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RF POSITIONING

FUNDAMENTALS, APPLICATIONS, and TOOLS

Rafael Saraiva Campos
Lisandro Lovisolo

RF Positioning

Fundamentals, Applications, and Tools

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Rafael Saraiva Campos
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Preface

Radio-frequency positioning is a vast and exciting field. Its possible applications are virtually limitless, from guiding unmanned aircraft to finding nearby stores. However, almost 10 years ago, what drew our attention to this subject was the issue of locating emergency calls originated from cell phones, and the need to explore other positioning techniques—rather than rely solely on a Global Positioning System (GPS)—to increase the availability of such a critical localization service. Throughout the years, we have expanded our research to other applications of radio-frequency positioning. This book congregates a lot of material we have developed during these nine years of partnership, working with and researching radio-frequency positioning services and applications. Additionally, the reference lists contain many works recently published by a variety of authors, which will provide the reader an insight into the state-of-the-art studies on radio-frequency positioning.

This book has been organized in such a way as to allow the reader to progress at a fast pace, from the fundamentals of radio-frequency positioning until the use of advanced tools such as artificial intelligence systems and application development environments. To achieve that, this textbook presents numerous MATLAB examples, accompanied by the corresponding MATLAB code, made available at the http://www.artechhouse.com/static/Downloads/campos.zip. The MATLAB code to most figures is also provided, as well as databases of measurements collected during experiments conducted both in cellular and Wi-Fi networks. These tools are offered so that the reader, after getting acquainted with radio-frequency localization fundamentals—described in depth and presented preserving the required mathematical rigor—is capable of using them to develop his or her own applications or to use them for their scientific research.

As a result, this book can be used by those seeking an entry point into radio-frequency positioning, and also by those already familiar with radio-frequency localization fundamentals. The latter can still benefit from the ancillary material accompanying the book (MATLAB codes, measurement databases, and Android apps source codes). Therefore, the book audience is found both in academia and industry: undergraduate and graduate students, researchers and field engineers.

The structure of the book reflects its title: *RF Positioning: Fundamentals, Applications and Tools*. The first part, comprising Chapters 1 to 4, covers the fundamentals of radio-frequency localization. The second part, composed of Chapters 5 to 8, addresses the application of those fundamentals in several types of wireless networks. Finally, the third part, formed by Chapters 9 and 10, and by the ancillary material accompanying the book (referring also to several other chapters) and available online, presents several tools to allow rapid development of positioning applications for mobile devices, as well as to support implementation and research of localization algorithms.

The chapters are organized as follows:

- Chapter 1 provides a brief history of radio-frequency positioning, from its origins in the beginning of the twentieth century up to the present day, defines a basic terminology that is followed throughout the book, and also provides a taxonomy of localization methods, as well as covering some topics concerning technical recommendations and regulatory demands for radio-frequency positioning.
- Chapter 2 discusses the fundamentals of triangulation-based positioning, introducing circular multilateration using time and received signal measurements, hyperbolic multilateration and multiangulation; the mathematical methods employed to solve the nonlinear sets of equations arising from the application of the aforementioned methods are also studied in depth with the help of computer simulations.
- Chapter 3 discusses the methods to obtain time, received signal strength, and angle measurements in wireless networks. This chapter complements Chapter 2, where those measurements are employed for mobile station localization.
- Chapter 4 introduces the fundamentals of radio-frequency fingerprinting, a positioning technique that is widely used in a variety of wireless networks. The basic elements of fingerprinting methods (radio-frequency fingerprint, correlation database or radio map, search space reduction technique; location server, and correlation or matching function) are studied in detail.
- Chapter 5 covers the positioning methods, which include algorithms, network elements to support localization, and specific protocols, applied in 2G, 3G, and 4G cellular networks, as well as the technical specifications addressing this issue on those networks. This chapter also presents a brief review on the evolution of cellular networks.
- Chapter 6 examines the application of several positioning techniques in Wi-Fi and wireless sensor networks both in indoor and outdoor environments. This chapter also provides a brief review on Wi-Fi protocols and an introduction to wireless sensor networks. A large literature review has been conducted in this chapter for the evaluation of several positioning techniques in those networks, in a wide variety of scenarios.
- Chapter 7 discusses Global Navigation Satellite Systems (GNSSs). These are probably and arguably the most well known and successful positioning technology embarked in consumer products. Systems already in operation as GPS from the United States, and GLONASS from Russia, as well as others under deployment such as BeiDou from China and Galileo from the European Union, are addressed. A brief historical perspective of GNSSs is presented tracing back to their military origins. The fundamentals of GNSSs are presented using a general framework that attempts to consider the common aspects across the different systems; specificities of each system are shown so that the reader can grasp the main (although small) differences among them. The ubiquity of applications based on GNSSs requires maintenance, which leads to the modernization of the systems already in use and the main aspects and results of this process, are listed. Finally, the international satellite-based system for search & rescue is also surveyed, and its convergent path to GNSSs is examined;

- Chapter 8 deals with radio-frequency positioning in wireless personal area networks, implemented using Bluetooth or ultrawideband technologies. Again, the basics of those types of networks are presented and several location methods are evaluated.
- Chapter 9 explains the basics of machine learning and fuzzy logic, applied to mobile station positioning. Detailed descriptions of several experiments conducted by the authors in cellular and Wi-Fi networks are presented, both in outdoor and indoor scenarios, and all databases and MATLAB codes employed during those tests are made available online to reader.
- Chapter 10 provides practical guidelines for the development of positioning applications for mobile devices. It introduces the basics of the MIT App Inventor 2 development tool and presents a tutorial about the installation of the Eclipse IDE with Android System Development kit, for users already familiar with Java programming and the Android Application Programming Interfaces.

Radio-frequency positioning is indeed a vast subject, and this book tries to cover many relevant topics. However, it could not possibly intend to be a substitute for all the existing literature on this field neither to exhaust the topic. It is intended to be a starting point for those taking first steps into this area, and as a source of useful tools for those already familiar with positioning basics. We sincerely hope that this book can be of use to you, the reader, that you relish it, and that it makes you want to learn more and continue delving into this very interesting field.

CHAPTER 1

Introduction to RF Positioning Systems

1.1 Introduction

On 12th December 1901, Marconi successfully transmitted a Morse-code letter "S" through a radio link across the Atlantic, proving that low-frequency radio waves could travel far beyond the horizon, following Earth's curvature [1]. This scientific breakthrough was the beginning of a revolution in communications.[1] Even before this transhorizon radio transmission experiment, it was realized that radio waves, apart from being able to convey information through great distances, could also be used as a navigational aid to ships at sea. This marked the beginning of the radio-frequency (RF) positioning systems.

It has been a long evolution, from the first navigational aid radio direction-finding system, patented in 1902 [2], to the location-based social networks—such as Foursquare and Facebook Places—where smartphone users locate each other. Along the way, a lot has changed—transmission frequencies, modulation, and other signal processing techniques, positioning system operational ranges and availability, type of mobile stations being localized (ships, airplanes, missiles, cellphones), and how the position estimate is used (e.g., to assist ships in navigating safely at sea, to help a bomber finding a target at night, to help mobile phone users locating stores in a shopping mall). However, the principles underlying all those RF positioning systems remain the same as they rely on the properties of electromagnetic waves and some basic geometric principles.

For almost 100 years, from 1902 until the late 1990s, RF positioning applications were mainly used as a navigational aid to ships, aircrafts, and terrestrial vehicles (after the popularization of Global Positioning System (GPS) receivers in the early 1990s [3]). The evolution of mobile cellular telephony profoundly changed this scenario, opening a wide range of new applications. Location-based services (LBSs) in cellular networks have grown considerably in the last few years, becoming the mainstay of RF positioning applications today. Recent estimates indicate that the global LBS market would reach revenues of USD $10.7 billion in 2013 [4]. This can be attributed mainly to the

- *Worldwide rapid growth of mobile cell phone users in the last 10 years*: From 2004 to 2011, the global average number of mobile cellular subscriptions per 100 people has risen from 27.4 to 85.5 [5].

