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RF-Based Location Since World War II

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Abstract—This paper presents a brief historical overview of RF-based location technologies since the Second World War. Although direction-finding (DF) was critical to the Allied victory over German U-Boats in the north Atlantic, this paper focuses on more recent RF-based location technologies including Time-Difference of Arrival (TDOA), and ultra-wideband (UWB) technologies. More recent advances, including satellite navigation, RF fingerprinting, and near-field electromagnetic ranging technologies are also considered.

Keywords - Navigation, Position measurement, Radio position measurement.

I. Introduction

Direction finding (DF) played a significant role in the Second World War. The Second World War led to the development of time difference of arrival RF navigation as well as ultra-wideband (UWB) radio systems. The launch of Sputnik in 1957 inspired the inventors behind the first satellite navigation system that ultimately led to the ubiquitous Global Positioning System (GPS). More recent RF-based location technologies include RF fingerprinting and near-field electromagnetic ranging.

II. Radar and HF/DF in World War II and Beyond

The invention of radar long predated the Second World War. Christian Hülsmeyer (1881-1957) invented the first radar system in 1904. [1] His "telemobileoscope" (see Figure 1) failed to attract investment and was forgotten. However, the need for air defense drove a renaissance in radar during the late 1930's and throughout the war. The story of radar has been told elsewhere in histories and in memoirs. [2, 3]

High Frequency Direction Finding (HF/DF or "Huff-Duff") played a critical role in the Second World War. Shore based DF determined the location of German U-boat packs enabling convoys to be routed around them. Ship and airborne DF in conjunction with centimetric radar enabled effective antisubmarine warfare. [4, 5] One of the leading pioneers in the British radar effort, Robert Watson-Watt (1892-1973), earlier devised an instantaneous reading goniometer that enable precise DF measurements, even on the short duration or burst signals employed by U-boats. [6]

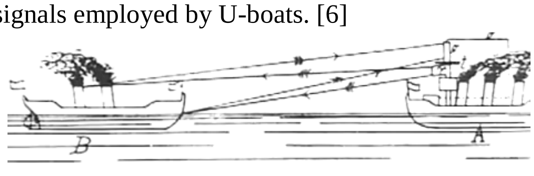

Figure 1: *Hülsmeyer's German 165,546 (1904) telemobileoscope was one of the earliest radar inventions, but failed to attract investment and was forgotten.*

The Japanese homed in on the signals of AM broadcast station KGMB on December 7, 1941 to help guide them to Pearl Harbor [7]. KGMB would not normally have been broadcasting in the early morning hours of Sunday December 7. Ironically, the station was broadcasting under a special contract to the Army Air Corp to help provide DF guidance to a flight of B-17 bombers due in from the mainland that same morning.

Fearing fleets of Soviet bombers might do the same, the US implemented "Control of Electromagnetic Radiation" (CONELRAD) in 1951 [8]. Under CONELRAD, in an emergency most AM stations would shut down. A few stations would broadcast civil defense information on 640KHz or 1240kHz in round-robin patterns intended to confuse enemy DF. Figure 2 shows a CONELRAD poster and radio dial. In addition, amateur radio operators were required to monitor a broadcast station at least once every ten minutes and stop transmitting if broadcast stations were not on the air. CONELRAD was abandoned in 1963 when it became evident that ballistic missiles, not bombers, were the real threat.

Figure 2: *CONELRAD poster.*

III. Long Range Navigation (LORAN)

The Second World War also spurred further innovation in RF-based navigation. The first wide-scale deployment of an RF-based location system was the Long Range Navigation or "LORAN" system invented by Alfred Lee Loomis during the war. [9] Patent rights to the system were a subject of prolonged wrangling. [10]

LORAN was an evolution from a shorter range British system called "GEE." Like GEE, LORAN employed synchronized impulse signal transmissions from paired transmit towers. By measuring the Time Difference of Arrival (TDOA) of the paired signals, users could determine which of a family of hyperbolic curves passed through their location. The intersection of two such curves defines the user's location. Figure 3 illustrates two overlapping families of hyperbolic curves. Each curve denotes a line of constant TDOA for signals from a pair of stations. Two measurements of TDOA yield the 2-D position of the receiver.

