On the origins of RF-based location

Conference Paper · February 2011

DOI: 10.1109/WISNET.2011.5725029 · Source: IEEE Xplore

Hans G. Schantz
Geeks and Nerds Corporation

Preprint/Draft: *Submitted to 2011 IEEE Radio & Wireless Symposium, Phoenix, AZ 16-20 Jan., 2011*

On the Origins of RF-Based Location

Hans Gregory Schantz

Q-Track Corporation, Huntsville, Alabama 35805, USA

***Abstract*— This paper will provide a brief survey of the origins of RF-based location technology through the beginning of the Second World War. Direction finding (DF) was invented by John Stone Stone in 1902 and improved upon by Lee de Forest, Ettore Bellini and Alessandro Tosi. Both radar and amplitude ranging date to 1904, although these concepts were in advance of the ability of RF technology to implement. DF played a critical role in the First World War, most notably in the naval Battle of Jutland. The requirement for accurate night-time direction led classicist and cryptographer Frank Adcock to invent an improved DF system. In the 1920's, DF and related concepts came of age for civilian applications like navigation. Inventors of the period introduced a variety of other techniques were introduced including time-of-flight or transponder ranging. By the time of the Second World War, DF was a mature field and additional novel RF-based technologies were ready to be developed.**

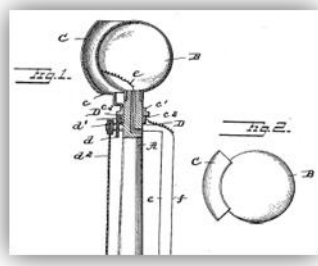
Keywords - Navigation, Position measurement, Radio position measurement.

I. INTRODUCTION

Communications may have been the first commercial application of wireless technology, but RF-based location was close behind. This paper will provide a brief survey of the origins of RF-based location technology. Fundamental techniques like Direction Finding (DF) and amplitude ranging date back over a hundred years to the early days of radio. DF in particular played a critical role in both World Wars, influencing the course of history.

II. FALSE STARTS AND MISUNDERSTANDINGS

In the first few years of radio, a variety of aggressive inventors recognized the problem of RF-based location and leapt to offer solutions. Some of their ideas illustrated the inventors' misunderstanding of the behavior of radio waves. Inventors assumed (erroneously) that long wavelength RF signals would cast sharp shadows in an optical fashion. Isidor Kitsee and Charles E. Wilson, for instance, proposed a spherically end-loaded antenna with a shield to block signals from a particular direction (see Figure 1a). [1] Hermon W. Ladd similarly proposed a whip antenna with a rotatable shield. [2] In Ladd's proposed system (shown in Figure 1b), a narrow slit in a rotating shield is supposed to allow the antenna to be illuminated only when the slit is aligned with the direction of incidence of the signal. Both these DF antennas fail to work, because the low frequency signals (typically <300kHz) they aimed to detect have wavelengths too long to be shadowed by such a small shield or to illuminate such a small slit.



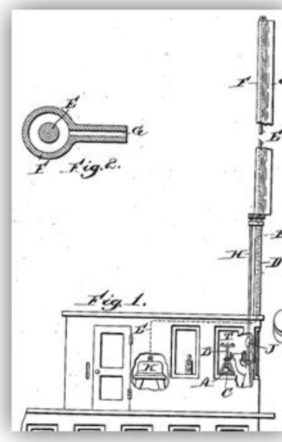


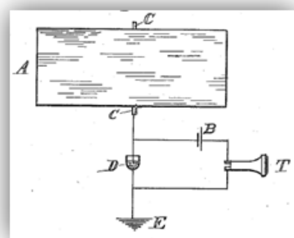
Figure 1a (left): *Kitsee and Wilson's US 651,014 (1900) direction finding antenna relied on shielding of a spherical capacitive end load to "shadow" signals.*

Figure 1b (right): *Ladd's US 733,910 (1903) direction finding antenna employed a rotating slit intended to allow the antenna to be illuminated only if the slit were aligned with a distant transmitter.*