---

[1] There is a great amount of controversy regarding the invention of radio [6, 7], and some sources claim that the transatlantic Marconi experiment was faked [8, 9]. This discussion could, by itself, fill an entire volume. However, despite the dispute regarding the first transatlantic radio transmission, Marconi did establish and operate the first successful radio link beyond a line-of-sight path in 1899 between the French resort of Wimereux and Chelmsford, 128 km away [10].

- *Popularization of smartphones with positioning capabilities*: Recent data (May 2013) from a developed economy illustrates that 91% of USA inhabitants have a cell phone. Among those cell phone users, 49% use LBS; this number rises to 74% among smartphone owners, which comprise 55% of all cell phone users in the United States [11], which gives an estimated 117 million[2] LBS users in the United States alone.
- *Regulatory issues*: Even before the popularization of LBS in cellular networks, cell phone positioning was addressed by regulatory boards, like the U.S. Federal Communications Commission (FCC) [12], to allow location (within certain precision boundaries) of users originating emergency calls.

Even before LBS, some level of mobile station location awareness was inherent to cellular networks operation. However, enhanced mobile station positioning capabilities can help improve handover[3] and paging[4] efficiency [13]. In cellular networks, both operations are critical in terms of resource allocation in the radio access network, directly affecting several key performance indicators. If the mobile station position is known with higher precision at all times (even when in idle mode, i.e., when the mobile station is not engaged in a call), the network can not only better direct the handover (which happens in active mode), diminishing dropped call indicators, but also reduce the resource allocation when sending paging messages (which happens in idle mode) by decreasing the number of target base stations (i.e., the number of base stations that will receive and retransmit those paging messages). Besides that operational advantage, RF positioning made possible a wide range of location-based applications in cellular networks, such as:

- *Emergency call location*, which is a nonprofitable application aimed at security; the Federal Communications Commission (FCC) in the United States pioneered in the regulatory demands for emergency call location [12], and was soon followed by the European Union [14];
- *Location-based billing*, where a home zone is defined for the user and within that zone, he or she is charged lower costs for cell phone call. Rates are usually competitive with those of wireline phone service. Outside the user's home zone, they are charged the standard rate [15];
- *Workforce and fleet management*, which is knowing where the employees are (workforce management) and knowing the location of the fleet's cars and trucks (fleet management) [16];

---

[2] This value was obtained multiplying the USA population (316 million in January 2013) [17], by the percentage of inhabitants with cell phones (91%), by the percentage of cell phone users who have a smartphone (55%) and by the percentage of smartphone owners who use LBS (74%).

[3] Handover is the transfer of an on-going call from one base station to another, to allow call continuity as the mobile station moves between coverage areas of neighbor base stations.

[4] Paging is the broadcast of different types of messages destined to a specific mobile station, or to a group of mobile stations. In the absence of high accuracy mobile station location information, those messages are broadcasted to a group of base stations belonging to the logic register zone where the mobile station last registered.

- *People tracking*, which are public safety applications, like on-demand localization of criminals under house arrest who have fled, lost children, and elderly people [18];
- *Route guidance*, which is a navigational aid for cars (driving assistance) or for users on foot that helps subscribers get to their destinations [19];
- *Location-based marketing* (also known as mobile yellow pages), where the user receives advertisements based on his or her current location that alert them to nearby points of interest, such as restaurants, shopping malls, and cinemas [20];
- *Geofencing*, which is a trigger for other applications rather than an application of itself. It works as follows: if a mobile station has entered or left predetermined geographic boundaries (a virtual fence), yellow pages messages (mobile marketing) or warning messages (people and asset tracking) can be sent to specific recipients. For example, security forces might be warned if a prisoner under house arrest has left his or her confinement zone, or parents might be warned if their child has left a predetermined safe zone[5];
- *Location-based social networks* (also known as geosocial networks), which are applications that extend the interaction provided by online social networks, allowing users to check into places (like restaurants, theaters, and malls) and interact based on their current location. Geosocial networks are relatively recent[6] and are still not as popular as other LBS applications – recent data indicates that only 8% of cell phone users check into places and share their location [11].

Another factor that helps enhance LBS usage among cell phone users is the increasing number of smartphones with built-in wireless fidelity (Wi-Fi) adapters. This has sparked the development of many applications for RF positioning in WiFi networks. The development of positioning applications for mobile devices is studied in Chapter 10.

Before moving on to studying RF positioning fundamentals, applications, and tools in the subsequent chapters, it is important to define some basic terminology that will be used throughout the book. This is done in Section 1.2. Then, Section 1.3 presents a brief history of RF positioning systems and applications from 1902 to 2013. After that, it will be possible to organize a classification or taxonomy of RF positioning methods based on different criteria (position estimation method, level of participation of the mobile station in the position calculation, the minimum number of reference fixed ground stations required for the mobile station location). This is done in Section 1.4. Closing the chapter, Section 1.5 discusses some RF positioning technical recommendations and regulatory demands, with the main focus on precision requirements for emergency call location in cellular networks.

---

[5] Some geofencing applications, like StealthGenie [21], are also mobile spy softwares, which might bring about privacy violation issues [22]. This discussion, however, is beyond the scope of this book.

[6] Among the major players in geosocial networks, Facebook Places was launched in 2010 and Foursquare in 2009. Google Latitude, also launched in 2009, was retired in August 9, 2013 [23].

1.2 Some Basic Terminology

Several key terms are repeatedly used throughout this book, and therefore will be unambiguously defined.

1.2.1 Location or Position

A location or position—in this book the two terms are used interchangeably—is a place in a three-dimensional (3D) space, or over a bidimensional (2D) surface (e.g., Earth's surface or a building floor). A location can be either physical or symbolic [24].

Physical locations are usually represented within a fixed reference system, such as World Geodetic System (WGS) [25], which expresses physical locations over Earth's curved surface as latitude and longitudes, or as northings (distances in the North/South direction) and eastings (distances in the East/West direction) using the rectangular Universal Transverse Mercator (UTM) projection [26].

A symbolic location provides abstract information about where something is, using some form of infrastructure or architectonic information (e.g., the 2D floor plan of a building). A symbolic location might be a room, a floor within a building, or an area of the city where the target object—the one to be found—is located. A symbolic location might be converted into a physical one; for example, if the target object is within a particular floor of a building, a Cartesian coordinate system, with its origin at the southeast corner of the building, might be used to convert this symbolic location (the floor) into a physical one (coordinates x and y in meters, within that floor).

1.2.2 Positioning

Positioning, also referred to as position location, localization, or position fix, is the estimation of the target station position or location. It returns a physical or symbolic—or both—position estimate of an object.

1.2.3 Target Mobile Station

The target mobile station (MS) is a station able to move, which might contain a transmitter, receiver, and/or a transponder, and whose position must be estimated.

1.2.4 Reference or Anchor Station

A reference station is either a fixed or mobile station, which might contain a transmitter, receiver, and/or a transponder, whose signals are used by the target MS to estimate its own position or that uses the target MS transmissions to calculate the target position. The coordinates of the reference stations must be known at all times and with the highest possible degree of confidence.

1.2.5 Radio Determination

Radio determination is the calculation of the position, velocity, and/or other characteristics of an object, or the obtaining of information related to these parameters, by means of the propagation properties of radio waves [27]. There are three types of radio determination: ranging, radiolocation, and radio navigation. Ranging is the most basic one, which is estimating the distance between two objects. Radiolocation is the positioning of an object. Radio navigation encompasses both ranging and radiolocation, adding the estimation of velocity and direction of movement, among other properties of a moving target MS.

1.2.6 Line-of-Position

A line-of-position (LOP) is the set of points at which the target MS can be located. LOPs are generated when positioning methods based on triangulation (multilateration or multiangulation) are used. Different positioning techniques yield different types of LOPs: linear, circular, or hyperbolic. The MS estimated position is given by the intersection of two or more LOPs.

