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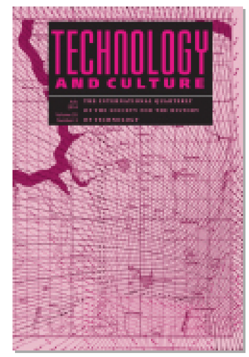

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On the cloudy night of October 30, 1944, a British bomber leaves England on its way to Germany. On board, the navigator is primarily occupied with two objects—or possibly three. The first is a black box with knobs and an oscilloscope display, as in figure 1. The navigator spends most of his time fiddling with these knobs trying to make two wavy signals align on the screen; doing this results in two numbers—something like 49.1 and 4.8. At least one of these numbers is constantly changing and the navigator's box requires ongoing attention. The second object is a simple map known as a lattice chart that shows a dense network of colored hyberbolas, as in figure 2. Each of these curves corresponds to one of the numbers from the machine; finding the intersection of the lines labeled 49.1 and 4.8 puts the bomber just north of Leeds. From here, it will head east over the North Sea to join in formation with more than nine hundred other aircraft, all carrying similar equipment, before turning south for yet another bombing raid on German civilians—this time, in the suburbs of Cologne. Hidden by the clouds, not a single plane will be lost.

This combination of a black box and a map was known as the "interpretation system" for a radionavigation system codenamed Gee that first came online in March 1942. This system was an urgent necessity, since the British had realized that most of their nighttime bombers weren't able to navigate anywhere near their intended targets, let alone bomb accurately once they arrived. Gee stood for "grid"; in the words of Robert Watson-

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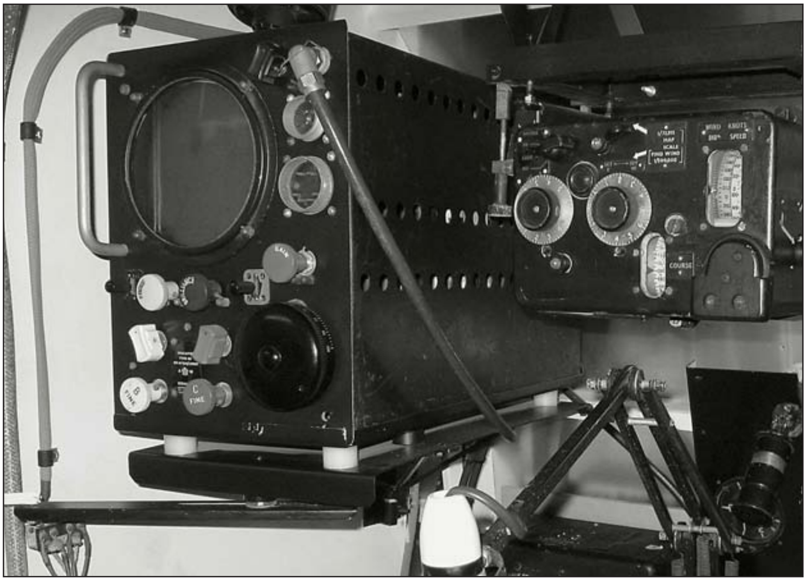

FIG. 1 Mock-up of the black boxes used for radionavigation in an Avro Lancaster, one of the principal heavy bombers of the British Royal Air Force during the second half of World War II. The large circle on the left is an oscilloscope display that would show two wavy lines; using the knobs below to adjust the position of the wavy peaks would result in a pair of numbers. (Source: Photo from Peter Zijlstra, http://home.versatel.nl/gmwzijlstra-prummel/lancaster.htm.)

Watt, leader of the British radar project, the goal was to "unfold [an] electronic grid over Germany."[1] Following Watson-Watt's logic, the third object in the cockpit—one which I'll argue should be seen as no less a part of the material culture of technology than the other two—is the network of Gee radio signals that had been "unfolded" over the Western Front.

Although the distinction may seem subtle, understanding how radio waves can sometimes act more like a stable physical artifact than a fleeting communications signal ultimately suggests a broad reinterpretation of the importance of radionavigation in the mid-twentieth century. Focusing on the physical presence of the Gee radio signals (or those of any of the dozens of other radionavigation systems developed around the same time) also

1. For RAF sorties, see campaign diaries (published 2002) at http://webarchive.nationalarchives.gov.uk/20070706011932/http://www.raf.mod.uk/bombercommand/oct44.html. For an overview of Gee, see R. J. Dippy, "Gee." On interpretation systems, see "Minutes of a Meeting Held in Air Ministry, Abbey House on Thursday, 25th May, 1944 to Agree Action Required to Provide Interpretation Systems for Use with Stations Type 7000 on the Continent," in NARA, RG 331, entry 268, box 75, folder "Lattice Charts Production—Policy." For Robert Watson-Watt, see his *The Pulse of Radar*, 338. For G meaning Grid, see Robert I. Colin, "Robert J. Dippy," 476.

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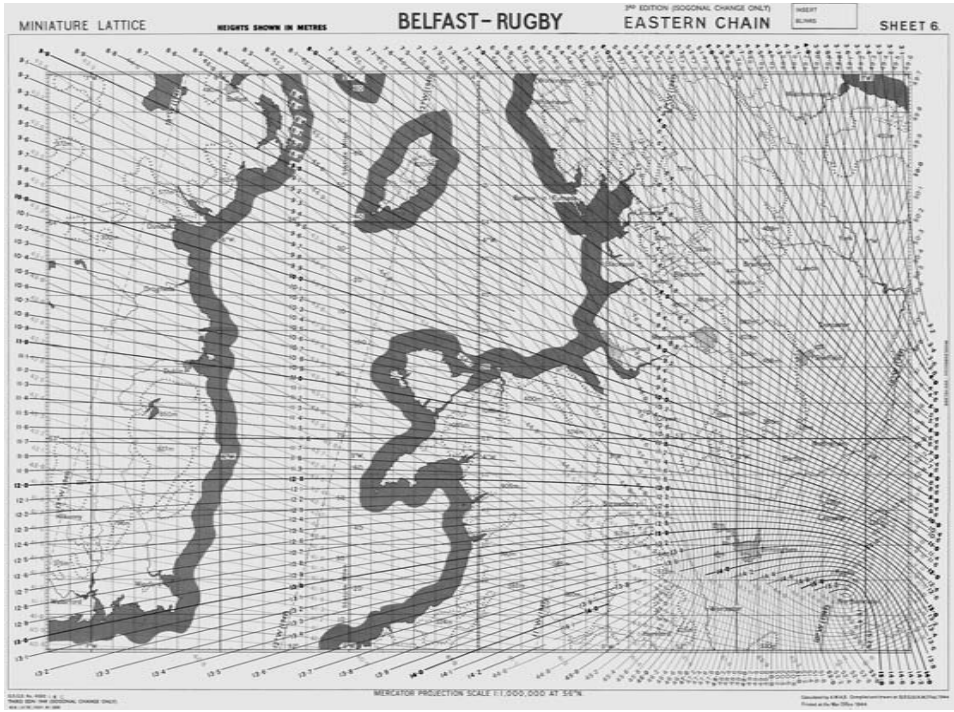

FIG. 2 Lattice chart showing central Great Britain and eastern Ireland. The two numbers from the black box in figure 1 correspond to two of the (colored) hyperbolic lines crisscrossing the map. The intersection of 49.1 (purple) and 4.8 (red) is in the upper right, just north of Leeds. This postwar reprint of a British map is dated February 1944 (Source: NARA Cartographic Records, RG 77, box 54 of 215, folder "907.2: Raydist, Decca.")

opens up a larger set of political and conceptual questions about a broad class of related phenomena—a class that might include everything from radiation and gases to sound or even odors. As a group, I call these *intangible artifacts*. The larger goal of this article is to analyze radionavigation systems as an exemplar of these artifacts—selectively visible, semi-permanent, and always flirting strategically with conventional forms of physicality. To do this, I want to show that radio signals are not just a tool for dropping bombs (or transporting passengers) in unfriendly weather; they have also been an important and overlooked part of the built environment at a macro-geographic scale. The widespread installation of radionavigation systems—begun in the 1910s but greatly accelerated in the 1940s—has had a profound impact on the organization of transportation networks, national territorial claims, and even the basic geographic distinction between land and water. Radionavigation systems, like many other intangible artifacts, not only have a politics (in Langdon Winner's sense); they also share a particular geographic and temporal logic. Tracing the historical ebbs and flows of this logic is crucial for understanding the emergence of new forms of geographic power in the twentieth century.[2]

This article advances two main arguments—one historical, one methodological. My historical argument is about the role of radionavigation in the postwar construction of a new kind of transnational geography, one characterized more by the spatial integration of land, air, and ocean than by any cultural or economic integration across countries. Although the pursuit of universal spatial legibility is easily associated with the global ambitions of the American military—especially under the banner of the Global Positioning System, which first received funding in 1973 and finally came online in the early 1990s—my central claim is that a robust and transnational electromagnetic infrastructure was largely in place by the 1960s and resulted as much from political failure and commercial competition as from any top-down military project.[3] Indeed, the key historical dynamic I want to highlight is the large-scale spatial and political alignment that took place in the decades after World War II among a heterogeneous collection of radio user groups, each pursuing their own technological solutions. The major contrast is therefore not between the satellite and pre-satellite eras, but between the radio logic of the 1930s and the era of grid-like, boundary-crossing systems that began in the early 1940s and continues today.[4]

2. Like Langdon Winner, I want to stress the hybridity of material and social form; see Winner, "Do Artifacts Have Politics?"

3. For military- and GPS-centric analyses of spatial change, see Michael Rip and James Hasik, *Precision Revolution*, or Caren Kaplan, "Precision Targets." Not coincidentally, both see *precision* as the crucial variable at play. The singular—even teleological—importance of GPS is also a common feature of the histories of navigation cited in the next footnote.

4. Historians of navigation almost universally see an important break between ter-

In the 1930s, radio systems were geographically (and politically) distinct, with a particularly strong division between the United States and Europe. By the 1960s, radionavigation—along with its new cousin, radiosurveying—was thoroughly transnational (and transnationalizing), and it was used for similar geographic ends in domains as diverse as transatlantic jet service, offshore oil exploration, and the targeting of intercontinental ballistic missiles. The efforts of civilian agencies and private corporations were just as important as those of the military, and the major technologies were not just American, but also German, French, and especially British.

In other words, my empirical argument is largely about recasting the historical significance of the radio technology of World War II. Rather than seeing radionavigation as a side note to the story of radar and focusing primarily on its origins or its immediate wartime impact (as other historians have done), I want to focus instead on the longer-term and somewhat more diffuse relationship between radio and geographic space. I do not dispute the influence of radar on the course of the war or the influence of laboratories like the Rad Lab at the Massachusetts Institute of Technology on the organization of scientific research. I do, however, want to suggest that looking only at immediate causes and effects gives an incomplete understanding of large-scale political-geographic change.[5]

Second, my methodological argument is about the porous boundary between the tangible and the intangible. In the last fifteen years, scholars in several fields—ranging from anthropology to cultural studies to the history of science—have focused on *thingness* as a way to analyze how the physical and cultural world are entwined and co-produced. "Thing theory," as it is usually called, has proven particularly valuable for providing a vocabulary that can navigate between the twinned pitfalls of technological determinism and pure social construction. In particular, the German philosophical distinction between *Ding* and *Objekt* emphasizes the raw materiality of the former: the essence of thingness is that physical artifacts, while always wrapped in cultural assumptions, can nevertheless still exceed human intentions and

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restrial and satellite systems. This distinction, however, is less meaningful than one might imagine, since it does not cleanly divide systems according to accuracy, user experience, political status, or even geographic coverage. See J. E. D. Williams, *From Sails to Satellites*, Mark Denny, *The Science of Navigation*, W. F. Blanchard, ed., *Air Navigation*, or the paired essays of Per Enge et al., "Terrestrial Radionavigation Technologies," and Bradford Parkinson et al., "A History of Satellite Navigation."