The well known radio inventor, Lee de Forest (1873-1961), fell prey to a similar confusion. De Forest assumed that the larger the antenna's physical cross-sectional area, the more signal would be collected. This is not necessarily true even for an antenna comparable in dimension to a wavelength. For an electrically small antenna, actual and effective aperture are often two different things. Nevertheless, de Forest argued:

> *"…a large screen will collect a larger amount of energy than a small one…. When such a screen is broadside onto the waves - that is, normal to their direction of travel - it will manifestly collect the largest possible amount of energy, while it is edge on, or in a plane coinciding with the direction of travel of the waves, it will collect the smallest amount of energy."*[3]

Figure 2a shows de Forest's 6ft by 15ft capacitive "collecting screen." [4] This antenna actually exhibits an omni-directional reception pattern for frequencies below 25MHz. Only at 30MHz where the antenna begins to be an appreciable fraction of the 10m (30ft) wavelength does the antenna pattern begin to deviate. Even there, the deviation enhances reception in the plane of the antenna, not broadside to it. Figure 2b shows a NEC simulation of the azimuthal pattern of de Forest's antenna at 10MHz and 30MHz. De Forest's claim to be able to detect a seven-mile-distant station to an accuracy of within ten degrees using this system seems unsupportable given the LF (<300kHz), long-wavelength nature of the transmit signal.



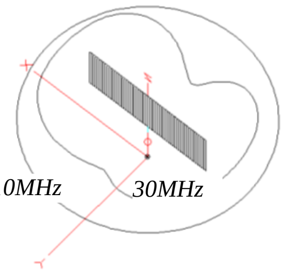


Figure 2a (left): *De Forest's US 771,818 (1904) direction finding antenna operated under the false assumption that received signal strength of an electrically small electric antenna depends on the broadside area the antenna presents to the signal.*

Figure 2b (right): *NEC simulation of the pattern of de Forest's antenna demonstrates that its response is omnidirectional for signals of frequency 25MHz or lower, and begins to have enhanced sensitivity in the plane of the antenna at 30MHz.*

III. THE FIRST RF-BASED LOCATION SYSTEMS

John Stone Stone (1869-1943) patented the first effective direction finding system in 1902. [5, 6] Stone's scheme involved a two element antenna with a first element (V) arranged no more than a half wavelength away from a second element (V'). Figure 3 shows Stone's invention. The two elements are arranged so that their respective signals add up 180 degrees out of phase with respect to each other. Thus, a signal incident in a direction normal to the plane containing the two elements their combined action is nil. Stone also embellished upon his invention in later years. [7, 8]

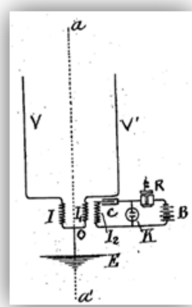


Figure 3: *Stone's US 716,134 and US 716,135 (1902) direction finding antenna system.*

Soon thereafter, de Forest also invented a similar direction finding antenna system. [9] De Forest's US 771,819 system involved a horizontal dipole, an "L" monopole, or a loop antenna – in each case, rotated so as to null out an incident signal. This basic principle, first discovered by de Forest, underlies many small aperture direction finding techniques to this day. Figure 4 shows three alternate embodiments of de Forest's 1904 invention, each of which rotates about the *C* coupler.