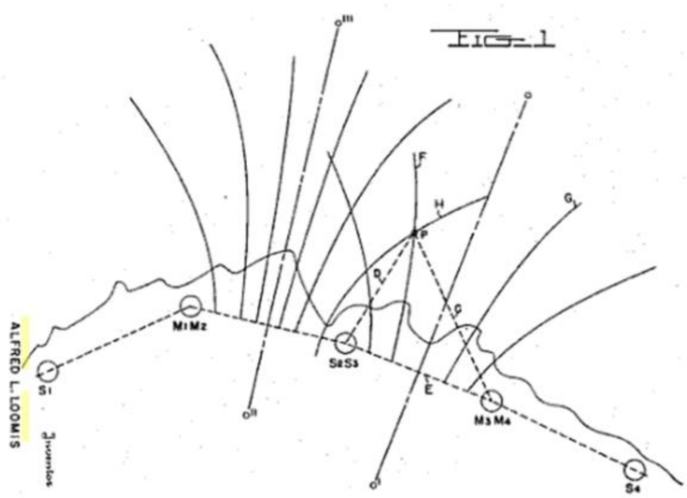

Figure 3: *Loomis's US 2,884,628 (1959) Long Range Navigation system was the basis of LORAN.*

The original LORAN-A system operated in the band 1750-1950kHz, within the 160m amateur radio band, just above the commercial AM broadcast band (530-1710kHz). LORAN-A had a range under 1000km. The frequencies used made it vulnerable to interference between ground wave and sky wave propagation, particularly at night. LORAN-A ceased operation late in 1980. A higher accuracy version, LORAN-C, began development in the 1950's. Operating in the band from 90-110kHz, LORAN-C yields absolute accuracy of about 185-463m with repeatability of 18-91m. Range depends on the signal-to-noise ratio, but can be as far as 1100km. Largely redundant due to the proliferation of GPS, the future of LORAN-C is in doubt. A very readable discussion of LORAN including its history and technical details is available elsewhere. [11]

IV. Ultra-Wideband (UWB) RF Systems

The Second World War also witnessed the development of spread-spectrum and ultra-wideband (UWB) technology. Actress Hedy Keisler Markey (better known by her screen name, Hedy Lamarr) and George Antheil invented a frequency-hopping secret communication system. [12] Figure 4 shows the frequency hopping transmitter. A record tape encodes a unique coding pattern to a network of tuning capacitors controlling a variable frequency carrier oscillator. The signal is thus virtually impossible to decode without knowledge of the frequency hopping pattern. The lack of regard for Lamarr's invention at the time is evidenced by the fact that it was promptly allowed and published instead of being kept confidential for the duration of the conflict.

More comprehensive histories of the development of spread spectrum and ultra-wideband technology are available elsewhere. [13, 14]

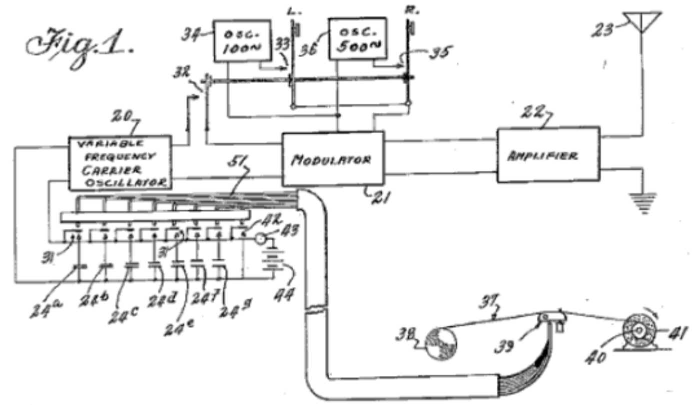

Figure 4: *Lamarr's and Antheil's US 2,292,387 (1942).*

V. Satellite Navigation and GPS

With the launch and tracking of Sputnik in 1957, it soon became obvious that the location of the satellite could be tracked by monitoring its Doppler shift. Frank McClure persuaded fellow researchers at Johns Hopkins Applied Physics Lab to devise a satellite navigation and positioning system based on the Doppler shift of satellite signals. [15] The team, led by Richard Kershner, developed the first satellite positioning system: the US Navy's Transit constellation (also known as NAVSAT). Transit provided up to 100 m location accuracy. [16] Due to coverage limitations, the 10-15 minute processing time required for a position, and position inaccuracies, the DoD sought an alternative solution and formed the GPS Joint Program Office.