1.2.7 Accuracy

The accuracy of a position estimate can be defined as the Euclidean distance between the MS reference position[7] (x_0,y_0) and the MS estimated position $(\hat{x},\hat{y})$. Therefore, numerically, the accuracy is equal to the position estimate error, given by:

$$e = \sqrt{(x_0 - \hat{x})^2 + (y_0 - \hat{y})^2} \tag{1.1}$$

The accuracy definition expressed by (1.1) refers to individual position estimates. Within this context, it is possible to refer to the accuracy of a position estimate, not to the accuracy of a positioning method. In an attempt to define the accuracy of a positioning method, it is possible to use a statistical estimator, such as the average error of a set of M position estimates provided by that method [28] (i.e.,

$$\overline{e} = \frac{1}{M}\sum_{i=1}^{M} e_i \tag{1.2}$$

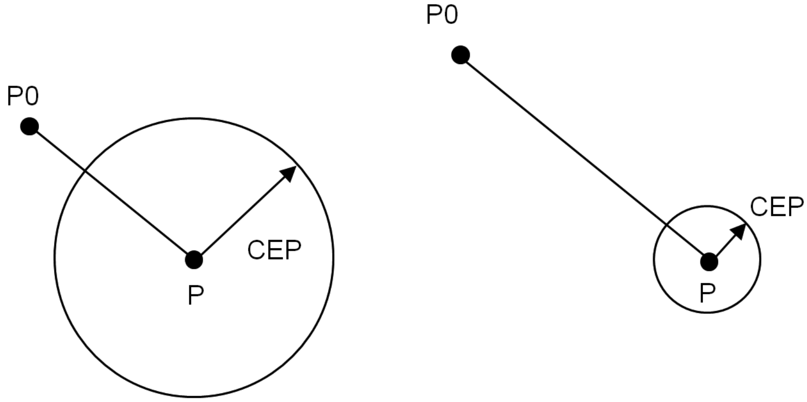
where e_i is the accuracy of the ith position estimate, given by (1.1)).

1.2.8 Precision

The precision of a positioning method can be defined as the probability distribution of the accuracy of a set of position estimates. If all position estimates are obtained while the MS is stationary in a fixed reference point, then precision can be characterized by the circular error probability (CEP) [29].

---

[7] The MS reference position is given by highly accurate positioning methods, such as differential GPS (DGPS), or by topographical charts.



(a) (b)

Figure 1.1 Precision vs. accuracy: (a) and (b) compare the performance of two hypothetical positioning methods. Assuming that a set of position estimates have been carried out by each method for a stationary target MS, method (a) achieved a lower precision than method (b), as its CEP is much larger; however, it has a better accuracy, as its PP_0 distance is shorter than in method (b).

Consider the pair $(\bar{\hat{x}},\bar{\hat{y}})$, obtained by the arithmetic mean of the position estimates $(\hat{x}_i,\hat{y}_i)$, $i = 1,2,\ldots,M$, given by a positioning method while the MS is stationary at the reference point (x_0,y_0). The CEP is equal to the radius of the circle centered at $(\bar{\hat{x}},\bar{\hat{y}})$ and within which lie 50% of the M position estimates. The higher the CEP, the lower the positioning method's precision, as the dispersion of the position estimates around the mean will be greater.[8]

Note that a positioning method can be precise (i.e., have a low CEP) and at the same time have a poor accuracy (i.e., the Euclidean distance between the reference position (x_0,y_0) and $(\bar{\hat{x}},\bar{\hat{y}})$ can be high). This condition is depicted in Figure 1.1(b), where $P0$ is the reference position and P is located at $(\bar{\hat{x}},\bar{\hat{y}})$.

Precision can also be defined by the cumulative distribution function (CDF), which is typically used to compare different positioning methods [28] or to specify minimum precision requirements [12]. Assume that the assessment of the positioning error in meters (discarding the fractional values in centimeters) of each position estimate is a random experiment. Let E be the discrete random variable that maps the results of this experiment into nonnegative integer values. Let e be the value of E for a given realization of the random experiment. The CDF of random variable E, which represents the positioning error, is a function defined by:

$$F(e) = P\{E \leq e\} = \sum_{i=0}^{e} P\{E = i\} \tag{1.3}$$

where $P\ \{E = i\}$ is the probability that the positioning error is equal to i meters and $P\ \{E < e\}$ is the probability that the positioning error is equal to or less than e. The value of $P\ \{E = i\}$ is experimentally defined as:

$$P\{E = i\} = \frac{m}{M} \tag{1.4}$$

---

[8] Dispersion measures, as the variance or standard deviation, can also be used to characterize the precision of a positioning method.

where M is the number of realizations of the random experiment (i.e., the number of position estimates), and m is the number of realizations where the positioning error is equal to i meters.

1.3 A Brief History of RF Positioning

Early RF positioning systems were based on radio direction finding (RDF), most widely known today as the angle of arrival (AOA) technique. The idea, which is based on a very simple geometric principle, is to determine the bearing of two fixed ground stations in relation to the mobile station that is to be localized. Each bearing provides a line along which both the mobile and the fixed stations are located. By taking two bearings, the mobile station position can be estimated at the interception of the corresponding lines of position. The first RDF positioning systems, like the one patented in 1902 by J. S. Stone [2], used rotating loop antennas placed at the mobile station, detecting omnidirectional transmissions from fixed ground stations. This scheme required the installation at each mobile station—initially ships and later airplanes—of a rotating beacon with a carefully controlled angular velocity. However, it soon became apparent that the opposite alternative (i.e., using an omnidirectional receiver at the mobile station and directional antennas at the ground stations) was a much more reliable option. Those were sometimes called reverse RDF systems.

1.3.1 Telefunken Kompass Sender

One of the first reverse RDF systems was the Telefunken Kompass Sender, developed in Germany in 1908. Some years later, it found extensive use throughout World War I, aiding Zeppelins finding their targets on bombing missions over Britain [30]. Each ground station had a pole, approximately 20m high, to which thirty-two 60m long wires were attached. A rotating switch connected each pair of opposing wires, forming 16 dipoles. The system operated in cycles comprising two phases: first, a ground station repeatedly broadcasted its unique identifier in Morse code; second, the switch was connected to the north dipole and began rotating, completing a full turn every 30 seconds. In the first phase, the transmitter was connected to all dipoles in the array, so the ground station identifier was irradiated in an omnidirectional manner. In the second phase, the rotation of the switch provided for the rotation of the radiation pattern, connecting to a different dipole every 15/16 of a second. At each connection, a single Morse code dot was transmitted. The operator would wait until receiving a ground station identifier. After the ground station stopped transmitting its Morse code unique identifier, the operator would start a specially designed stopwatch with just one indicator needle and 32 fixed indications at the same angles of the dipoles at the ground stations. The operator would stop the watch when the signal reached its lower level (i.e., when the operator heard the null). The indicator angle would then give the ground station bearing in relation to the user. By taking these bearing measurements from at least two ground stations, the mobile station position could be estimated as shown in Figure 1.2.

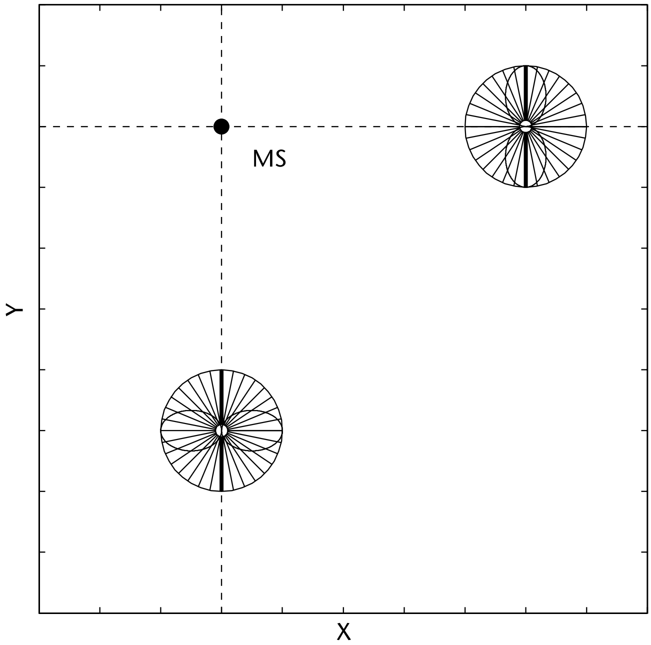


Figure 1.2 Mobile station position estimate using two Telefunken Kompass Sender ground stations. The figure shows the radial disposition of the wires at the ground stations and the horizontal radiation patterns of the active dipoles (indicated by the wider black lines).