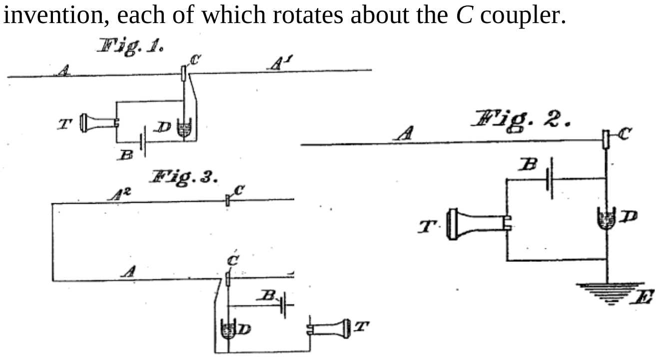
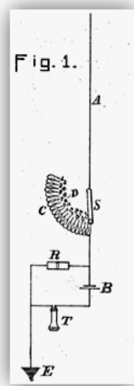


Figure 4: *De Forest's US 771,819 (1904) rotatable direction finding antennas: a horizontal dipole (top-left), an "L" monopole (right), and a loop antenna (bottom-left).*



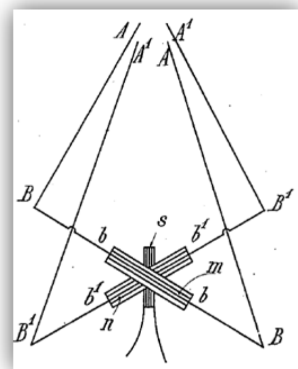


Figure 5a (left): *De Forest's US 771,819 (1904) signal strength ranging apparatus employing a variable resistor to evaluate signal strength and correlate it to range.*

Figure 5b (right): *Bellini's and Tosi's US 943,960 (1909) direction finding system used a fixed orthogonal DF array and a rotatable transformer for steering.*

A prolific inventor, de Forest also receives the credit for having invented the first RF ranging system. Realizing that signal strength declines with distance, de Forest proposed inserting a variable resistor into the RF circuit to enable a measurement of signal strength. Given a previously determined table of signal strength versus range, the range may be determined from this measurement of signal strength. [10] Figure 5a shows two embodiments of de Forest's 1904 "Wireless range finder." De Forest later proposed using variable capacitance or inductance to gauge signal strength. This approach would likely change antenna tuning, yielding invalid results. [11] In 1916, de Forest proposed an audio indication of signal strength using different tones to denote different ranges in a signal strength or amplitude ranging system. [12]

Ettore Bellini (1876-1943) and Alessandro Tosi devised a much improved direction-finding system in 1907. [13] Their scheme deployed two orthogonal arrays similar to those of Stone. The key advantage of the Bellini-Tosi direction finder was a rotating transformer coupling. Rather than rotate a potentially large antenna system, the Bellini-Tosi system uses fixed orthogonal antennas with a rotatable transformer. Figure 5b shows the Bellini-Tosi array. Bellini developed many improvements to their invention including a version with a cardiod pattern (with Tosi) [14], and a capacitive goniometer [15, 16].

IV. RF-BASED LOCATION GOES TO WAR

In 1902, a reporter asked Marconi about the vulnerability of wireless signals to interception. Marconi reassured the journalist, "It isn't possible without a special installation and without guessing the frequency." [17] The First World War demonstrated the magnitude of Marconi's error.

Triumphs of signal intelligence like Tannenberg and the Romanian campaign were principally matters of intercepting and decoding military communications. Nevertheless, direction finding often provided valuable clues to enemy intentions and dispositions even without actually decoding the transmissions themselves.

The English were able to detect and track the locations of both Zeppelin air raids and German U-Boats due to their DF network. [18] The French had a sophisticated DF network along the Western Front. In 1918, for instance, the French were able to correctly predict an impending German retreat by detecting the withdrawal of German weather stations to locations deeper behind the lines. [19]

The greatest triumph of direction-finding came in naval warfare. On 30 May, 1916, the British Royal Navy noted an unusual increase in German naval radio traffic. Careful measurements of a ship known to be at Wilhelmshaven indicated a 1½ degree change in bearing angle. Capt. H. G. Round correctly interpreted this motion as the ship taking up a position in the Jade River ready to put to sea. On the basis of this signal intelligence, the British Grand Fleet sortied to the North Sea so quickly that they overran the intended line of German U-Boats before the U-Boats were able to arrive and take up position. [20] Although overall British signal intelligence efforts were plagued by miscommunication and misunderstanding of vital data, the potential value of direction finding was clear. [21, 22]