5. My views on historical significance largely follow David Edgerton, "Innovation, Technology, or History." Histories of radar—both scholarly and semi-popular—are mostly concerned with showing that radar was a weapon with significant military payoff; postwar interest is limited to "spin-offs" with scientific or high-tech appeal. See David Fisher, *A Race on the Edge of Time*, Robert Buderi, *The Invention that Changed the World*, Louis Brown, *A Radar History of World War II,* or David Zimmerman, *Britain's Shield*. For the place of radar in the history of science, see Dan Kevles, *The Physicists*, chapter 20, Stuart Leslie, *The Cold War and American Science*, chapter 1, or Peter Galison, *Image and Logic*, chapter 4.

provoke new surprises. In this sense, radio has undoubtedly been a *thing* at crucial moments in its history, and analyzing its thingyness can help foreground its geopolitical importance. Not only has radio been understood using a wide variety of material metaphors—just in navigation and surveying, radio has been treated as a railroad, a yardstick, a street sign, a grid, even a kind of paint—but it can also be just as permanent, obdurate, and determinant as other, more familiar infrastructures.[6]

But by bringing thing theory to bear on electromagnetic waves, I also want to challenge its basic prejudice—namely, the emphasis on tangible, material objects. As Lorraine Daston put it in 2004, thing theory is typically concerned with "matter and meaning"; this implies a strong dichotomy between the tangible world of objects and an intangible thought-world of ideas and culture.[7] Embracing this dichotomy, however, means ignoring a wide range of politically contested artifacts and forms of geographic power. The physical world is not made of matter alone, and tangibles are always entwined with vast intangible materialities that, I would argue, are only *sometimes* thingy—that is, they can oscillate between visibility and invisibility, obstinacy and malleability, presence and absence.[8] Intangible artifacts are thus a provocation to look historically at how strategies and geographies of thingness can change over time. The physicality of radio, for example, was initially quite obvious and explicitly emphasized. As radionavigation became commonplace and black-boxed, however, its geographic presence became increasingly invisible; at times radio could even be thingy and unthingy at the same time, depending on the user or the strength of its connections to conventional objects. Similar shifts can be found with other intangible artifacts as well. Indeed, the politics of tangibility and invisibility have been at the forefront of debates over public health, the environment, property rights, sovereignty, and the role of government—again, especially in the twentieth century.

My narrative is divided into three parts. I begin with the radionavigation systems of the 1920s and 1930s; I then analyze radionavigation during World War II, with an emphasis on unexpected lessons and new tech-

6. Thing theory has much in common with Winner's analysis of artifacts; see Arjun Appadurai, ed., *The Social Life of Things*, Bill Brown, "Thing Theory," Lorraine Daston, ed., *Things That Talk*, or Ken Alder, "Introduction." For a useful analysis of obduracy in particular, see Anique Hommels, "Studying Obduracy in the City."

7. Lorraine Daston, "Speechless," 10. For dichotomies between material and immaterial, see Mario Biagioli, "How Patent Law Is Redefining Materiality."

8. To be clear, I am not suggesting that intangible artifacts ever lose their raw materiality, in the philosophical sense of the thing-in-itself. Rather, I am proposing that the best way to understand intangibles is to see thingyness as an *effect* rather than an inherent property—one that is itself a negotiation between raw materiality and human intention. It would be very difficult to render conventional matter unthingy (a chair, for example), but it is quite easy in the case of, say, invisible odorless gases. Additionally, I would not posit any sharp distinction between tangible and intangible artifacts. Smoke and steam, for example, seem like boundary cases.

niques; I end by showing how, through roughly the mid-1960s, the large and ever-expanding number of navigation and surveying systems all contributed to a similar spatial project. Throughout this narrative, I highlight the wide diversity of radio strategies, not just at the level of engineering but also at the level of political and cultural meaning. Although the late-twentieth-century ubiquity of GPS can make earlier systems seem like nothing but incomplete manifestations of its global coordinate logic, before the 1970s it was hardly obvious that a single one-size-fits-all global solution was even desirable, let alone possible.[9] Finally, I zoom out to ask what the history of radionavigation suggests—methodologically, geographically, and politically—for the analysis of other intangible artifacts.

Railroads of the Sky vs. the Air Ocean

Before World War II, there were two main approaches to radionavigation. Air travel in the United States relied on a point-to-point system called the Radio Range, while navigation in Europe used a wide-area system known as Radio Direction Finding (or D/F).[10] These were not just different technological solutions; they were also different ways of understanding the physicality—the potential thingyness—of radio waves. The Radio Range created stable paths that were seen explicitly as a kind of aerial railway, while D/F had much in common with the nautical logic of lighthouses and was used by ships and aircraft alike. By physicalizing these two analogies—the railroad and the ocean—radio technology channeled the much broader use of these metaphors in early aviation. These metaphors were in common use in both the United States and Europe, but they implied different practical goals, different relationships to the state, and different ways of making aviation a stable, dependable civilian industry. The two radio strategies of the United States and Europe thus participated in two very different political and geographic projects. The railway-like Radio Range was a project of territorial consolidation, domestic services, and subsidies. The lighthouse-like D/F, in contrast, was part of a wide-ranging discussion about international coordination and the limits of sovereignty.

Wherever it appeared, the railroad metaphor was invoked to stress the importance of ground installations; it was most directly at work in the idea of an "airway." The implicit argument was that regular air service was not just as simple as flying from point A to point B. Instead it required stable pathways composed of things like radio beacons, rotating searchlights, meteorological facilities, emergency airfields, refueling posts, and wireless

9. The inevitable push of an inherent "technical imperative" is found even in recent work on radar; see Brown, *Radar History*.

10. The acronym RDF is likewise used, but since this was also used as an intentionally misleading code name for early British radar efforts, I avoid it here; see Brown, *Radar History*, 83.

telegraphy stations. As an American airline executive put it in 1927, “an airway is just as truly on the surface of the earth as is a railway.”[11] As a result, the politics of the railroad analogy were aligned with state sponsorship of ground support and explicit governmental attempts to establish new commercial and administrative links. In France, for example, aviation pundits borrowed railroading vocabulary when arguing for state support for signals, weather services, and land acquisition.[12] The United States and Canada likewise each organized their air systems around state-supported “transcontinental” airways (with a “terminus” on both coasts), and in both Africa and the Americas ambitious continent-spanning airway schemes were seen as the direct heirs of Cecil Rhodes’s abortive Cape-to-Cairo line and the unbuilt Pan-American Railway.[13] And when keeping tallies of the progress of aviation in various countries, the usual unit of comparison was, in the tradition of railroad oneupmanship, miles of airways.[14] The airway, in other words, was a physical construction—an expensive kind of territorial engineering—with distinctly national or imperial overtones.

Over the course of the 1920s and 1930s, the Radio Range gave physical form to this rhetoric. Figure 3 shows how it worked: a set of radio antennas sent out audible Morse code signals in four directions, with slight overlaps. A pilot listening on headphones would hear either an A (dot-dash-

11. Quote from Paul Henderson, general manager of National Air Transport, Inc., “Airways and Airdromes,” 139; he also compares airways to highways and navigable rivers (both of which require investment and maintenance). For lists and discussion of the facilities needed on an airway, see Frederick H. Sykes, “Imperial Air Routes,” 249, or Dennis H. Handover, “A New Empire Link,” 414.

12. In particular, the French government paid for railroad *infrastructure*, while private companies supplied the *superstructure*. This duality was first used by railroad engineers in the 1860s and had acquired a political/financial connotation by the 1870s. It was applied to aviation in the 1920s. See, for example, Congrès des Transports Aériens, *Rapports et discussions, 29 Novembre—2 Decembre, 1934*, especially the reports by Laignier, Bregi, and Alessandri, where the financial analogy with railroads is explicit.

13. The “transcontinental” in the United States was initiated by the Post Office in 1919; by 1941 there were five “transcontinentals” in the United States and one in Canada; see U.S. Office of Assistant Secretary for Aeronautics, “Civil Aeronautics in America,” Information Bulletin No. 1, 5th ed., 1 October 1927, in HULL, NAC 2795 US, 5, and Civil Aeronautics Administration press release, “New Airways Set-Up Groups Canadian and American Facilities,” 1 June 1941, in NARA, RG 237, box 444, “Central Files. 935.1 Australia—940 Canada,” folder 940. For Africa, see Sykes, “Imperial Air Routes,” 246, or Robert Brenard, “The Romance of the Air Mail to East and South Africa,” 47. For the Americas, see George E. Sanford, “The Intercontinental Airways System,” typescript for a presentation made 20 September 1926, in NARA, RG 237, box 445, “Central Files. 940 Central America—943 Canada,” folder 940, or William A. M. Burden, *The Struggle for Airways in Latin America*, 188.

14. The use of mileage for comparative purposes—either miles of airways or miles flown—was ubiquitous. For some particularly bald examples, see Stephen B. Sweeney, “Some Economic Aspects of Aircraft Transportation,” 161; P. R. C. Groves, “The Influence of Aviation on International Affairs,” 289; Russell E. Hall, “Expanding Airways in the Far East”; or Melvin Hall and Walter Peck, “Wings for the Trojan Horse.”