Testing for GPS continued throughout the 1970's and 1980's with the full constellation of 24 satellites coming on line in 1995. GPS operates by time of flight principles with precise ephemeris, timing synchronization, and a variety of corrections including atmospheric and relativistic effects. The satellites are placed in geosynchronous orbit and can provide global location metrics with measured accuracies within 9 m (95% confidence) or better. The primary limitation of the current GPS system is that the microwave signals are largely blocked indoors and vulnerable to multipath in urban canyons. [17]

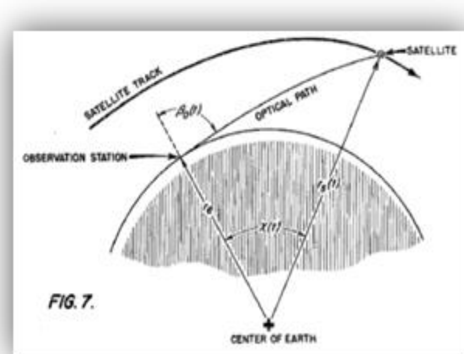

Figure 5: *McClure's US 3,172,108 (1965) described the first satellite navigation system.*

VI. RF FINGERPRINTING

More recently, a variety of inventors have sought to overcome complicated propagation environments by mapping a signal characteristic corresponding to particular locations of interest. These techniques are sometimes collectively referred to as "RF fingerprinting." The motivation behind these techniques is the hope that a sufficiently accurate map can be made to uniquely identify a particular transmit position in the same way a human fingerprint serves to uniquely identify a particular person.

One RF fingerprinting approach is to deploy a network of sensors throughout an area in which one desires to track personnel or assets. Received signal strengths at each sensor may be compared to calibration, reference or experimental data to determine which previously measured location yields the best fit to a currently received signal. Christ [18] proposed using this technique to localize personnel and Gray et al [19] suggest using this technique to track wireless devices. However, positioning based on relative signal strength is notoriously inaccurate. Network signal strength measurements may serve to localize a transmitter to a particular zone, but usually require at least one sensor per zone. This often makes it uneconomical to achieve high precision positioning. Also, the propagation environment may change significantly based on the presence of people, goods, or other transient objects that may not have been present or may have been in different positions at the time a calibration was performed.

An alternate RF fingerprinting technique attempts to use multi-path signals arriving at an antenna array to localize a transmitter. Multipath signals arriving at the antenna array are compared to a database of calibrated multipath signal signatures and corresponding locations. The location whose calibrated signal signature best matches the measured signature is selected as the most likely transmitter location. Hilsenrath [20] suggested this technique in conjunction with a system to localize cellular phone transmissions. More sophisticated techniques for signature matching were taught by Wax et al [21, 22, 23, 24]. These techniques may be used to make more economical assignments of cellular subscribers to base stations as taught by Grubeck et al [25], or applied to CDMA systems as taught by Wax et al [26]. Furthermore, Wang et al [27] teach using time of arrival signals and simulated ray tracing. All of these techniques rely on the hope that the multi-path environment will be sufficiently stable and static to be repeatable.