1.3.2 Orfordness Rotating Beacon

In 1929, the British began operating a similar system, but with smaller ground stations and higher accuracy. The Orfordness rotating beacon system had two ground stations on the British southeast coast, one in Orfordness and another at the Farnborough Airfield [31]. Both stations used a loop antenna that rotated 360 degrees per minute (6 degrees/second). Each station irradiated a 288.5-KHz amplitude modulated signal. When the null passed the north direction, a Morse code letter “V” (for the Orfordness station) or “G” (for the Farnborough Airfield station) was transmitted. After hearing the ground station identifier (“V” or “G”), the operator would start a watch, and stop it as soon as he heard the null. By multiplying the number of seconds elapsed between the reception of the station identifier and the null, by the angular velocity of 6 degrees per second, the operator could calculate the mobile station bearing in relation to each ground station. As both stations used the same frequency, some time-multiplexing had to be used. Therefore, the Orfordness station transmitted the first 5 minutes of every 10-minute period, and the Farnborough Airfield station, the other 5 minutes. The loop antenna rotated continuously, unlike the rotating switch of the Telefunken Kompass Sender, which had only 16 possible angular positions. This resulted in higher accuracy in the British system, where 80% of the bearings had errors below 2 degrees for distances up to 160 km [32].

In both aforementioned positioning systems, the operators at the mobile stations (aircraft or ships) listened for the signal’s null and not for its peak. Figure 1.2 illustrates why: (1) the null point lies along the LOP passing through the ground and mobile stations, whereas the peak is perpendicular to it, and (2) the null in the dipole radiation pattern is clearly distinguishable, while the direction of the highest gain is not, due to the low directivity of the dipole or loop antennas.

1.3.3 Sonne

The next main step in RDF positioning development was the Sonne system, which was used in Germany from 1940 on for aircraft and sea vessel navigation during the Second World War. It consisted of ground stations with three collinear antennas, as shown in Figure 1.3, transmitting at the 300-KHz band. The outer antennas received one-quarter of the power fed to the central antenna and the signal fed to the outer antennas was shifted, producing a complex polar radiation pattern, as shown in Figure 1.4 [33]. The system operated in 40-second cycles. During the first 6 seconds, the transmitter was connected only to the central antenna, which irradiated the ground station identifier in Morse code omnidirectionally. After a 2-second pause, the transmitter was connected during 30 seconds to all three antennas and started transmitting Morse code dots (1/8 of a second) and dashes (3/8 of a second) alternately. During the Morse code dashes transmission, the phase shifts of the outer antennas were interchanged, resulting in a mirror radiation pattern for the dashes transmission in relation to the dots transmission. The phase shifts of the outer antennas were slowly rotated 7.5 degrees every 30 seconds. These features resulted in two symmetrical radiation patterns, one rotating clockwise (dots), the other counter clockwise (dashes), as shown if Figure 1.5. After the phase sweep,

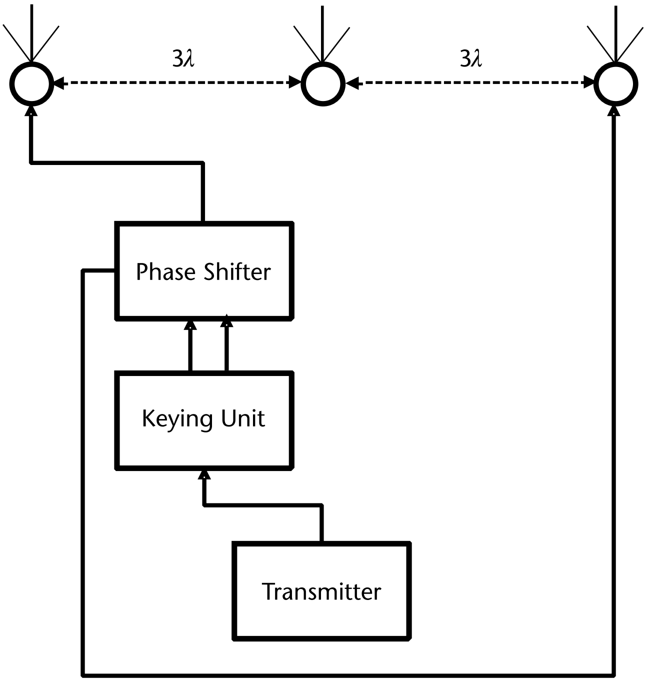


Figure 1.3 Schematic representation of a Sonne ground station, depicting the central and outer antennas with a three-wavelength inter-antenna spacing. The keying unit switched between Morse code dots and dashes. The phase-shifter allowed for the horizontal radiation pattern rotation.

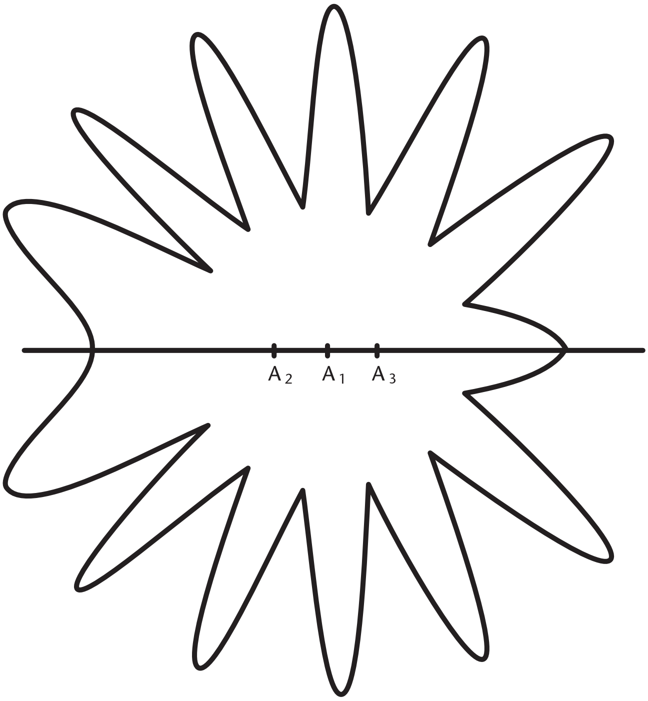


Figure 1.4 Sonne horizontal radiation pattern for outer antenna phase shifts of –90 and +90 degrees in relation to the central antenna. The inter-antenna spacing is three wavelengths.