Under optimal conditions during daylight hours, DF accuracy could be as good as one to two degrees (300m at 10km range). [23] At night, however, the ionosphere reflects distant signals from over the horizon. The resulting "skywave" signals have a mix of vertical and horizontal polarization components that can confound DF systems by introducing phase offsets. DF error could increase to as much as 30 or even 90 degrees at night. [24]

In 1918, a British Army Officer, Frank Adcock (1886-1968), devised a solution to this problem "in which the aerials, which have identically the same dimensions, are so mounted and connected that only the vertical parts are effectively influenced by the electromagnetic radiation, the horizontal parts, or those parts having a horizontal component, being so arranged that the effect on them is eliminated or reduced to a minimum." [25] Figure 6 shows two embodiments of Adcock's array. Later testing by the Marconi company indicated that a well designed Adcock array could achieve three degree accuracy, even at night. [26]

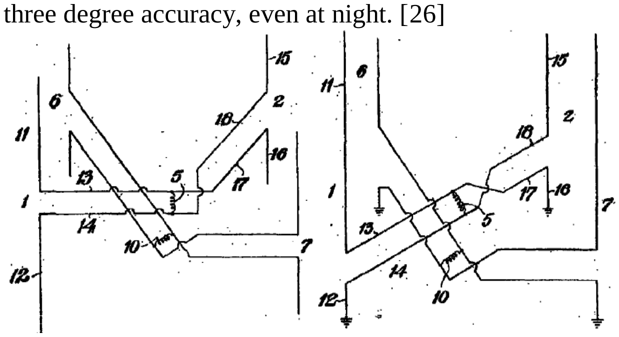


Figure 6: *Two embodiments of Adcock's GB 130,490 (1919) direction finding antenna system, a dipole version (left) and a monopole version (right). Adcock's configuration minimized horizontal coupling to ensure accurate readings even in the presence of skywave signals at night.*

V. RF-BASED LOCATION AND NAVIGATION

By the 1920's direction finding was well-advanced, and DF techniques began to see everyday use in both marine and aerial navigation. [27] A good example of a sophisticated and relatively simple to use DF system from the period is the one developed by the noted French engineer, Henri Busignies (1905-1981) in 1927. [28] Adcock type antennas were used to mark out routes for aviation. By sending out complementary signals, such as "A" (· —) and "N" (— ·), the signal heard on the equi-signal line yields constant dash tones. This provided a simple aural signal to keep pilots on a desired path and provide feedback if they happened to stray. [29, 30] With the well-established interest in RF-based location for navigation purposes, a variety of inventors began to explore alternate technological solutions.

Richard Howland Ranger (1889-1962) of RCA proposed a ranging system requiring synchronized oscillators between a transmitter and a distant receiver. [31] Ranger's system involved counting the beats between the synchronized oscillators to determine how many half-wavelengths the distance has changed from some starting point. The degree of precision necessary to make this system work remains as unachievable today as it was then. Figure 7 shows Ranger's concept.

In ground wave propagation, higher frequency signals tend to attenuate more quickly with distance than lower frequency signals. Edward Gage proposed an RF ranging system based on the physics of this differential attenuation in 1930. [32], [33] This interesting approach to the problem of RF-based location does not appear to have achieved any widespread success, however.