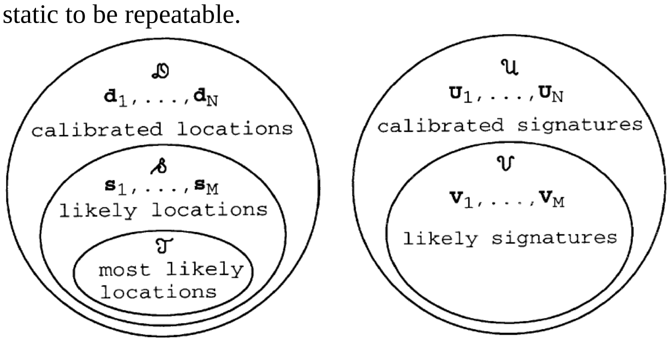

Figure 6: *Signature matching concept of Wax's, Meng's, and Hilsenrath's US 6,064,339 (2000).*

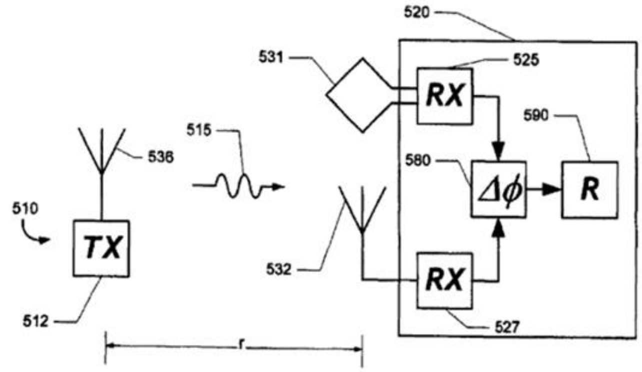

Figure 7: *Schantz's and De Pierre's US 6,963,301 (2005).*

Chen et al [28] teach a system in which the geographical location of a mobile terminal is identified by comparing characteristics such as pilot strength and chip offset from the mobile terminal with the same attributes for a variety of sub-cells and determining which sub-cell most closely matches the observed set of RF characteristics.

Other inventors have proposed supplementing RF-based location data with a priori information about the propagation environment, or with additional sensors. Werb et al [29] proposed user selectable configuration packages in conjunction with a system for determining location of a tag using stored data. Moriya et al [30] suggest using accelerometers and Kalman filtering to supplement electromagnetic position measurements.

VII. NEAR-FIELD ELECTROMAGNETIC RANGING

A relative newcomer to the arena of RF-based location technologies, near-field electromagnetic ranging exploits the near-field properties of long wavelength, low frequency radio waves to obtain location solutions. [31] One implementation compares the phase difference between the electric field phase (detected by an electric antenna, like a whip) and the magnetic field phase (detected by a magnetic antenna, like a loop) in the near-field zone around an electrically small transmit antenna. Figure 7 shows this configuration. In one recent test for instance, near-field electromagnetic ranging systems demonstrated location accuracy of about 55cm through multiple walls at ranges of up to 25m in an office industrial environment. [32] The author is one of the pioneers in near-field electromagnetic ranging technology and is involved in its development.

VIII. CONCLUSIONS

The history of RF-based location spans over a century of innovation and real-world applications. Although hardly exhaustive, this paper has surveyed the origins of a few of the more important technologies underlying the practice of RF-based location.

Amplitude Ranging: invented by Lee de Forest in 1904, amplitude ranging provides a rough indication of range subject to variations in the range dependence of RF signals.

Direction finding (DF): invented by John Stone Stone in 1902 and refined by Bellini and Tosi, Adcock, and Watson-Watt among others, DF can provide angle-of-arrival data to an accuracy of 1-2 degrees in support of signal intelligence or radio-navigation systems.

Time-of-Flight: conceived before the Second World War, time-of-flight or transponder ranging can enable 30cm accuracy when implemented with nanosecond precision electronics.

Time difference of arrival (TDOA): came of age during the Second World War. Accuracy depends on timing precision and the variability of the propagation environment.

Ultrawideband (UWB): also arose during the Second World War. UWB techniques may be combined with transponder or TDOA approaches to yield accurate location information, particularly in line-of-sight or short-range applications.

Satellite Navigation (GPS): born out of the Cold War Space Race, early satellite systems were Doppler based. The current GPS/NAVSTAR system operates on time-of-flight principles with corrections for Doppler and other effects.

Near-field electromagnetic ranging: a recent breakthrough in RF-based location, near-field electromagnetic ranging can yield accurate locations even in complicated indoor propagation environments.

A familiarity with the history and origins of RF-based location is essential for engineers and inventors alike, because understanding the past is the first step in building the future.

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