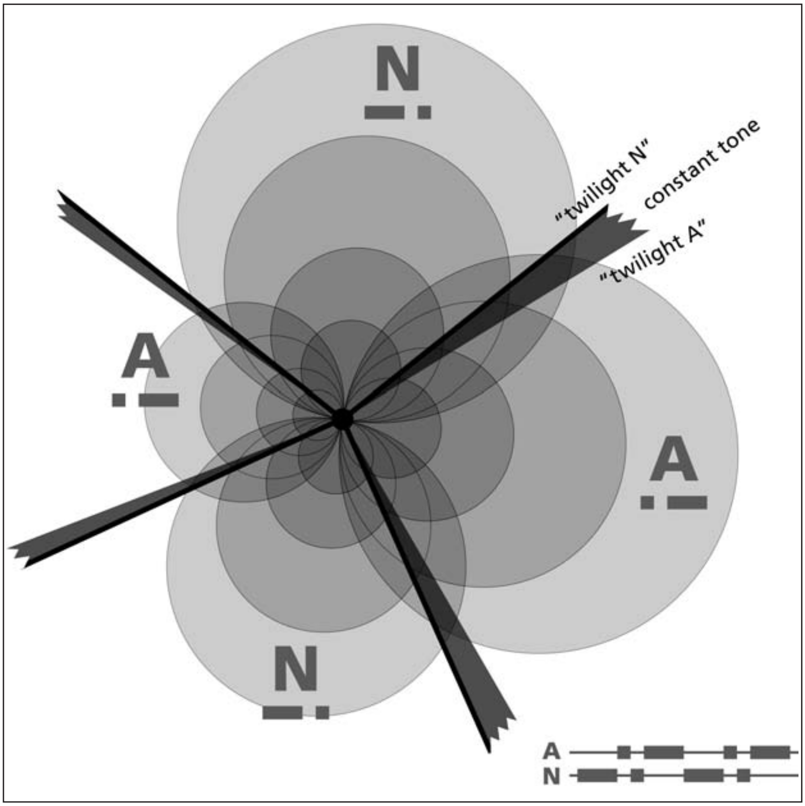

FIG. 3 The directional beams of the Four-Course Radio Range, developed at the U.S. National Bureau of Standards in the 1920s. A single antenna (shown here as a single dot, but actually composed of four interconnected, closely spaced aerials) transmits Morse code signals for A and N in four directions, with varying power; the shaded circles show signal strength. The dark gray beams are an artifact of adjacent signals blending into one another to create a constant tone: the diagram in the lower right shows how the Morse code A and N signals interlock. The edges of the beams are thus somewhat indistinct—hence the "twilight" names for the edges—but note that these beams can be quite narrow despite none of the actual transmissions being at all focused. By changing the power in the aerials, the beams can be oriented in almost any direction. (Source: Diagram by the author.)

pause) or an N (dash-dot-pause) depending on the quadrant; when flying "on the beam," the A and N would merge to create a steady tone that indicated the correct course—either directly toward or directly away from an antenna.[15] By adjusting the power and orientation of the four directional

15. "On the beam" evidently became a common phrase outside of aviation as well; see J. M. Ramsden, "Air Navigation," 407.

transmissions, these narrow equisignal zones could be pointed in almost any direction, and multiple beams could be strung together to make a stable airway, with each antenna typically sited near an airfield. These kinds of directional pathways were a continuation of earlier American navigational techniques—before radio, pilots would commonly "steer a range" by using the visual alignment of two distant landmarks—but by 1941, a Radio-Range primer noted that pilots, especially inexperienced ones, would often "think of a beam as a railroad track . . . us[ing] the published course as if it were a pair of rails."[16]

The Radio Range was an explicitly nationalizing project. Its development was wholly sponsored by the U.S. government, and the goal was to create a national network of airways for internal services, especially airmail and domestic military aviation. It was designed in the 1920s by engineers at the National Bureau of Standards and the Army Air Corps, with funding coming first from the Army Air Service and then from the Department of Commerce.[17] One of the major features of the Radio Range was that the only equipment needed in the aircraft was a simple radio receiver; not even a transmitter was required. This was especially important in the mid-1920s, since the delivery of airmail—the first major civil use of aviation in the United States after World War I—was moving from direct government operation to contract flying, and the private planes used were generally small and cheap. The Radio Range was thus a way of subsidizing these routes: its designers explained that "the complicated and expensive apparatus is on the ground . . . maintained by the Government." This balance between public and private again followed closely from railroad precedent, with mail used in both cases to make passenger service more economically viable.[18]

As a government service and a strategy of domestic consolidation, the Radio Range was remarkably successful, and the Radio Range network defined American aviation for decades. It was first installed on airways around 1929, starting with the Transcontinental.[19] By 1933 there were

16. For the origin of the name, see Ronald Keen, *Wireless Direction Finding*, 476. For the railway analogy, see C. H. McIntosh (pilot instructor for American Airlines), *Radio Range Flying,* 17.

17. Substantially the same invention was described in German patents by Otto Scheller from 1907 and 1916 (and additionally by Franz Kiebitz in 1911), but none of the developers of the Radio Range knew of these until about 1926. See Robert I. Colin, "Otto Scheller and the Invention and Applications of the Radio-Range Principle," 365. For the system's early history, see J. H. Dellinger, H. Diamond, and F. W. Dunmore, "Development of the Visual-Type Airway Radiobeacon System."

18. Quote from H. Dellinger and Haraden Pratt, "Development of Radio Aids to Air Navigation," 894. For explicit comparison with railroad practice, see "Air Lines to Span Nation," 13.

19. See H. J. Walls, "The Civil Airways and Their Radio Facilities"; F. G. Kear and W. E. Jackson, "Applying the Radio Range to the Airways"; H. Diamond, "Applying the Visual Double-Modulation Type Radio Range to the Airways"; Dellinger, Diamond, and Dunmore, "Development of the Visual-Type Airway Radiobeacon System"; W. E.

eighty-two Radio Range stations in operation; by the end of the decade there were more than 250 Ranges covering the entire country, with routes often closely following existing rail lines (see figure 4). At its peak around 1950, the network included almost 400 stations, the last of which was turned off only in 1974.[20] But even as the Radio Range itself became obsolete and was gradually replaced by its successor (the more flexible and reliable VHF Omni-Range), American air traffic control continued to be structured as a linear network of stable radio pathways.

The oceanic metaphor was not incompatible with these domestic concerns, but it conjured a rather different political vocabulary. While it could sometimes be used to make a case for public investment, it was more commonly part of debates about international air law and the limits of national sovereignty. In contrast to railway talk, these debates often assumed that the atmosphere was inherently navigable: what mattered was the "natural state" of the air, not ground services.[21] Especially before World War I, oceanic analogies appeared widely in legal debates about the extension of territorial sovereignty into a country's airspace, with advocates for the "freedom of the air" invoking ships' longstanding right of innocent passage through territorial waters. But even after the peace talks of 1919 definitively settled the question in favor of total sovereign control, questions about the inherent "freedoms" of civil aviation continued to be debated well into the 1950s, and Hugo Grotius, the seventeenth-century theorist of international waters, continued to be cited in arguments about unrestricted competition, cabotage rights, and the potential for military espionage by overflying airplanes. The oceanic metaphor was thus immediately aligned with problems of foreign relations rather than internal development.[22]

Direction Finding technology channeled much of this discussion; it provoked debates about pilot autonomy and relied more on international standardization than state-sponsored construction. As the name implies, D/F equipment simply indicates the direction to a radio source; it works by exploiting the directional reception properties of certain kinds of antennas.

Jackson and S. L. Bailey, "The Development of a Visual Type of Radio Range Transmitter Having a Universal Application to the Airways."

20. R. V. Jones, "Navigation and War," 5; "Radio Ranges in America," 463; Museum of Air Traffic Control, "Four-Course Radio Range."

21. Roger F. Williams, "Federal Legislation Concerning Civil Aeronautics," 803, which also discusses foreign air law. Compare to John C. Cooper, "Air Transport and World Organization," 1196–97.

22. Arthur K. Kuhn, "The Beginnings of an Aërial Law"; Arthur K. Kuhn, "International Aerial Navigation and the Peace Conference"; S. W. Buxton, "Freedom of Transit in the Air"; H. Burchall, "The Politics of International Air Routes," 98–99; John C. Cooper, "Some Historic Phases of British International Civil Aviation Policy"; Cooper, "Air Transport and World Organization," 1197; D. Goedhuis, "Sovereignty and Freedom in the Air Space," 137.

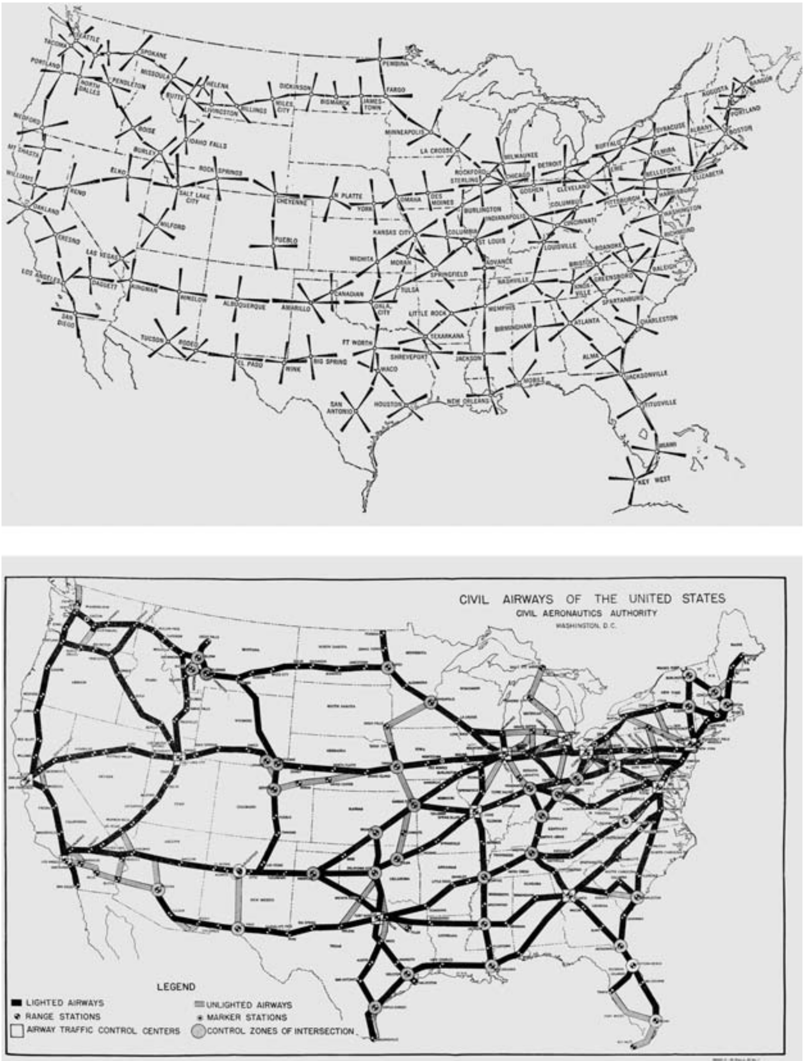

FIG. 4 The railroad-like airway system of the United States in the late 1930s. The top map shows the orientation of individual Radio-Range stations; the bottom map shows the routes as actually used. Note how the east–west "Transcontinental Airway" stretching from New York to San Francisco followed much the same route as the original transcontinental railroad of the 1860s. (Source: Top map from Ronald Keen, *Wireless Direction Finding*, 484; bottom map from Civil Aeronautics Authority, *First Annual Report of the Civil Aeronautics Authority*, appendix B.)

With a ring-loop antenna, for example, the signal from a distant radio source will be greatest when the antenna is aligned edge-on with the transmission and at a minimum when the open ring faces the source; direction can be found by simply rotating the antenna. For aircraft, this principle was turned into a navigational system through the creation of a network of direction-finding stations on the ground that could track transmissions from planes flying overhead. A pilot would simply use a radio telephone or wireless telegraphy to ask ground stations for D/F readings of his transmission.[23] Staff at these stations—at least two, but usually three—would coordinate among themselves to combine their readings and then radio the result back to the pilot in whatever form was most convenient.[24] (What might seem like the simpler solution—D/F equipment in the plane—was actually more complex, for both electrical and navigational reasons.[25]) Like a mariner using lighthouses near shore, a pilot was thus not confined to predetermined routes—at times even to the chagrin of air-traffic planners.[26]

The use of D/F for aviation in fact followed directly from marine precedent, and the same systems were used for sea and air alike. The first experiments with Direction Finding dated to the 1890s and early 1900s—before the Wright brothers had even taken their first flight—and the first D/F stations were established for shipping in the early 1910s. The British Post Office began a coastal D/F service in 1912, and stand-alone equipment was also installed on large ships like the *Mauritania*. The first use of D/F in aviation came during World War I, when Germany used ground stations to direct not just its warships and U-boats, but its Zeppelins as well; the Allies in turn installed a network of D/F stations in Great Britain and northern France to track the German fleet and shoot down the airships.[27] Even the

23. Women were explicitly prohibited from serving on the crew of any aircraft engaged in public transport; see International Commission for Air Navigation, *Convention Relating to the Regulation of Aerial Navigation Dated 13th October 1919*, 28.