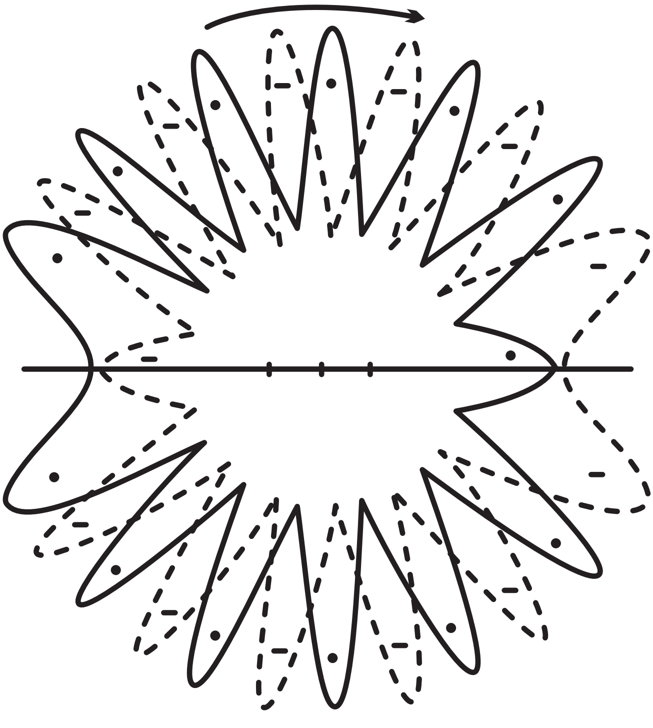


Figure 1.5 Sonne horizontal radiation patterns (dots and dashes). The arrow indicates the clockwise rotation of the dot horizontal radiation pattern.

there was another 2-second pause. The radiation patterns superposition created ***equisignal*** zones—sections of the lobes where a continuous signal was transmitted due to the juxtaposition of Morse code dots and dashes.

To locate the aircraft, the operator would first estimate its approximate position using one of the simpler RDF techniques. Thereby, he could know within which lobe of the horizontal radiation pattern of a given Sonne station he was located. Then, after hearing the station identifier for 6 seconds and waiting the 2-second pause, the operator would count how many dots (or dashes, depending on which lobe he was located) he heard before starting to receive the equisignal. As the diagrams rotated 7.5 degrees every 30 seconds and one dot (or one dash) was transmitted every second, the operator would know its angular position within the lobe. Special nautical charts were issued with lines of position containing the number of dots (or dashes) for different Sonne stations, thereby simplifying the position estimation process. The theoretical Sonne system accuracy was 7.5/30 of a degree (1/4 of a degree). In practice, accuracies of 1/2 degree were obtainable, which were at least four times better than previous RDF systems.

In 1944, the secrecy of the Sonne system was compromised by the capture of Sonne receivers and nautical charts on board the German submarine U-505 [34]. The Royal Air Force quickly realized the superior accuracy of the German system in relation to all RDF techniques the British had at the time, and started using the Sonne system under the name Consol. After the war, the Consol system remained available for civilian use until 1991 [35].

1.3.4 Gee

Gee became operational in 1942 and was the first hyperbolic RF positioning system: its lines of position were hyperbolas, having two ground stations as foci. It operated in the upper high frequency (HF) band and lower very high frequency (VHF) band, with channels spanning from 20 to 85 MHz [35]. The system had groups of three or four ground stations called Gee chains. Each Gee chain operated in a different channel and comprised a master station and two or three slave stations. All stations within a Gee chain shared the same time reference, controlled by the master. The system operated in 4-ms cycles using 6-μs pulses.[9] At the mobile station (airplane) to be localized, a receiver connected to a oscilloscope showed the received pulses. By adjusting the oscilloscope time base, it was possible to measure the time differences between the reception of the master station pulse (A) and the first (B) and second (C) slave stations pulses—Δt_{AB} and Δt_{AC}. Each time difference defined a hyperbola on Earth's surface, having each pair of stations (A and B, A and C) as foci. Groups of hyperbolic lines of position were calculated for each Gee

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[9] Each Gee chain with one master and two slave stations had an operation cycle that followed the transmission pattern ABDACD, where A was a pulse transmitted by the master station, B and C were pulses transmitted by the first and second slave stations, respectively, and D was a double pulse transmitted by the master station. The interval between pulses was 1 ms, so the full cycle lasted 4 ms (there was no interval between the D and the subsequent A pulse). The D double pulse was required to discriminate the master station pulses from the slave stations pulses.

chain and plotted on charts called Gee lattices [36]. By measuring Δt_{AB} and Δt_{AC} for a given Gee chain, and looking up the values on the Gee lattice, the navigator could identify its position at the hyperbolas' intersection. Two hyperbolas might intercept at two points, one of which could be discarded by dead reckoning. The third slave station was used as backup and for system calibration. Gee accuracy varied as a function of distance between the mobile and ground stations: 150m for short ranges and approximately 1.6 km for long ranges, which was considered enough for aerial bombing of cities.

1.3.5 Oboe

Oboe became operational by the end of 1942 and was primarily used for aerial blind bombing during the Second World War [37]. The system operated in the upper VHF band at 200 MHz. A ground station transmitted a pulse, which was received by an airplane carrying a transponder. The transponder received, amplified, and retransmitted the pulse. The distance between the airplane and the ground station was given by:

$$d = c\frac{(\mathrm{RTT} - \Delta t)}{2} \tag{1.5}$$

where c is the speed of light, RTT is the pulse round-trip time between the ground station and the airplane, and Δt is the signal processing time at the transponder. The distance d defined a circular LOP, containing all possible locations for the airplane. A second ground station was required to produce a second circular LOP. Those two lines of position intercepted at two points, as seen in Figure 1.6, one of which could be rejected by dead reckoning (the plane was on a bombing mission over Germany, so the intersection over England could be discarded). The remaining interception point provided the airplane estimated position.

Figure 1.6 The Oboe system: the picture depicts two Oboe ground stations on the channel coast of England and the intersection of the two circular lines of position over western Germany, marking the target area.

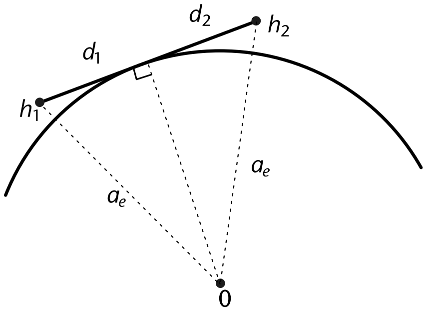

Figure 1.7 Estimation of LOS distance, considering tropospheric refraction. From the triangles in the figure, one obtains $d = d_1 + d_2 = \sqrt{2a_e}\left(\sqrt{h_1} + \sqrt{h_2}\right)$, where $a_e = \left(\dfrac{157}{157 + \dfrac{dN}{dh}}\right)a$; $a = 6370$ km is Earth's radius [38].

An Oboe ground station could handle only one plane at a time, so the Oboe transponder was carried by pathfinder bombers, which would drop flares to mark the targets for the bomber formations. The ground stations operated in pairs; one was the ***cat*** and the other was the ***mouse***. The pathfinder bomber would travel along the circular LOP centered at the cat station. The cat station would continuously send Morse code dots if the plane were within the course and dashes if the plane was deviating from the course. When the plane reached the target area at the intersection of the two circular lines of position, the mouse station would send five dots and a dash. The Oboe accuracy was around 110m, which made it one of the most accurate RF positioning systems at the time. However, from a military point of view, it had serious disadvantages, as it could handle only one plane at a time, and the plane had to follow a predetermined course and transmitted a signal back—both of which made the plane more susceptible to interception by German fighters. Unlike RDF systems operating in the upper low frequency (LF) band, which relied on surface wave propagation to achieve ranges of several hundred kilometers, both Oboe and Gee systems were restricted to line-of-sight (LOS) propagation conditions as they operated in the VHF band. Therefore, the higher the plane altitude, the longer the Oboe and Gee operational range. This range could be calculated from simple trigonometric relations as shown in Figure 1.7. Assuming a standard troposphere, with a vertical refractivity gradient dN/dh of –39 units/km[10], a ground station antenna height h_1 of 20m, and a flying altitude h_2 of 4,000m, the range would be approximately 280 km.