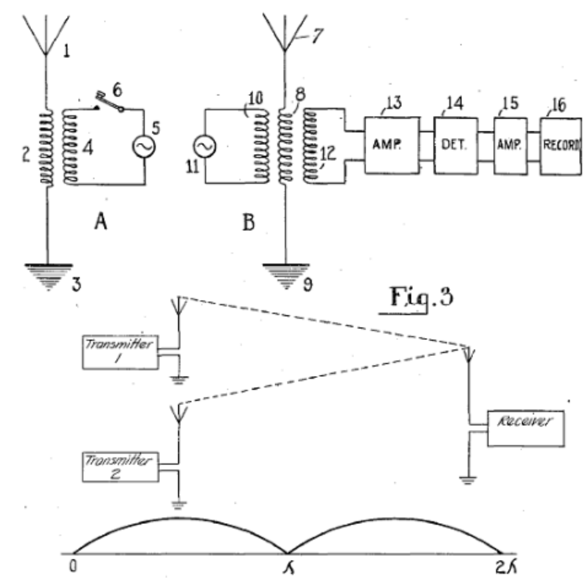


Figure 7: *Ranger's US 1,639,667 (1927) direction finding antenna system requires precisely synchronized oscillators at transmitter and receiver and determines distance from a starting point by counting the number of half wavelength beats in the rectified signal.*

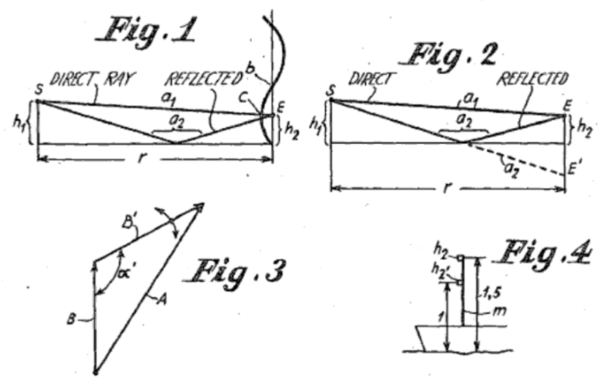


Figure 8: *Runge's US 2,134,535 (1938) distance determining system employed the interference between direct and reflected signals as a navigational aid.*

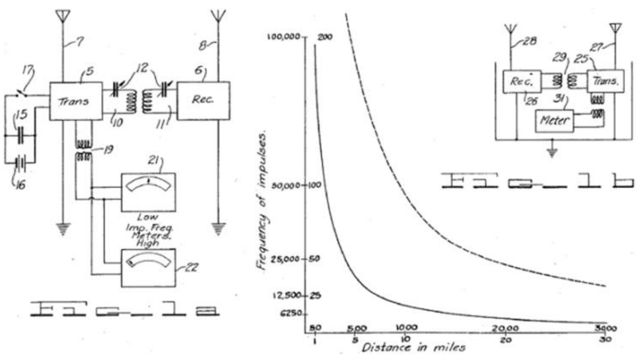


Figure 9 *Nicolson's US 1,945,952 (1931) radio range finder employed standing waves, exploiting time-of-flight of a signal to a transponder and back to determine range.*

German engineer Wilhelm Runge (1895-1987) invented a marine ranging system that used interference between direct and reflected signals to indicate distance as a navigational aid. [34] Figure 8 shows Runge's invention. Runge went on to play a key role in German radar development during World War II.

Time-of-flight or transponder ranging traces its origin back to the radio range finder invented by Alexander McLean Nicolson (1880-1950) in 1930. [35] Nicholson invented the concept of transmitting a signal from a first point, receiving and reradiating it from a second point. By measuring the time-of-flight, one may infer the range. Nicolson's system operated "on the principle that for every unit of length, there is a frequency which when reflected will have a phase shift equal to 180° or 360°. That is, by tuning the oscillator and broadcasting a certain frequency to a reflecting station, the return wave and the initiated wave will exactly neutralize or will double in value (if the original and return amplitudes are equal) at two definite distances." Figure 9 shows his scheme.

REFERENCES

[1] Isidor Kitsee and Charles E. Wilson, Space Telegraphy, US Patent 651,014, June 5, 1900.

[2] Hermon Ladd, Art of Determining the Nautical Bearing of Navigable Vessels, US Patent 733,910, July 14, 1903.

[3] Lee de Forest, Wireless Signaling Apparatus, US Patent 771,818, October 11, 1904.