24. There were different reporting norms in different countries. In the United Kingdom and France, for example, locations were usually reported using nearby town names, while elsewhere latitude and longitude were used. See ICAN Maps Sub-Commission, "Minutes No. 18: Sittings of 22nd November 1938," in ICAN archives, 7–8. Ground D/F could also be used to "talk down" a pilot to a landing field using only bearings rather than point locations; see Keen, *Wireless Direction Finding*, 616.

25. For problems with interference from insufficiently screened engines, see Brian Kendal, "Air Navigation Systems Chapter 3," 325. For the navigational problems involved (and the need for a good compass), see Robert I. Colin, "Survey of Radio Navigational Aids," 221–25.

26. The tension between pilot autonomy and air-traffic efficiency in the United States was largely a question of competing technological systems; see Erik Conway, "The Politics of Blind Landing." In Europe, however, D/F could enable either autonomy or control, depending on what information was transmitted to the pilot (see note 24). For use of D/F in traffic control, see H. A. Taylor, "Radio and Air Traffic." For a lament about the "problem of the itinerant aircraft not flying over a regular route," see Roderick Denman, "Radio Air Navigation." Yet Denman's proposed solution, which he called "fanciful," was not a system of rigid routes but a "radio grid" of stable coordinates!

27. The physics of directional radio had been investigated since the 1890s by Hertz,

basic method used to coordinate D/F readings carried an oceanic flavor: D/F ground staff would typically combine multiple bearings by drawing intersecting lines on a map in exactly the way that ship navigators were taught to use lighthouses for determining their location at sea.[28]

The growth of the European D/F network roughly paralleled the expansion of the Radio Range, but both its geography and its structure were irreducibly international. Although marine services were installed in both Europe and North America soon after World War I, the European aeronautical network was only organized in the late 1920s, primarily to facilitate travel across the English Channel (see figure 5). By 1938 there were roughly a hundred aeronautical stations throughout Europe.[29] Although each station was financed by its host country, D/F equipment and communication protocols—along with maps and various other navigational paraphernalia—were regulated by the International Commission for Air Navigation, an international organization associated with the League of Nations that did not include the United States.[30]

The interwar period was thus defined by two sharply contrasting understandings of how radio could organize space. The United States was crisscrossed by railroad-like beams defining stable paths as part of a project of domestic consolidation, while western Europe was dotted with lighthouse-like beacons that allowed flexible navigation across international boundaries. The overall goal in both cases was to ease the frictions of space, but neither solution was easily universalized—they were responses to different political geographies, different strategies of state support, even different types of aircraft. By the end of the 1930s there were signs that this clear distinction might gradually fade, but relatively little happened before

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Marconi, and others. The first patents specifically for direction finding came just after those for directional transmission, in the early 1900s. See Keen, *Wireless Direction Finding*, 6–10. For use in the 1910s, see Ken Beauchamp, *History of Telegraphy*, 243, 269–72, 315, 324–26.

28. For details of using the "Position Line Method" at sea (used since the mid-nineteenth century), including both ship and ground D/F, see Edward J. Willis, *The Methods of Modern Navigation*. For maps and D/F, see Keen, *Wireless Direction Finding*, chapter 8.

29. For 1920s stations, see Kendal, "Air Navigation Systems Chapter 3," 324; Claud Powell, "Radio Navigation in the 1920s," 297; Gerald C. Gross, "European Aviation Radio," 346. For expansion into the 1930s, see "Short-Wave Direction Finding" and Keen, *Wireless Direction Finding,* 549, 577. For coastal D/F provided by the U.S. Lighthouse Service and the U.S. Navy, see George R. Putnam, "Radio Fog Signals for the Protection of Navigation," and Dellinger and Pratt, "Development of Radio Aids to Air Navigation," 892. For Canada, see Harold S. Patton, "Canada's Advance to Hudson Bay," 233.

30. For requirements for carrying wireless apparatus, see International Commission for Air Navigation, *Bulletin Officiel* 20, 58, and International Commission for Air Navigation, *Bulletin Officiel* 24, 148–49. Likewise, the International Commission for Air Navigation's *Regulations for the International Radioelectric Service of Air Navigation* are almost entirely devoted to communications. For standardization of frequencies in 1934, see Kendal, "Air Navigation Systems Chapter 3," 324. For standardized beacon services (again modeled on marine precedent), see Denman, "Radio Air Navigation," 54.

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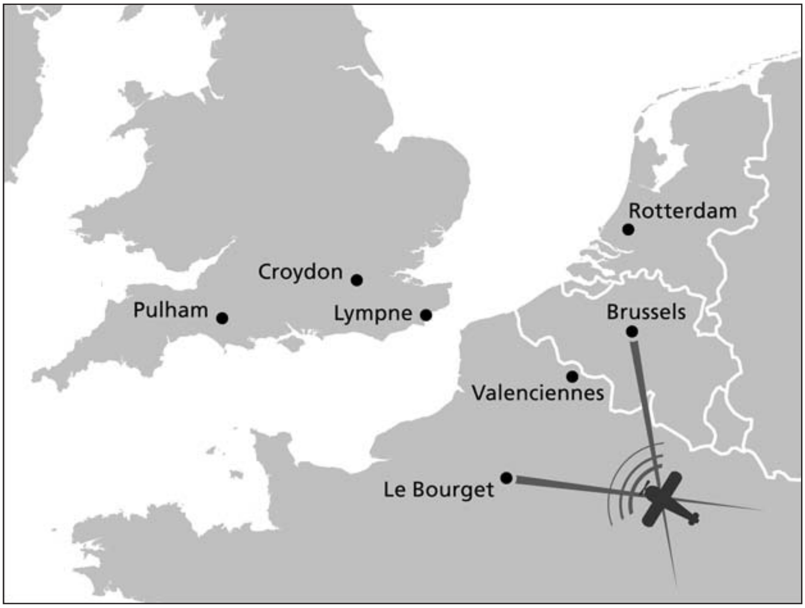


FIG. 5 Aeronautical Direction-Finding (D/F) stations in western Europe as of 1931. The aircraft in the lower right has sent out a request for its location to Brussels and Le Bourget, and these two stations have used directional antennas to determine their bearing to the plane. After coordinating among themselves, one of the ground stations would radio back to the pilot the name of a nearby town that the pilot could find on a map. (Source: Map by the author; station locations from Gerald C. Gross, "European Aviation Radio," 346.)

the start of the war. European engineers did begin adopting American beam technology (especially as blind-landing equipment on individual runways), and American regulators began requiring U.S. aircraft to carry D/F equipment. The system that would eventually replace the Radio Range—which was already under development at RCA by 1936—was also presented in both the United States and Europe as an exciting compromise between fixed paths and free flying.[31] This inchoate convergence, however, was sharply diverted by the start of the war, and rather than any gradual

31. For landing apparatus, see Robert I. Colin, "Ernst L. Kramar," 82; Keen, *Wireless Direction Finding*, 616f; Kendal, "Air Navigation Systems Chapter 3," 321. Germany had also built fourteen full-size Radio-Range stations (there were also two in Austria); see W. F. Blanchard, "Another Look at the Great Area-Coverage Controversy of the 1950's," 351. These blurred the line between railroading and international standardization; compare "All Landings Blind When Necessary," and Denman, "Radio Air Navigation," 56. For D/F in the United States, see H. M. Samuelson, "The Future of Aircraft Radio," and "Navigation—Fourth Rate." For presentation of the Omnirange in explicitly lighthouse-like terms, see "The Radio Range Beacon." For British interest, see "An Aerial Radio Lighthouse" or "Omni-directional Radio Range."

stabilization of radio techniques, the 1940s instead saw the advent of several new technological strategies.

The New Radio Landscapes of World War II

World War II provoked a rapid and somewhat slapdash reconsideration of radionavigation techniques. Both D/F and the Radio Range continued to be used extensively, but there was also wide development and experimentation with new systems. At least a dozen were initiated by the United States and the United Kingdom, while no less than twenty-five were pursued by Germany. Almost none, however, were developed by Japan, Italy, or other countries.[32] Unsurprisingly, these systems rarely lived up to engineers' expectations (or postwar rhetoric), but the confrontation between new technological systems and the realities of war led to significant changes in the political geography of radio.

Wartime radionavigation strategies can be divided into three types, each with a different geographic logic and postwar trajectory. The first two were primarily offensive and were used extensively for blind bombing; these were the intersecting-beam systems deployed by Germany and the distance-measuring systems developed mostly by the Allies. The third kind of radionavigation was a new class of area-navigation systems, including Gee, that created a lattice of electronic coordinates. These systems were used for basic navigation and did not push any limits of precision or lethality, but their supporting role was quite substantial. (A common quip among British radar engineers was that D-day should have rightly been called "G-day."[33])

None of these three techniques worked entirely as planned; the latter two, however, did end up leading to new geographic projects. The distance-measuring systems, while never a bombing panacea, were quickly adopted for use in wartime survey and reconnaissance, with the result that radio became seen as a "precision yardstick" of unprecedented length and exactness.[34] The area-navigation systems, in turn, were a new kind of radio infrastructure that combined the territorializing presence of the Radio Range with the flexibility of D/F. Following the metaphor of the grid, these coordinate systems ended up being treated as a semi-permanent, even politically

32. For an overview of German systems, including those that never advanced beyond proposals or experimental trials, see Fritz Trenkle, *Bordfunkgeräte*. For Japan, see U.S. Naval Technical Mission to Japan, "Japanese Navigational Aids," and Roger I. Wilkinson, "Short Survey of Japanese Radar," 372, 459. For Soviet proposals, see R. V. Whelpton and P. G. Redgment, "The Development of C. W. Radio Navigation Aids," 246.

33. See Watson-Watt, quoted in Colin, "Robert J. Dippy," 479, or R. A. Smith, *Radio Aids to Navigation*, 49.

34. Stuart William Seeley (the system's inventor), "Shoran Precision Radar," 232; see also Stuart William Seeley, "Shoran—a Precision Five Hundred Mile Yardstick."