1.3.6 Gee-H

Gee-H became operational in 1943 and was an attempt to overcome the operational limitations of the Oboe system by reusing the Gee chains ground stations and receivers (on board the aircraft) to speed up deployment. It was a circular multilateration positioning system, just like Oboe, but in Gee-H the transmitter/receiver (interrogator/responsor, to use radar terminology) was on board the aircraft, while

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[10] The vertical refractivity gradient is used to obtain the effective Earth radius, used in radio propagation calculations to compensate for the ray bending due to the vertical stratification of the tropospheric refractive index.

the transponder (the beacon, to use radar terminology), was placed on the ground stations (i.e., the reverse of the Oboe system). The aircraft determined its position by measuring the RTT of the signal to two ground stations with known locations. This produced two circular lines of position and from this point on localization was carried out just like in the Oboe system. Gee-H operated from 80 to 100 MHz for interrogation (downlink transmission, from the airplane to the ground station) and from 20 to 40 MHz for reply (uplink transmission, from the ground station to the aircraft) [36]. Gee-H had an accuracy similar to the one achieved by Oboe. However, unlike the latter, Gee-H was able to guide several planes simultaneously—in Oboe, one plane was directed at a time by each pair of ground stations [39].

1.3.7 Loran-A

Long range navigation (LORAN) or Loran-A was a hyperbolic multilateration positioning system developed by the United States that was similar to the British Gee. Loran-A became operational in 1943. It had sets of ground stations, known as ***Loran chains*** (just like the Gee chains), with three or more ground stations. Hyperbolic multilateration requires at least four reference stations to yield an unambiguous position estimate because two hyperbolas might intercept at two points, requiring a fourth station to produce a third hyperbola. However, using dead reckoning in long-range navigation, one of the interception points might be discarded, making three stations the practical minimum required to produce a position fix (one master and two slaves). This minimum set was known as a ***Loran triplet***. Loran-A operated in the upper medium frequency (MF) band, at 1.95 MHz. At this frequency, propagation occurs by ground wave and sky wave (signal reflection at the ionosphere), especially at night [38]. During the day (ground wave only), over saltwater, Loran-A operational range extended up to 1,500 km. During the night, the sky wave component increased this range to up to 2,600 km. Loran-A minimum positioning error was 165m [36]. Loran-A remained available for civilian use until 1980 [40].

1.3.8 VOR/DME

VHF Omnidirectional Ranging (VOR) is a RDF system that began being used in the early 1950s and today is still the standard short-range aircraft navigation system. It operates in the VHF band, from 108 to 117.5 MHz, in 50-KHz channels. Each ground station transmits two signals simultaneously, one omnidirectional, containing the ground station identifier, and another directional. The directional signal rotates, and its phase is compared to the omnidirectional signal phase at the VOR receiver on board the plane. This phase difference indicates the aircraft bearing[11] [41].

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[11] VOR operation principles are very similar to those of earlier RDF systems, like the Telefunken Kompass Sender. In the latter, radiation pattern rotation was provided by a mechanical rotating switch and the bearing was taken manually using the received signal intensity; in the former, the radiation pattern rotation is done electrically and the bearing is taken automatically using phase differences between the omnidirectional and directional signals, transmitted at different subcarriers. Both VOR and the old Telefunken Kompass Sender use an omnidirectional signal to broadcast the ground station identifier.

VOR stations are typically equipped with a distance measuring equipment (DME) for estimating the distance between the ground station and the aircraft. DME is a kind of active radar where a signal is transmitted by the aircraft and received, amplified, and retransmitted back by a transponder at the ground station [41]. The distance is estimated from the RTT, just like in the Oboe system. The VOR bearing provides a linear LOP. The DME distance estimate provides a circular LOP centered at the ground station. The aircraft estimated position is given by the interception of the two LOPs. With such an arrangement, the aircraft can be located with a single VOR/DME ground station.

1.3.9 Loran-C

Loran-C became operational in 1948 and is a hyperbolic multilateration system operating at 100 KHz, with greater range—due to the lower frequencies—and higher accuracy than the previous Loran-A. Along its development, Loran-C chains have received atomic clocks for precise timing of the pulses, which accounts for the higher accuracy in relation to Loran-A. Typical Loran-C accuracies range from 18 to 90m [42]. Technical details about the Loran-C signals can be found in [41]. Loran-C system is being upgraded to eLoran, and most of the Loran-C stations have been closed—all Loran-C stations in the United States, Canada, and England had been shut off by 2010.

1.3.10 GNSS

Global Navigation Satellite Systems (GNSS) have worldwide coverage and use constellations of medium earth orbit (MEO) satellites to provide location and navigation capabilities to compatible receivers. Even though there are several satellite-based navigational systems, as of 2013, only two such systems can be considered GNSS (i.e., have global coverage): the United State's GPS, fully operational since 1995, and the Russian GLONASS, fully operational since 1993. Two other systems are still in the process of development or activation (which includes launching several satellites into orbit): Galileo (European Union) and Compass (China). Among these, GPS is the one with the most widespread use—from aircraft and ship navigation to people tracking—especially after its integration with smartphones, which has revolutionized the LBS market. GNSS systems are studied in detail in Chapter 7.

1.3.11 Positioning in Cellular, Wi-Fi, and Sensor Networks

As discussed in Section 1.1, the popularization of cell phones sparked the LBS market. Even before the advent of smartphones with built-in GPS receivers, regulatory demands for emergency call locating were issued by the FCC in 1996. After the integration of GPS into smartphones, the usage of LBS into cellular networks increased significantly. The fact that most smartphones also have built-in Wi-Fi receivers has also improved the usage of positioning applications in Wi-Fi networks. The technical details of localization in cellular networks are studied in Chapter 5, and the technical details of positioning in Wi-Fi and sensor networks are studied in Chapter 6.

1.3.12 eLoran

Enhanced Loran (eLoran) is an improvement over Loran-C receivers and transmitted signals to achieve better accuracy, enabling it to serve as a GNSS backup. When calculating its position, an eLoran receiver is not restricted to the ground stations of a single chain because it can use signals of up to 40 stations. As well, additional pulses transmit auxiliary data, such as DGPS corrections. The eLoran trial service began in 2007, and its development is not yet complete [43]. However, its long range (it operates in the same 90–100-kHz band of its predecessor, Loran-C) and high accuracy (up to 10 m) [44] make it a good candidate to act as a GNSS backup.

1.4 RF Positioning Taxonomy

This section presents a brief classification of RF positioning methods. Only three criteria are used: position calculation technique, MS participation in the position calculation, and the minimum number of reference stations required to produce a position estimate. These criteria are sufficient for a comparative evaluation of most methods. However, there are several other taxonomies available in the literature, especially for RF localization in cellular, Wi-Fi, and sensor networks [24, 28, 45, 46].

1.4.1 Classification According to the Position Calculation Technique

The first classification criterion is how the target MS position is calculated. There are five main techniques: proximity, triangulation (multiangulation and multilateration), RF fingerprinting (also known as database correlation method (DCM)), centroids, and hybrid.

1.4.1.1 Proximity

Proximity methods assume that the MS is located at the coordinates of the nearest reference station. This kind of method relies on the assumption that the closest reference station is the one whose signal reaches the target MS with the highest received signal strength (RSS). It is not always necessarily true, particularly in nonline-of-sight (NLOS) propagation conditions, where the signal of a farther reference station might reach the target MS with a higher RSS than a closer reference station, but whose direct path to the target MS is obstructed by a building or wall. This kind of method is used in Wi-Fi and sensor networks, where the reference stations density is typically high. It is also used in cellular networks, where it is usually called cell identity (CID) or cell of origin (COO) [45]. It is the simplest RF positioning technique, but its accuracy is highly dependent on the reference stations density—the higher the density, the lower the error. Therefore, in cellular networks, its accuracy is usually poor, being usable only in urban areas where the base stations density is higher. However, due to its simplicity and ubiquity, it is used as a backup method when more precise ones are not available, and is defined the by FCC as the basic method for emergency call locating [12].

1.4.1.2 Triangulation (Multilateration and Multiangulation)

Triangulation techniques use distance (multilateration) or angular (multiangulation) measurements between the target MS and the reference stations to estimate the MS position [28]. All triangulation methods assume LOS propagation between the MS and the reference stations. Multipath propagation and obstacles between the MS and the reference stations might impair angular measurements as well as time-of-flight and attenuation measurements, both of which are used for multilateration. In fact, NLOS propagation is the main source of error for those methods. This is particularly true in cellular networks in urban areas, where NLOS propagation conditions are prevalent. In such environments, the accuracy of triangulation methods might be seriously compromised. Besides NLOS propagation, another limiting factor of the triangulation method's accuracy is the finite resolution of the measurements used in position calculation: time, RSS, and angle of arrival. Time resolution depends on the signal bandwidth and RSS resolution depends on the type of network and the sensibility of the receivers. Angular resolution depends on the configuration of the reference station antenna arrays.