[4] J.A. Fleming, ***The Principles of Electric Wave Telegraphy***, (New York: Longmans, Green, And Co., 1906), pp. 631-633.

[5] John Stone Stone, Method of determining the direction of space telegraph signals, US Patent 716,134, December 16, 1902.

[6] John Stone Stone, Apparatus for determining the direction of space telegraph signals, US Patent 716,135, December 16, 1902.

[7] John Stone Stone, Apparatus for determining the direction of space telegraph signals, US Patent 899,272, September 22, 1908.

[8] John Stone Stone, Apparatus for determining the direction of space telegraph signals, US Patent 961,265, June 14, 1910.

[9] Lee de Forest, Wireless signaling apparatus, US Patent 771,819, October 11, 1904.

[10] Lee de Forest, Wireless telegraph range finder, US Patent 749,436, January 12, 2004.

[11] Lee deForest, Art of wireless telegraphy, US Patent 758,517, April 26, 1904.

[12] Lee deForest, Range teller, US Patent 1,183,802, May 16, 1916.

[13] Ettore Bellini and Alessandro Tosi, System of directed wireless telegraphy, US Patent 943,960, December 21, 1909.

[14] Ettore Bellini and Alessandro Tosi, Directed wireless telegraphy, US Patent 948,086, February 1, 1910.

[15] Ettore Bellini, Apparatus for directed wireless telegraphy and telephony, US Patent 1,221,787, April 3, 1917.

[16] Ettore Bellini, Apparatus for directed wireless telegraphy and telephony, US Patent 1,297,313, March 18, 1919.

[17] Giancarlo Masini, ***Marconi***, (New York: Marsilio Publishers, 1995), p. 200.

[18] Wilhelm Flicke, ***War Secrets in the Ether***, (Laguna Hills, CA: Aegean Press, 1994), p. 21.

[19] Wilhelm Flicke, ***War Secrets in the Ether***, (Laguna Hills, CA: Aegean Press, 1994), p. 30.

[20] R. N. Vyvyan, ***Wireless Over Thirty Years***, (London: George Routledge & Sons, Ltd., 1933), p. 128-129.

[21] Nigel West, ***The SIGINT Secrets***, (New York: William Morrow and Company, 1988), p. 70-74.

[22] Peter J. Hugill, ***Global Communications Since 1844: Geopolitics and Technology***, (Baltimore: Johns Hopkins University Press, 1999), p. 143.

[23] R. N. Vyvyan, Op. Cit., p. 115.

[24] R. N. Vyvyan, Op. Cit., p. 128, 164.

[25] Frank Adcock, Improvement in Means for Determining the Direction of a Distant Source of Electro-magnetic Radiation, UK Patent 130,490, August 7, 1919.

[26] R. N. Vyvyan, Op. Cit., p. 164.

[27] John H. Morecroft, ***Principles of Radio Communication***, 2nd ed. (New York: John Wiley & Sons, Inc., 1927), pp. 884-894.

[28] Henri Busignies, Radio direction finder, Hertzian compass, and the like, US Patent 1,741,282, December 31, 1929.

[29] Frederick Emmons Terman, ***Radio Engineering***, 1st ed. (New York: McGraw-Hill Book Company, 1932), pp. 588-597.

[30] Frederick Emmons Terman, ***Radio Engineering***, 2nd ed. (New York: McGraw-Hill Book Company, 1937), pp. 722-733.

[31] Richard Howland Ranger, Method for radio position finding, US Patent 1,639,667, August 23, 1927.

[32] Edward G. Gage, Radiant energy distance determining system and apparatus, US Patent 1,961,757, June 5, 1934.

[33] Edward G. Gage, Radiant energy distance determining system and apparatus, US Patent 1,828,531, October 20, 1931.

[34] Wilhelm Runge, Distance determining system, US Patent 2,134,535, October 25, 1938.

[35] Alexander McLean Nicolson, Radio range finder, US Patent 1,945,952, February 6, 1934.