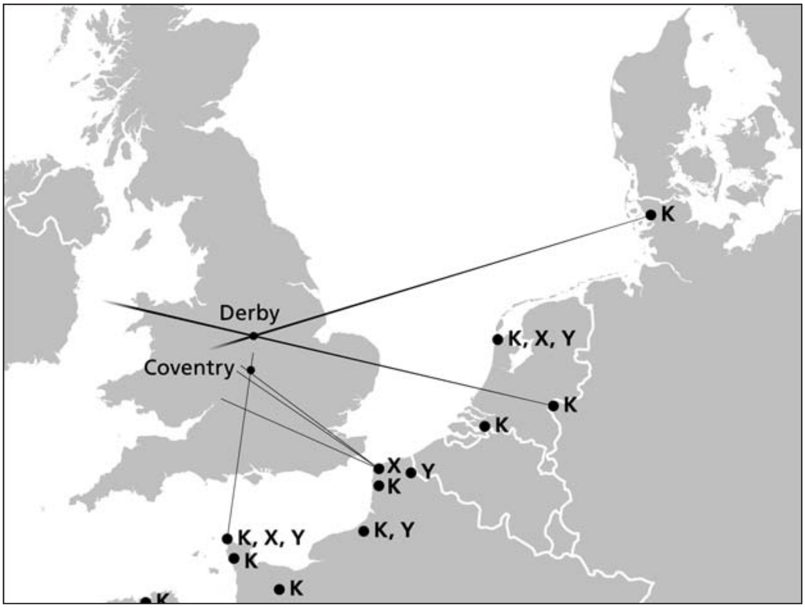


FIG. 6 The German beam-based navigation systems of the Battle of Britain (as of summer 1941), showing Knickebein beams aimed at Derby and X-Gerät beams aimed at Coventry. The beams were created using the same principle as the U.S. Radio Range, but they were designed to be much narrower to allow for high-accuracy bombing. (Source: Map by the author; adapted from R. V. Jones, *Most Secret War*, 203.)

neutral feature of the landscape, despite their transnational scale. Neither of these two characteristics—permanence and neutrality—was entirely expected, but they were crucial for the grid systems' postwar longevity.

The German intersecting-beam systems are perhaps the best-known navigational technology of the war; they were conceptually quite simple and played a dramatic role in early battles. These beams came in several varieties—the most well-known were Knickebein and the X-Gerät—but they all used principles similar to the Radio Range.[35] Figure 6 shows how they worked: German transmitters were installed along the west coast of Europe, and narrow beams were aimed to intersect over various targets in England. In the first months of the war these beams were responsible for unprecedented destruction; the surprise bombing of Coventry in November 1940 was especially horrific. As dramatic as these beam systems were, however, they were disabled relatively quickly by British countermeasures.

35. Chronologically, the narrow-beam X-Gerät (also known as Wotan I) was developed before Knickebein; the latter was produced as a more user-friendly version of the former. See Brown, *Radar History of World War II*, 113–14; Alfred Price, *Instruments of Darkness*, 21; Karl Hecks, *Bombing 1939–1945*, 53.

The original beams were essentially useless by early 1941, while the more advanced systems deployed by Germany in 1942 were neutralized even before they were turned on. Indeed, it is precisely the beams' inflexibility that has made them so well-known. In his memoirs, Winston Churchill famously dubbed the raids over England the "Battle of the Beams"; they were a heroic moment when a ruthless German offensive was thwarted by the "scientific intelligence" of British boffins.[36]

The second type of radionavigation—based on precision distance measurement—was more versatile, but likewise had trouble living up to expectations, at least offensively. The logic here was similar to radar, except that instead of a ground station emitting pulsed signals to measure the distance to an unknown object, radar equipment was installed both on the ground and in the aircraft. The distance between the plane and the ground station could thus be known on board the aircraft and used for precision bombing.[37] Germany combined this technique with its directional beams to create two systems—the Y-Gerät (stations shown in figure 6) and Egon—that could supply both direction and distance from a single ground station. Like the pure beam systems, however, these were quickly disabled by countermeasures and ended up being used mostly for controlling defensive fighters.[38] The British and American systems—known as Oboe and Shoran, respectively—were instead designed using two different ground stations. Figure 7 shows the basic idea: a bomber would fly a constant distance away from one transmitter and then release its bombs at a predetermined distance from the second transmitter. In ideal circumstances, the performance of these systems was quite impressive: Oboe could place bombs within a circle only a few hundred yards in diameter, and one of the first uses of Shoran was to destroy bridges in northern Italy.[39] But similar

36. Winston Churchill, *Their Finest Hour*, 381f. For a detailed narrative, see R. V. Jones, *Most Secret War*, especially 127–29, 179, and chapter 16, or Brown, *Radar History*, 115, 119. For an overview of countermeasures, see Robert Cockburn (wartime head of Radio Countermeasures at TRE), "The Radio War," 423–34.

37. These systems developed from Identification Friend-or-Foe (IFF) equipment originally designed by Watson-Watt; see Lord Bowden of Chesterfield, "The Story of IFF." For other applications, see K. A. Wood, "200-Mc/s Radar Interrogator-Beacon Systems." For German IFF, see David Pritchard, *The Radar War*, 178–81.

38. For the continuous-phase Y-Gerät (also known as Wotan II), see Jones, "Navigation and War," 10–13; for intelligence against it, see R. V. Jones, "Scientific Intelligence," or R. V. Jones, *Reflections on Intelligence*. On the use of Y and Egon for fighter control, see Donald Caldwell and Richard Muller, *The Luftwaffe Over Germany*, 127–32, 243–429; Gebhard Aders, *History of the German Night Fighter Force 1917–1945*, 76, 127; Francisco Gallei, "American and German Fighter Control through 1945." On the use of Egon for bombing over England, see Jones, "Navigation and War," 21.

39. For Oboe, see F. E. Jones, "Oboe," or A. H. Reeves and J. E. N. Hooper, "Oboe." For Shoran, see Seeley, "Shoran Precision Radar," 232–40, or Frederick J. Green Jr., "Shoran Stations," 8 March 1945, in NARA, RG 331, entry 268, box 78, folder "Shoran and Rebecca-H Policy."

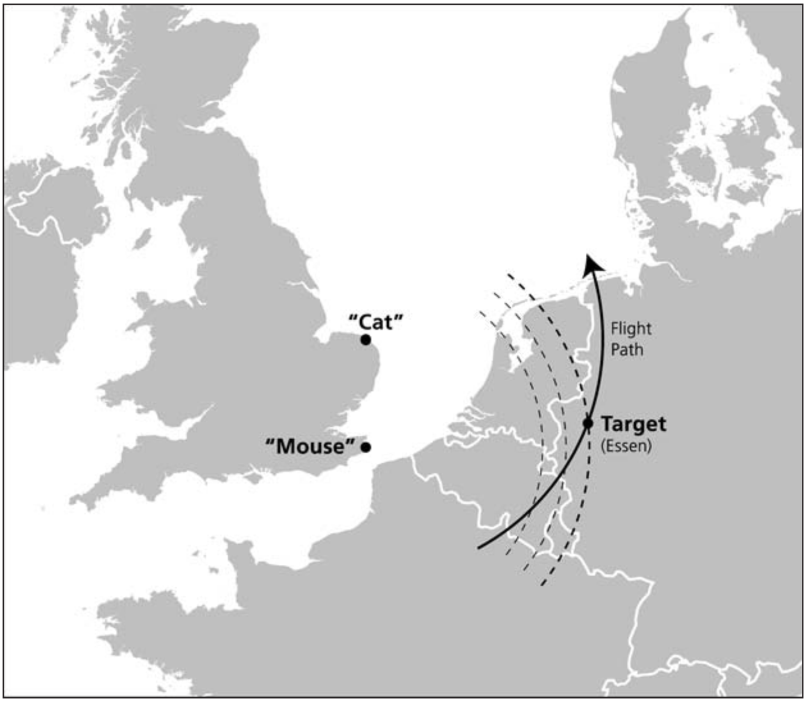


FIG. 7 The British Oboe system, as first deployed against targets in western Germany. The equipment measured the distance between the aircraft and two ground stations; the pilot would keep a constant distance from the "cat" station, and bombs would be released at a certain distance from "mouse." (Note that the pilot did not actually need to follow the entirety of the curved track shown here.) (Source: Map by the author; adapted from R. V. Jones, *Most Secret War*, 276.)

to other precision-bombing technology (especially the Norden bombsight), these systems were hardly foolproof. Equipment problems, operator error, and uncooperative atmospheric conditions all conspired to ensure that these systems were distinguished as much by their potential as by their actual record. The Ninth Bomber Command, for example, felt that Oboe was "oversold," while its experience with Shoran was "discouraging."[40]

But even though these systems did not inaugurate a brave new world

40. For quotes, see Henry E. Guerlac, *Radar in World War II,* 836, 903. For operational accuracy of Oboe, see Jones, "Oboe," 496; Reeves and Hooper, "Oboe," 398; or F. E. Jones et al., "D.S.R. Historical Monograph: Oboe," April 1946, in PRO AVIA 44/519, "Oboe," 208–13. For Shoran, see H. R. Crowley, "Shoran," 8 March 1945, in NARA, RG 331, Entry 276F, Box 131, "SHAEF Air Staff, Air Signal Division, Radar Section, Numeric Subject File, July 1943–December 1944." On the Norden bombsight, see Stephen L. McFarland, *America's Pursuit of Precision Bombing.*

of error-free warfare, they did introduce a new fluidity between navigation and mapping. The most obvious symmetry was between bombing and precise aerial photography. Radio-located photography was used not just for documenting bombing raids but also for conducting stand-alone surveys. Both Oboe and Shoran (along with three Oboe-like systems known as Rebecca-H, Gee-H, and Micro-H) were used in this way, everywhere from western Europe to the jungles of Southeast Asia.[41] But there was a more profound symmetry as well. Instead of using two well-located ground stations to guide a bomber (or a camera), a plane could also be used to measure the unknown distance between two antennas. Although neither Oboe nor Shoran was originally designed for this kind of survey work, the connection between bombing and mapping emerged quite forcefully during their development. Since their calculated accuracy was so high, it was difficult to distinguish equipment error from errors in the maps used to guide the bombers, and both Oboe and Shoran ended up discovering map errors during testing. It was these tests that prompted the designer of Shoran, RCA engineer Stuart Seeley, to describe his system as a "radio yardstick." By the end of the war, the complementarity of surveying and navigation was seen as "obvious."[42]

The third type—coordinate-based area-navigation systems like Gee—were hardly free from technical glitches, but they were much more amenable to mass deployment than any of the blind-bombing systems. Gee was the first such system; its debut in March 1942 sent British bombers to destroy Essen. A German system known as Sonne came online that June, and the U.S. Loran system began transmitting in October. A second British system—code-named QM during the war but later called the Decca Navigator after its original corporate sponsor, Decca Records—was ready just in time for the D-day landings.[43] These systems were less accurate than the

41. "H" was the British code letter for the range/range technique. For surveying use of Oboe, Gee, and G-H (also known as Gee-H, since it piggybacked on Gee equipment) from 1943 through the late 1940s, see "Discussion on 'Radar Navigation,'" and C. A. Hart, "Surveying from Air Photographs Fixed by Remote Radar Control," esp. 649. Rebecca-H used IFF-based equipment; see Wood, "200-Mc/s Radar Interrogator-Beacon Systems," 493. For Micro-H, see Charles W. McArthur, *Operations Analysis in the U.S. Army Eighth Air Force in World War II*, 175–76.

42. In 1946 Seeley reported that before the war, "it was not known, at first, to what uses a system for accurate transmission path length measurement could be put"; see his "Shoran Precision Radar," 232. For quote, see H. R. Crowley, "Shoran," 1.

43. For introduction of Gee, see UK Ministry of Civil Aviation, "An Outline of the Technical Performance of the 'Gee' Radio Navigation System During the War of 1939–45," August 1946, in NARA, RG 319, MLR NM3 82, "Publications ('P') Files, 1946–51," box 2727, 3. For Sonne, see "Radio Navigation Systems and Equipment," an August 1945 Allied translation of a captured German original written sometime after November 1944, in NARA, RG 165, entry 79, box 1954, folder "Radio Navigation Systems and Equipment." For Loran, see Pierce, "An Introduction to Loran." For Decca, see Claud Powell, "Early History of the Decca Navigator System."