Triangulation by multilateration requires distance or distance difference measurements. These are obtained indirectly from time or propagation loss measurements. As already seen, multilateration can be either circular or hyperbolic:

- In circular multilateration, the LOPs are circles centered at the reference stations. The LOPs radiuses are obtained from time (time-of-flight or RTT) or propagation loss measurements. Time-of-flight can be converted to a distance estimate if multiplied by the radiowave propagation speed. RTT can be converted to a distance estimate using (1.5). Propagation loss can be converted to a distance estimate if a mathematical model describing propagation loss as a function of distance is used and if the radiating systems characteristics (antenna radiation patterns, effective radiated power, etc.) are well known. As shown in Figure 1.8, at least three circular LOPs are required to obtain an unambiguous 2D position estimate. Circular multilateration was used in Oboe and Gee-H systems and is used today in GPS, as well as in a variety of RF localization methods in cellular, Wi-Fi, and sensor networks. Circular multilateration is studied in detail in Chapter 2.
- In hyperbolic multilateration, LOPs are hyperbolas having two reference stations as foci. A hyperbola is the locus of all points such that the difference in the distances to each focus is constant. This distance difference, in RF positioning, is indirectly obtained from time differences, as described in the Gee system. Under some circumstances, as shown in Figure 1.9, three hyperbolic LOPs might be required to obtain an unambiguous 2D position estimate. As each pair of reference stations produces one hyperbolic LOP, four reference stations are necessary to yield three independent LOPs. Hyperbolic multilateration was used in Gee, Loran-A, and Loran-C systems, and is used today in eLoran and a variety of RF positioning methods in cellular networks. Hyperbolic multilateration is studied in detail in Chapter 2.

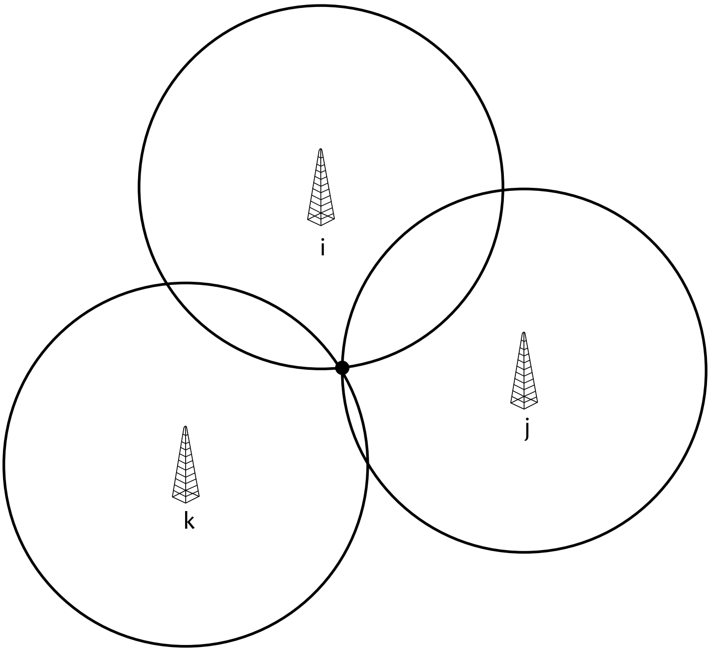

Figure 1.8 Circular multilateration: three reference stations providing three LOPs for an unambiguous MS position estimate.

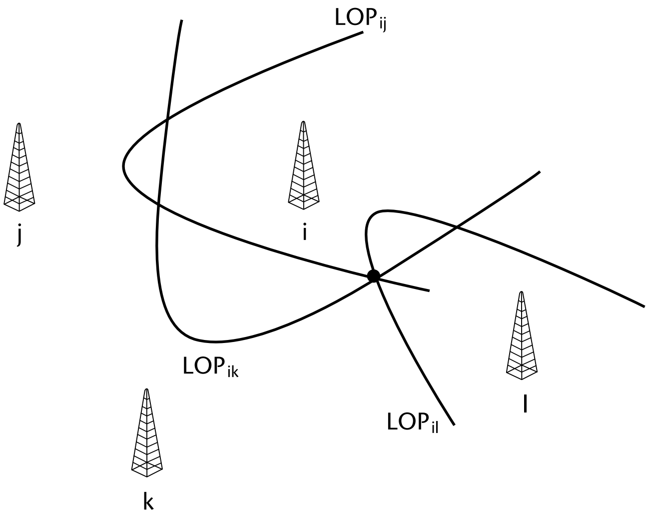

Figure 1.9 Hyperbolic multilateration: four reference stations providing three LOPs for an unambiguous MS position estimate.

Triangulation by multiangulation requires angle of arrival measurements, which can be made either at the MS or the reference stations. For that, directive antenna arrays are required, typically at the anchor stations. As already seen in the RDF systems, such as the Telefunken Kompass Sender and VOR, in multiangulation the LOPs are lines linear lines of position (LLOP), and only two noncollinear reference

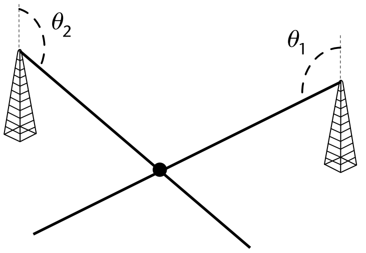

Figure 1.10 Multiangulation: two noncollinear reference stations providing two LLOPs for an unambiguous MS position estimate.

stations are required to yield an unambiguous position fix, as shown in Figure 1.10. Multiangulation is studied in detail in Chapter 2.

1.4.1.3 RF Fingerprinting (DCM)

Fingerprinting methods estimate the MS position by comparing an RF fingerprint collected by the MS (the target fingerprint) with georeferenced RF fingerprints previously stored in a database (the reference fingerprints). The coordinates of the reference fingerprint that is most similar to the target fingerprint are returned as the MS position estimate. An RF fingerprint is a set of RF parameters (e.g., RTT, RSS, or a list of detected reference stations) measured by the target MS or by the reference stations with which it is communicating. The parameters used in an RF fingerprint vary significantly depending on the type of wireless network where the positioning is being carried out. The key elements in any fingerprinting method are the RF fingerprint, the correlation database (the database that stores the reference fingerprints), and the correlation function (the function used to compare target and reference fingerprints). Fingerprinting methods are more common in cellular, Wi-Fi, and sensor networks. Fingerprinting methods are studied in detail in Chapter 4.

1.4.1.4 Centroid Methods

In this class of methods, the target MS position is estimated by the calculation of centroids of plane geometric figures. These techniques are used in cellular, Wi-Fi, and sensor networks. There are four main subtypes of this technique:

- *Simple centroid*. The target MS position is given by the centroid of the polygon whose vertexes are the reference stations [47], as shown in Figure 1.11. Let S be the set of reference stations used in the position fix. Let (x_i,y_i) be the coordinates of the ith reference station and $\#\mathcal{S}$ be the cardinality of $\mathcal{S}$. Then, the target MS position estimated is given by (1.6).
- *Weighted centroid*. Usually, the higher the RSS_i value, the closer the MS is to the ith reference station. Therefore, it is possible to apply a weighting factor W_i, defined in (1.7), to reduce positioning error in relation to the simple

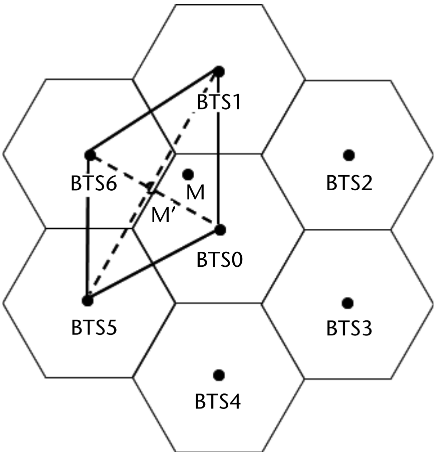

Figure 1.11 Simple centroid method in a cellular network. The figure shows seven omnidirectional BTSs in a hexagonal pattern, which is typically used in cellular network representation. Point *M* is the actual MS position at which it receives signals from BTSs 0, 1, 5, and 6. These are the vertexes of the polygon whose centroid, point *M´*, is the estimated MS position. Positioning error is given by the length of segment *MM´*.

centroid method [47]. Equation (1.8) gives the MS position estimate. The accuracy gain, in relation to the simple centroid method, is higher in areas where LOS propagation conditions are prevalent. In [48], a weighted centroid achieved a 14% accuracy gain in relation to a simple centroid in suburban areas. In urban areas, this improvement was around 10%.

