vertical: 7.5 m

1.3.2 Satellite Navigation Systems: GPS

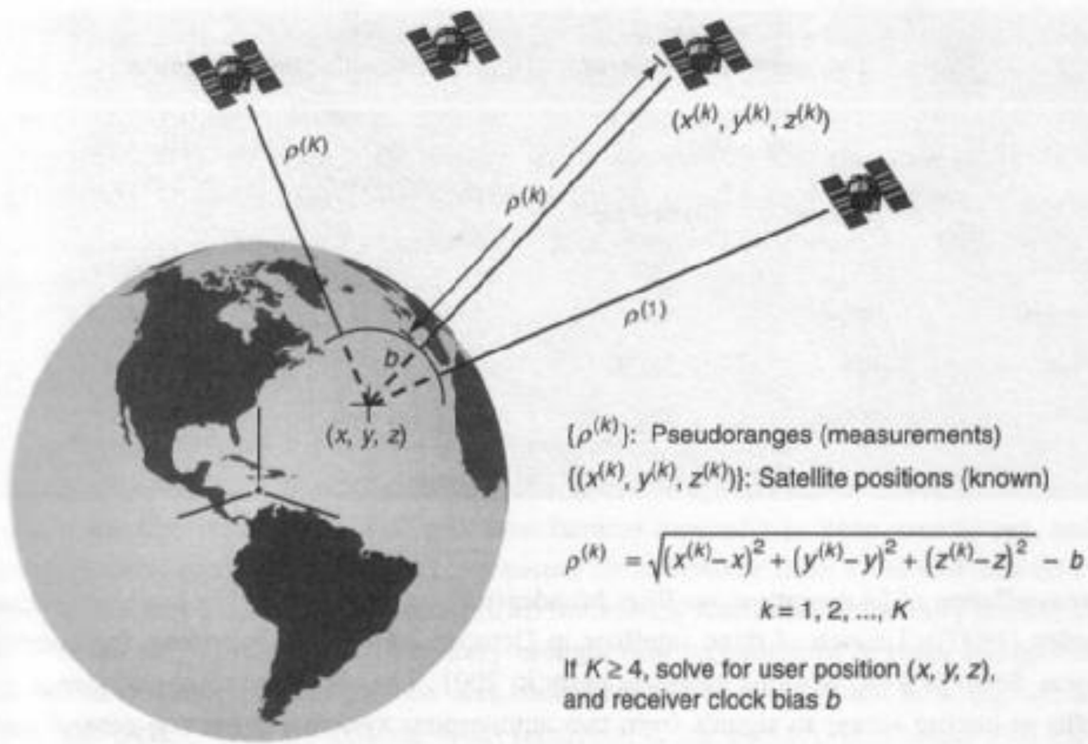


Figure 1.9 The principle of satellite navigation. The user-satellite range measurements based on the times of transmission and receipt of signals are biased by a common amount and are called pseudoranges. Pseudorange measurements are needed from at least four satellites to estimate the user position and receiver clock bias.

1.3.2 Satellite Navigation Systems: GPS (Contd').

Global Positioning System (GPS): a Transit follow-on program common between the U.S. Navy and the Air Force in the beginning 1970s.

Considerations for the GPS design:

Passive (vs. Active) system: unlimited number of users, nobody has to give signals which could reveal his position.

Trilateration (vs. Doppler or hyperbolic) positioning method: time-synchronized signal feasible (passive ranging signals).

Pulsed (vs. continuous) wave signals: time tags allowing to manage a different satellite transmission time. GPS is the first wide system using code division multiple access (CDMA) system. The signals share the same frequency.

L-band carrier frequency was a compromise: higher frequencies lower ionospheric effect but higher space loss and atmospheric attenuation. Moreover it was uncluttered in the 1970s to allow the 20MHz of spectrum.

Satellite constellation and orbits: MEOs at 20200 km height, a compromise between a reasonable number of LEOs to provide global service (~30 instead of hundreds LEOs), a geometry change rate (in front of GEOs), quite small atmospheric drag and other perturbation effects on the satellite (in front of LEOs). But more expensive launches and powerful transmitters than LEOs.

Finally GPS Constellation of 24+ satellites was completed in 1995 (1st launch in 1978), costed 10000 millions $ in development cost (500 millions $ / year).