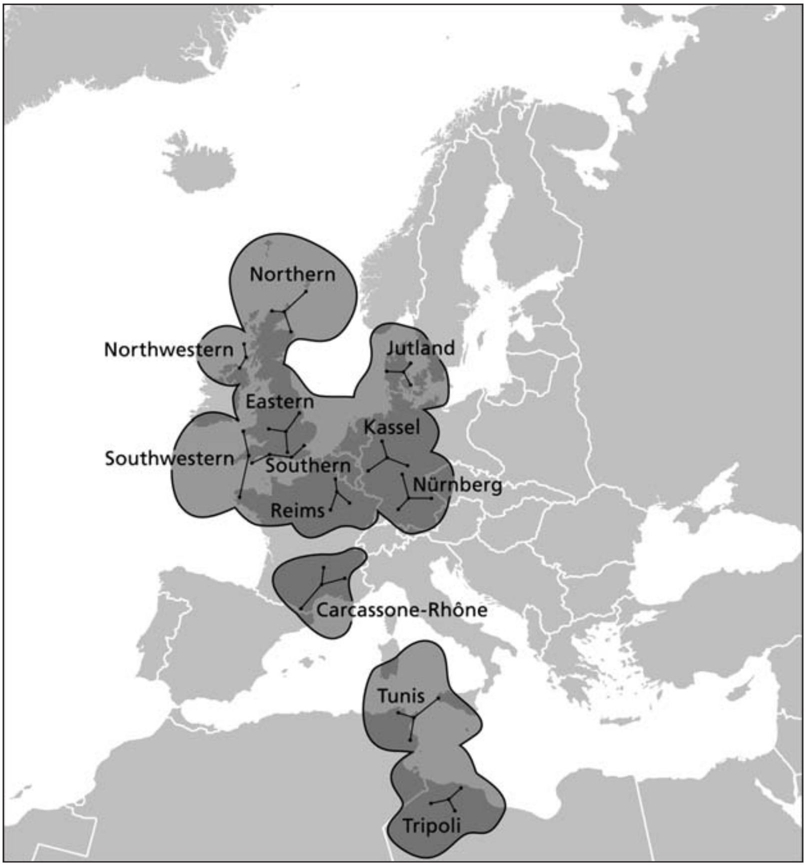


FIG. 8 Gee coverage as of late 1945 for planes flying at an altitude of a few thousand feet, with names and station locations for each "chain" of three synchronized antennas. (Source: Map by the author; coverage in the United Kingdom from John Hall, ed., *Radar Aids to Navigation*, 61; continental coverage from sketch map included in "Gee Cover—Europe—Phase II," 2 July 1945, in NARA, RG 331, entry 268, box 77, folder "Continental Cover Plan: Gee and G-H.")

blind-bombing ones, but they tended to be more reliable and covered vastly greater areas. Figures 8, 9, and 10 show the coverage of the three major systems at the end of the war. Gee spanned from northern Scotland to Tunisia; it was used not just by the British, but also by all U.S. forces in Europe (the Eighth U.S. Air Force installed it in 80 percent of its planes). Sonne blanketed nearly all of western Europe and was being expanded eastward. Loran receivers—over 75,000 of which were built during the war—were used in every major theater.[44] Wherever these systems provided

44. For Gee, see Watson-Watt, quoted in Colin, "Robert J. Dippy," 478; for Loran, see Pierce, "An Introduction to Loran," 219.

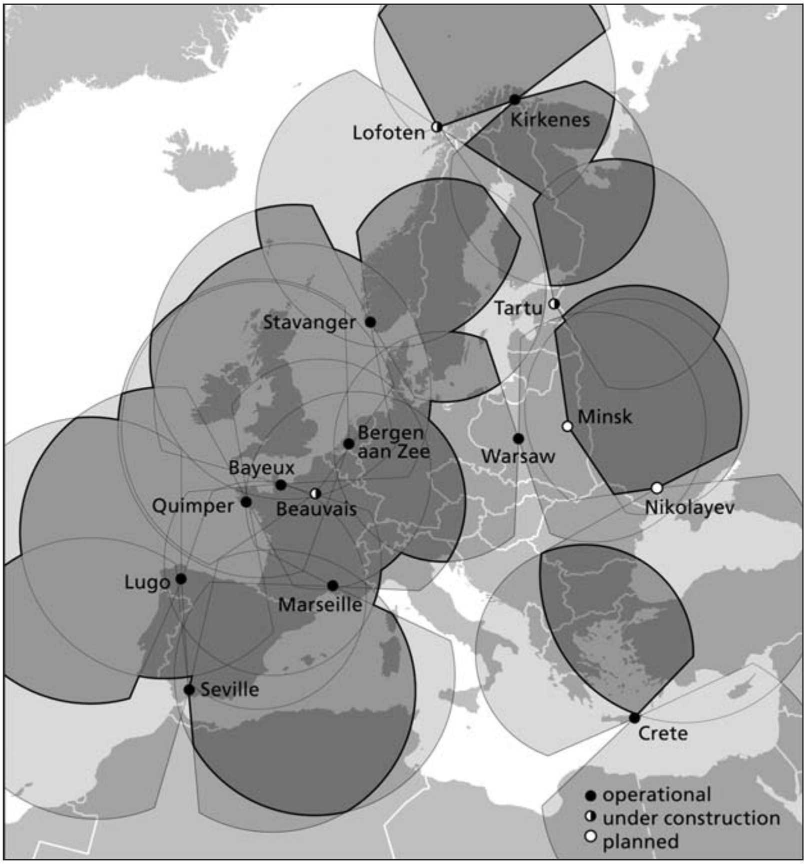
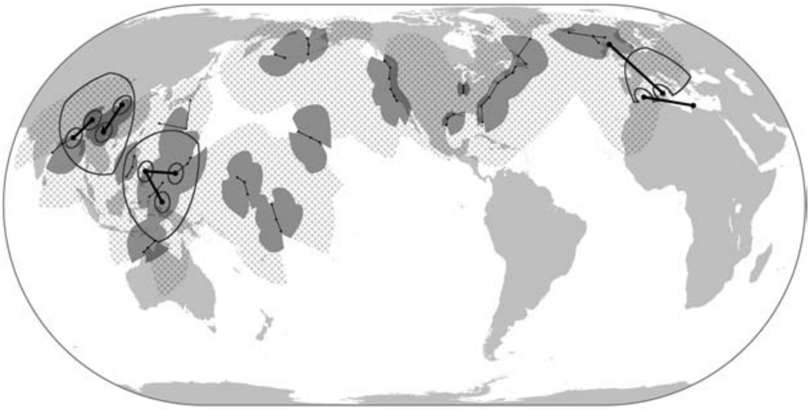


FIG. 9 German Sonne coverage as of mid-1945. Areas where two stations are available to give a full fix are shaded dark gray; in lighter areas only one line of position is available. (Note that although the range of each station is shown ending rather abruptly, in reality the signal would fade with distance.) (Source: Map by the author, adapted from a sketch map in "Radio Navigation Systems and Equipment," an August 1945 Allied translation of a captured German original written sometime after November 1944, in NARA, RG 165, entry 79, box 1954, folder "Radio Navigation Systems and Equipment.")

coverage, aircraft and ships could locate themselves (and their targets) on a stable grid of electronic coordinates.

Technologically, there were two approaches to creating these electronic grids. The Allies' systems—Gee, Loran, and Decca—were all based on time/distance measurements, again similar to radar. But instead of measuring the round-trip time delay between a single transmitter and a receiver, the important measurement was the difference in the time delay of two signals sent from two coordinated transmitters. Figure 11 shows this idea in



Daytime coverage ("groundwave")
Extended nighttime coverage ("skywave")
Additional nighttime-only "Skywave-Synchronized" Loran (SS Loran)

FIG. 10 U.S. Loran coverage as of late 1945. Range increased dramatically at night due to radio reflections off the ionosphere, though with some loss of accuracy. For Skywave-Synchronized Loran, transmitters were placed so far apart that stations could only be coordinated using these reflected signals. This technique allowed for coverage over nearly all of Europe without building any stations on the continent itself; it was also important for navigating over the "hump" separating India and China. (Source: Map by the author; station locations from J. A. Pierce, A. A. McKenzie, and R. H. Woodward, eds., *Loran*, appendix B; day and night coverage from U.S. Navy pamphlet "Loran: Long Range Radio Navigational Aid," August 1945, in ICAO, box "Com—Sub. 1, 2, & 3: 1945–1949," 4–5, with domestic training-chain coverage added; S-S Loran coverage derived from sketch maps in letter from UK Coastal Command, "Gee and Loran Accuracy Charts," 3 May 1945, in PRO, AVIA 7/2316.)

the abstract, while figure 12 shows how three stations could be combined to create a full coordinate system. (Because of the shape of the grid lines, this technique is known generically as "hyperbolic navigation."[45]) In contrast, the German Sonne system was a direct outgrowth of the earlier beam systems. The main difference was that instead of static beams defining fixed paths, the Sonne beams slowly rotated. This meant that a user listening on headphones would periodically hear a station identification tone, then a series of dashes, the constant tone of the beam as it passed, and finally a series of dots. Simply counting the number of dashes and dots could give a remarkably accurate measure of the direction to the station.[46]

45. For German experiments with hyperbolic systems, see Trenkle, *Bordfunkgeräte*, 134, 137. For an overview, see W. F. Blanchard, "Air Navigation Systems, Chapter 4."

46. For details on Sonne, see A. H. Jessell, "The Range and Accuracy of Consol"; and "Consol Navigation System," 66. Many years after the war, Sonne (and the VHF Omni-Range) were sometimes described as "collapsed" hyperbolic systems; see Ernst Kramar, "Hyperbolic Navigation—History and Outlook."

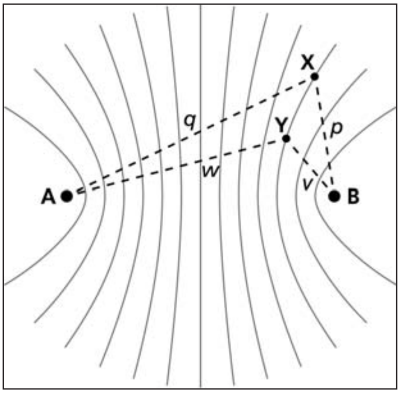


FIG. 11 Hyperbolic navigation. Two transmitter stations—A and B—send out time-synchronized radio signals. A user—at X, for example—only receives these signals passively, without sending signals in return. This means that it cannot measure the absolute distance to either station, but it can determine the *difference* in the distance between the two. (That is, it does not measure q or p, but rather q minus p.) This establishes its position somewhere along a hyperbola. Note that with only two stations, X and Y cannot be distinguished, since q minus p is the same as w minus v. (Source: Diagram by the author.)

To create a two-dimensional coordinate system, Sonne stations were simply positioned so that navigators could locate themselves at the intersection of two bearings. These bearings were printed on lattice charts, and the operational result was essentially the same as the hyperbolic systems.