- *Centroid of the angular ring section*. This variation is specific for cellular networks; for a sectorized base station transceiver (BTS)[12], the best server area[13] of a given sector can be represented by an angular section centered at the BTS. Direction, radius, and angular aperture of this section are determined by the sector antenna azimuth, the output power, and the antenna horizontal radiation pattern. If RTT values are used, this angular section can be reduced to an angular ring section [49]. This angular ring section defines the area where it is more likely that the target MS is located, as shown in Figure 1.12. The MS estimated position is given by the centroid of this area.
- *Centroid of the predicted best server area*. The best server area representation as an angular section is an extreme simplification; the real best server area of a BTS sector (in cellular networks) or a reference node (in Wi-Fi and sensor networks) is highly irregular and depends on the propagation environment and the radiating system characteristics (antenna radiation pattern, output power, etc.). A more realistic representation, like the one shown in Figure 1.13, can be obtained from coverage maps built using propagation modeling and digital elevation models of the terrain (or 2D floor plans, in the case of

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[12] A BTS might be physically and logically split into sectors—logically, because each sector or cell has its own unique identity within the cellular network, and physically, because cells usually have separated radiating systems and their antennas typically cover different areas.

[13] The geographic area at which a given sector signal is received with the highest RSS.

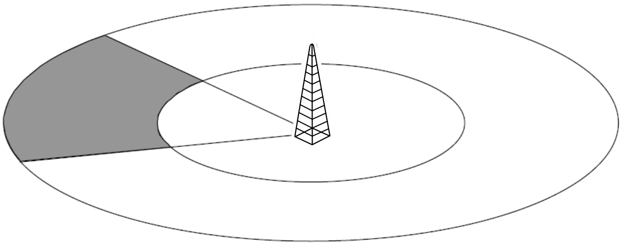

Figure 1.12 Angular ring section in gray indicates the area of higher probability for the MS position. The MS estimated position is given by the centroid of this area.

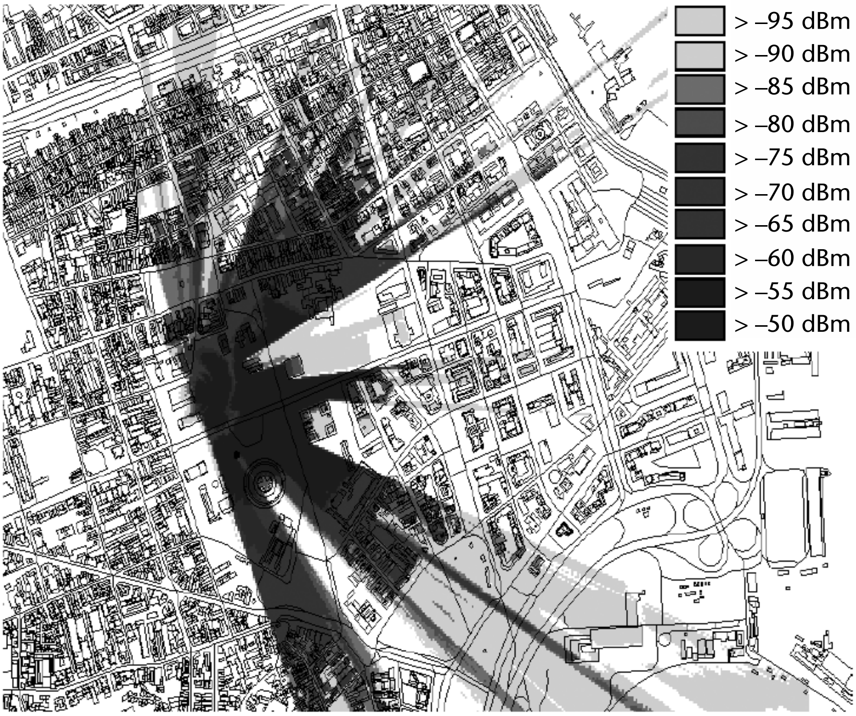

Figure 1.13 Predicted best server area of a BTS sector in a dense urban area.

indoor positioning). The MS estimated position can be given by the centroid of this predicted best server area. RTT values, if available, can be used to further reduce this area, increasing positioning accuracy. This method was originally proposed in [48].

$$\begin{bmatrix}\hat{x}\\ \hat{y}\end{bmatrix} = \frac{1}{\#\mathcal{S}}\begin{bmatrix}\sum_{i\in\mathcal{S}} x_i\\ \sum_{i\in\mathcal{S}} y_i\end{bmatrix} \tag{1.6}$$

$$\mathrm{W}_i = \frac{\mathrm{RSS}_i}{\sum_{k\in\mathcal{S}} \mathrm{RSS}_k} \tag{1.7}$$

$$\begin{bmatrix}\hat{x}\\ \hat{y}\end{bmatrix} = \frac{1}{\sum_{i\in\mathcal{S}} \mathrm{W}_i}\begin{bmatrix}\sum_{i\in\mathcal{S}} x_i \mathrm{W}_i\\ \sum_{i\in\mathcal{S}} y_i \mathrm{W}_i\end{bmatrix} \tag{1.8}$$

1.4.1.5 Hybrid Methods

It is possible to combine two or more of the previously presented positioning techniques into a hybrid localization method. One example of such a method is the VOR/DME, which combines angle and distance measurements. This method, as the AOA+RTT [46] proposed for use in cellular networks, requires only one reference ground station for the position fix. As shown in Figure 1.14, both VOR/DME and AOA+RTT estimate the MS position at the intersection of an LLOP obtained by the angular measurement with a circular LOP provided by the distance measurement. The circular LOP radius d is calculated by (1.5). The MS estimated position (x,y) is given by:

$$\begin{bmatrix}\hat{x}\\ \hat{y}\end{bmatrix} = \begin{bmatrix}x_0 + d\cdot\sin\theta\\ y_0 + d\cdot\cos\theta\end{bmatrix} \tag{1.9}$$

where θ is the angle of arrival measured at the MS, in the case of VOR/DME, and at the reference station, in the case of AOA+RTT, and (x_0,y_0) are the reference station coordinates.

1.4.2 Classification According to the MS Participation in the Position Calculation

Two classes are considered in this criterion: network-based and MS-based methods. A more detailed classification according to the MS participation in the position calculation is presented in Chapter 5, where several RF positioning methods specific to cellular networks are introduced.

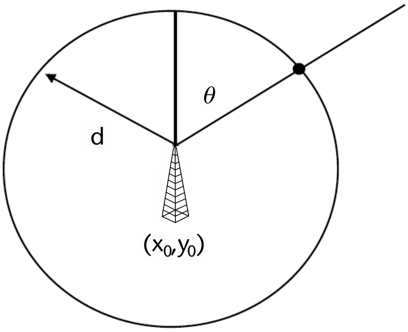

Figure 1.14 Hybrid AOA+RTT positioning. Only one reference station yields two LOPs (one linear and one circular) at the intersection of which the MS is assumed to be located.