There were significant differences between these systems—not just differences of accuracy, range, or equipment, but also origin, sponsorship, and strategic goals—but in all cases there was a close alignment between new operational requirements and the metaphor of the grid. Gee, for example, first found sponsorship in June 1940 when British Bomber Command approached the Telecommunications Research Establishment (TRE, the main British radar laboratory) in search of a remedy for its abysmal bombing performance. The designer of Gee, Roger Dippy, later recalled that the requirement was for "a sort of grid reference" that could be used as a common system by all aircraft at once.[47] The other systems were prompted by similar needs and understood in similar terms. Loran—designed at the Rad Lab, but largely derived from Gee—was needed to help route convoys through the vast and notoriously cloudy North Atlantic; its primary purpose was likewise "grid-laying."[48] Sonne, in turn, was first deployed for U-

47. See Dippy's remarks in Colin, "Robert J. Dippy," 476. Reginald Jones notes that resistance to radio navigation was still widespread in British high command a year later, when a scathing report was issued calling attention to the problem; see Jones, *Most Secret War*, 210, 217.

48. Pierce, McKenzie, and Woodward, eds., *Loran*, 20. Although traditionally credited to the American millionaire polymath Alfred Loomis, recent evidence suggests that

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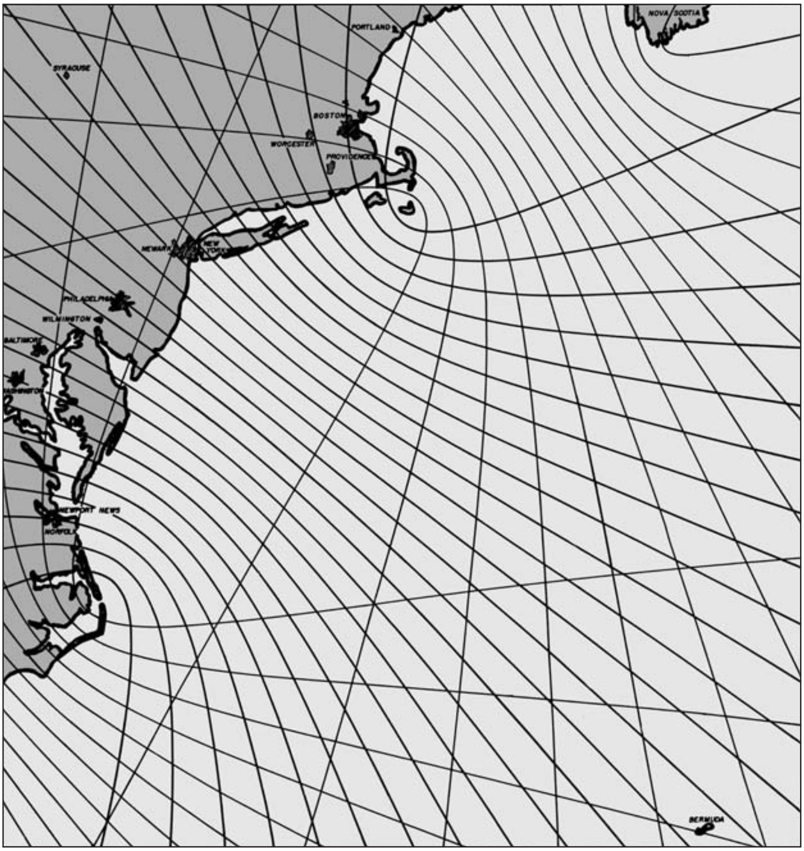

FIG. 12 Three Loran stations—in North Carolina, Nantucket, and Nova Scotia—create two intersecting sets of hyperbolas. In every group of stations, one is designated the "master" (here, Nantucket) and the others are "slaves" that use signals from the master for synchronization. (Map from J. A. Pierce, "An Introduction to Loran," 219; shading added.)

boat navigation off the west coast of France, and Decca found the sponsorship of the British navy in mid-1941 for offshore mine-sweeping (and mapping) in the English Channel. In preparing for the D-day landings, a manager at the TRE summed up these navigational requirements with a succinct, comprehensive catchphrase: what was needed was a "gridded bat-

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his ideas came from conversations with a loose-lipped British engineer during the famous Tizard Mission of September 1940; see E. G. Bowen, *Radar Days*, 171–74, and Jennet Conant, *Tuxedo Park*, 199–200, 231–34. Immediately after the war one of the leaders of the Loran effort suggested that Loran "may be said to have been invented in America in the sense in which Galileo is said to have invented the telescope": Pierce, "An Introduction to Loran," 217.

tlefield."[49] In other words, what was needed was a way to turn a large and featureless expanse of water, clouds, or darkness into something legible, something *coordinated*. In contrast both to the domestic metaphor of the railroad and the international metaphor of the ocean, the grid thus suggested a profoundly transnational geography. It was a physical construction, but it was not limited by international boundaries.[50]

The stubborn tendency of these grids toward geographic stability is best seen in the contrast between Gee and the other three systems. For the most part, the deployment of Sonne, Loran, and Decca was essentially cumulative. Stations were built and then remained in place, and the same coordinates (and maps) were used for the duration of the war. Gee, however, was designed to be reconfigured over time. For example, figure 13 shows a British plan for Gee installations on the European continent after D-day: it calls for a series of mobile Gee stations which would be advanced in leap-frog fashion as territory was won from the Germans. But this kind of planning was plagued with ongoing problems, since once the Allies finally broke from their foothold in Normandy, their eastward progress was much faster than expected. This led to a bitter rift between tactical forces and central command. In late 1944 and early 1945 a British air marshal in charge of tactical operations wrote a series of letters to headquarters expressing "grave concern" about the rigidity of Gee planning and delays in adapting to new conditions, arguing that there should never have been "any preconceived plan" at all—what was needed was ad hoc siting of a "local nature." But the charting office responded that greater latitude in moving the antennas would in fact render Gee useless, since the primary cause of operational delay was the need to resurvey the antennas and recalculate all the necessary lattice charts with every change of plans. This tense situation continued throughout the rest of the war, with ongoing complaints from all sides.[51]

The lesson here is not just about the specifics of Gee; indeed, a similar scheme involving mobile Loran stations was proposed for Southeast Asia

49. Wilfred Lewis, cited in J. W. S. Pringle, "The Work of TRE in the Invasion of Europe," 356. For Sonne in the Bay of Biscay, see A. G. Watson, "Radio Aids to Navigation," 130. For Decca, see Powell, "Early History of the Decca Navigator System."

50. For the inadequacy of fixed-path navigation in war, see Pierce, McKenzie, and Woodward, eds., *Loran*, 28, 35.

51. See letters from Air Marshal Commanding, Second Tactical Air Force, "Siting of Gee Stations," 3 October 1944, and from Director General of Signals, "Gee Chains on the Continent—Preparation of Charts," 23 October 1944, both in NARA, RG 331, entry 276F, box 128, "SHAEF Air Staff, Air Signal Division, Radar Section, Numeric Subject File, July 1943–December 1944," and from Air Marshal, Air Office Commanding in Chief, 2nd Tactical Air Force, "R.N.A. Plans (Overlord and Eclipse)," in NARA, RG 331, entry 268, box 77, folder "Continental Gee and G-H Cover Plan." For ongoing plans and problems, see for example the loose minute from David Bruce, 10 April 1945, in NARA, RG 331, entry 268, box 77, folder "Continental Gee and G-H Cover Plan" or folder "Continental Cover Plan, GEE and G-H," in NARA, RG 331, entry 268, box 77.

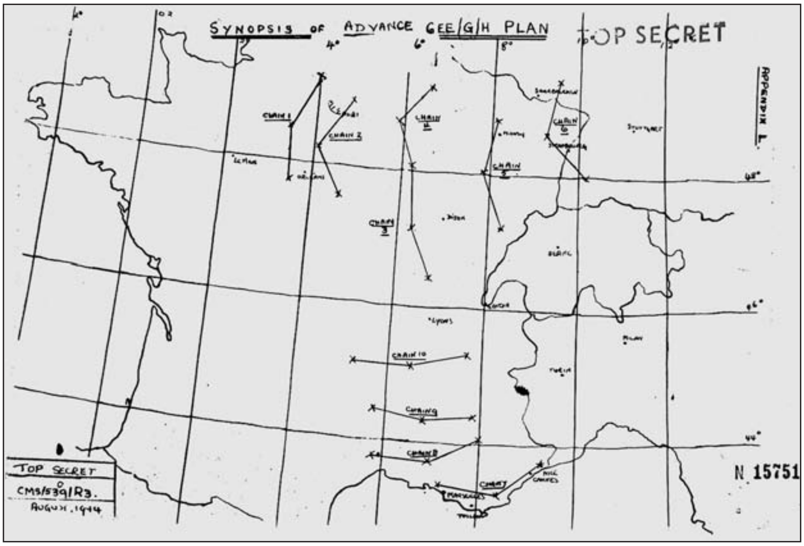

FIG. 13 Plan for advancing Gee coverage in France and Germany after D-day. Each set of open-jaw lines indicates one chain of three synchronized mobile Gee stations; chains would be moved east or north as territory was captured from the Germans. Of all the wartime grid-like systems, only Gee was made mobile; Loran, Decca, and Sonne used permanent installations. (Source: From "Advance Proposals for the Use of GEE and GH on the Continent," August 1944, in NARA, RG 331, entry 276F, box 128.)

but eventually abandoned for similar reasons.[52] Instead, the lesson is that radio waves were not rendered stable simply by virtue of certain metaphors, but because they were part of a complex system of paper charts, intensive calculation, accurate surveying, and difficult equipment. Moreover, the metaphor of the grid did not simply refer to the abstract idea of Cartesian rationality, but to a specific geographic configuration.[53]

The political neutrality of the wartime grids resulted from a similarly material set of concerns; it is best seen in the mutual appropriation of Sonne and Gee. Almost immediately after the British discovered the existence of Sonne in late 1943 by capturing a lattice chart, the arch-boffin Reginald Jones—who had earlier been responsible for intelligence against the German beams—suggested that instead of destroying the enemy transmitters, it would be better to find their precise location so that the British could issue their own set of charts. The head of navigation for the British Coastal Command agreed, later saying that "what was good for the U-boat prey was invaluable for the hunters": if Sonne was helping German U-boats hunt Allied

52. See Pierce, McKenzie, and Woodward eds., *Loran*, 93–94, 182–86.

53. Compare specifically with Hommels's discussion of embeddedness in "Studying Obduracy in the City."

ships, then the system—once rebranded as "Consol" to strip it of its Teutonic associations—would help the Allies hunt the U-boats in turn.[54] As the war progressed, the British made an ongoing effort to keep Sonne/Consol as a mutually beneficial aid. For example, when the Germans modified one of their transmitters so that it would no longer give coverage over German territory, it was promptly bombed by the United Kingdom—and subsequently rebuilt in its original configuration. And when a station in Spain began experiencing maintenance problems, it was the British who supplied the spare parts. After the war, Watson-Watt described Consol as a "delightful product of German–British co-operation."[55]

The Germans ended up reaching a similar conclusion with Gee. Although they began jamming Gee transmissions over Germany soon after they discovered the system in August 1942, the British subsequently developed anti-jamming countermeasures and had largely restored the system to full use by the middle of the next year. Beginning in late 1943, however, the Germans reversed their strategy and began taking steps to exploit (and likewise rename) the system for their own use, including manufacturing more than a thousand of their own receivers and building new ground stations in Poland and western Russia.[56] Both Britain and Germany continued to deploy countermeasures wherever possible, but by the end of the war such measures were increasingly selective. In early 1945, for example, British pilots found that their Gee sets were being jammed by directional antennas, and rather inconsistently at that.[57]

Thus even during the war, the politics of radionavigation were more nuanced than they might first appear. The obvious effect of the war was that radionavigation was reimagined as a way to project geographic legi-

54. Dickie Richardson, *Man Is Not Lost*, 233–34. Jones, "Navigation and War," 14.

55. Quote from "Closing Speech by Sir Robert Watson-Watt," in "Report on International Meeting on Radio Aids to Marine Navigation, London, 1946," in NARA, RG 43, "International Meeting on Marine Radio Aids to Navigation," box 8, folder "Jansky Papers," iv. The bombing and rebuilding is described in a letter from Sven Pran (a Swedish radio engineer) to Jerry Proc, http://jproc.ca/hyperbolic/consol.html (posted December 2008); this letter also mentions the repair of the station at Lugo, Spain. See also Blanchard, "Air Navigation Systems, Chapter 4," 312. The modifications required to give asymmetric coverage are described in A. H. Brown, "The Consol Navigation System," 973–74.

56. For German jamming and British countermeasures, see UK Ministry of Civil Aviation, "An Outline of the Technical Performance of the 'Gee' Radio Navigation System During the War of 1939–45," 3. The Germans did continue to try to jam Gee in certain areas—Normandy, for example—but British bombing of jammers and use of alternate frequencies thwarted these efforts; see R. A. Smith, "Radar Navigation," 335. For German plans for Truhe (a code name meaning "storage chest"), see "Radio Navigation Systems and Equipment," 15f, 26. The associated ground equipment was known as Bodentruhe; see Trenkle, *Bordfunkgeräte*, 134–37.

57. Col. Talbot (of IX Bombing Division), "Oboe and Gee Jamming," 14 March 1945, in NARA, RG 331, entry 276F, box 131, "SHAEF Air Staff, Air Signal Division, Radar Section, Numeric Subject File, July 1943–December 1944."

bility into areas beyond the traditional limits of territorial control. German beams, Allied measuring systems, and electronic grids were all means to this invasive goal, and all these systems ignored the clean national/international dichotomy that had structured the distinction between the Radio Range and D/F. At the same time, however, it is difficult to clearly distinguish military from non-military goals. There was no sharp line, for example, between wartime reconnaissance and postwar mapping: the same systems were used in the same way both before and after 1945. The politics of electronic coordinates were even more ambiguous, since even though they gave a clear advantage to their sponsors, the overall geographic result was to reduce spatial friction for aggressor and defender alike. As early as 1943, Robert Watson-Watt began convening Commonwealth-wide conferences to position Gee and other British systems as civilian technologies for commercial shipping and aviation. The designers of Loran made similar moves, with the U.S. Navy, for example, issuing a pamphlet just before the fall of Japan that advertised its system to an international audience and made it clear that its coverage would only expand in the years to come.[58] By the end of the war, not only were radiomapping and navigation both positioned as non-aggressive technologies, but both had also acquired an institutional momentum that transcended any immediate military goals.

After the War: Technological Proliferation and Geographic Unification

By the end of the war, there were thus four main ways that radio waves were understood as geographic entities: they could be a kind of railroad, a kind of light, a measuring rod, or an enormous grid, depending on the circumstances. And there were dozens of different devices that supported these interpretations. In the decades after the war, radionavigation (and radiosurveying) technologies continued to proliferate, with new systems created for each new task and new user group. The proliferation of systems and users, however, did not lead to spatial fragmentation, but instead to large-scale spatial unification. It also led to the abandonment of strong guiding metaphors and rendered radio increasingly invisible.

How did this diversity of applications, user groups, and metaphors add up to a coherent (and seemingly *un*thingy) transnational whole? Again, the advent of GPS in the 1970s makes it tempting to see a kind of techno-political zeitgeist pointing to the multifunctional global service we know today,

58. For the first and second Commonwealth and Empire Conferences on Radio for Civil Aviation, see "C.E.R.C.A." A third such conference was held in August 1945, chaired by Watson-Watt; its final report was filed as ICAO doc. 409, in ICAO, box "PICAO–Documents (1945–46): 401–1800." Glossy pamphlets explaining the postwar virtues of Loran were available in August 1945. See U.S. Navy, "Loran: Long Range Radio Navigational Aid," August 1945, in ICAO, box "Com—Sub. 1, 2, & 3: 1945–1949."

and the appeal of a single technological system seems obvious in hindsight. But in the 1950s and 1960s the trajectory was quite different. Instead of technological convergence toward something like GPS, the reigning sensibility circa 1970 was to promote translation between different systems. This was a both/and solution: it preserved the benefits of customization while adding the virtues of redundancy and flexibility. And while there were certainly agencies and individuals—especially, but not exclusively, in the United States—making a concerted effort to promote comprehensive transnational or global solutions, many of the strategies pursued by the United States (and the United Kingdom) did not in fact succeed; indeed, it was the very lack of any dominant technological or political hand that encouraged coordination and the creation of hybrid technologies.

This overall trend is apparent in both postwar navigation and postwar mapping. In both cases, there was no longer a clear one-to-one match between specific technological systems and different political-geographic projects. The same radio system could be used for local, national, or transnational ends, while the same geographic area could be covered by several systems at once. The resulting overlaps were thus ripe for exploitation, as different groups each saw how their own project could benefit by being connected to their neighbors'. Technological integration also ended up weakening familiar physical metaphors and emphasizing the uses of radio instead of its geography. The result was spatial integration without any clear directing hand.

In navigation, the main struggle of the postwar years was one of international standardization, and officials from dozens of countries met regularly to try to reduce the number of competing navigational systems. These debates took place everywhere from one-off marine-navigation conferences to the periodic meetings of international organizations, especially NATO, ICAO (International Civil Aviation Organization), and the ITU (International Telecommunications Union). In theory, the goal was to have a debate about "technical merits" and reach harmonious agreement about the one best system for each major navigational task, with as much overlap between ships and aircraft as possible.[59] In practice, however, these negotiations were not driven by discussions of precision, coverage, or multifunctionality, or even by the overarching logic of railroads, oceans, or grids. Instead they mostly consisted of officials from the United States and the United Kingdom pushing for their own homegrown systems—systems that had cost millions of dollars and were already installed in thousands of

59. For marine meetings, see R. B. Michell, "The Second International Meeting on Radio Aids to Marine Navigation." For frequency standardization, see, for example, records of the Special Administrative Conference for the North-East Atlantic, January–February 1949, in PRO, MT 9/5133, "LORAN Conference, Geneva, January 1949." For specific use of "technical merits," see testimony of Watkinson in *Parliamentary Debates*, col. 383.

ships and aircraft. American officials, for example, pushed not only for the successor to the Radio Range—the path-laying VHF Omni-Range (VOR)—but also for the expansive grid of Loran. The British advocated not just for the grid coverage of Consol (which they had completely appropriated from the Germans) and their own Decca system (which outperformed Gee in almost all respects), but also for a Decca-derived path-guidance system known as Dectra (DECca TRAck) that spanned the North Atlantic.[60] Much of this competition was driven by the lure of international markets for navigational equipment. For example, one of the most vigorous proselytizers of British systems was Robert Watson-Watt; in 1946 he reported to the Ministry of Transport that his overall goal was nothing less than "making the world fly and sail British"; at stake was "our exports and our prestige." In his memoirs, he described the Anglo-American struggle as "the cold war of radio aids."[61]

Some international standardization did in fact take place, especially for safety-critical systems in harbors or near airports, but for the most part agreements were partial at best. If anything, the protracted battles and messy compromises only encouraged greater pluralism. For example, one of the greatest U.S.–UK confrontations was the 1959 showdown at ICAO over "short-range" navigation equipment, with the American VOR pitted against the British Decca. The triumph of VOR—which the British press called a "débâcle" that might even threaten the legitimacy of ICAO—did indeed lead to international dominance of the American system in civil aviation. But it also pushed the Decca Navigator Company to focus more aggressively on the coastal marine and helicopter markets that it soon came to dominate.[62] Similarly, NATO's official adoption of Loran did little to alter the allegiance of commercial fishers to Consol. The result was that all systems continued to expand. By the 1970s Consol transmitters were installed not just in western Europe, but in the United States and the USSR as well. Figures 14 and 15 show the expansion of Decca and Loran

60. The main forum was the standing COM committee at ICAO, but there was also a special conference to discuss short-range aids in particular; see ICAO, boxes SP/COM/OPS/RAC and COM-1 through COM-7.

61. First quotes from Robert Watson-Watt, "Radio Aids to Air and Sea Navigation," 12 July 1946, in PRO, MT 9/4457, "Radio Aids to Marine Navigation: Proposal for a Combined GEE/LORAN (GLORAN) System for Marine Use"), and "Gee," December 1946, in PRO, BT 217/323; last from Watson-Watt, *The Pulse of Radar,* 340. For equipment-market strategy in the United States and United Kingdom, see "Minutes of a Meeting Held in Inveresk House at 1500 hours," 15 April 1946, or Watson-Watt's minute of 29 March 1946, both in PRO, BT 217/323. See also Blanchard, "Another Look at the Great Area-Coverage Controversy of the 1950's," 349–63.

62. For quote, see "Short Range Aide-Memoire," 733. For the existential threat to ICAO, see "Britain Accepts DMET." On Decca for helicopters, see J. G. Adam, "Decca for Helicopter Operations." For Decca on ships, see Claud Powell, "The Decca Navigator System for Ship and Aircraft Use," 225.

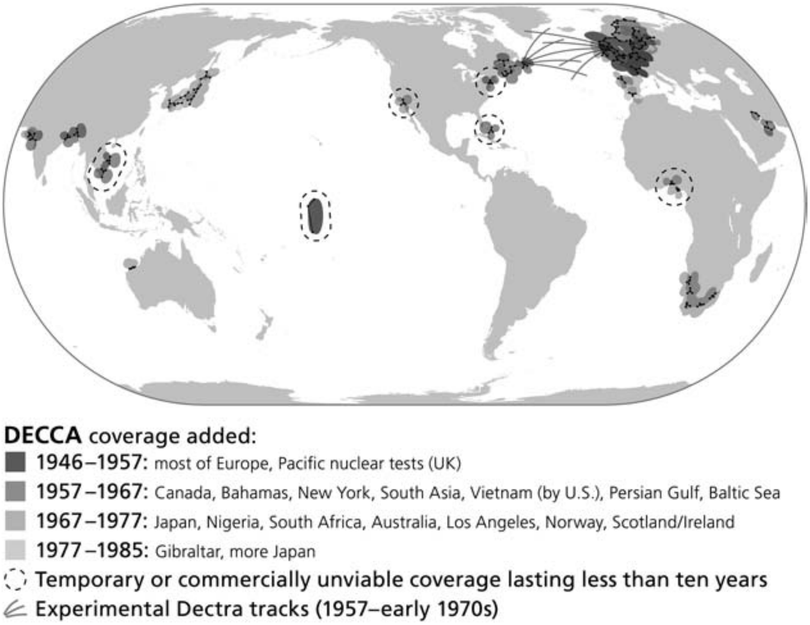

FIG. 14 Expansion of Decca coverage in the decades after World War II. By the time of the ICAO standardization meeting in 1959, Decca was installed throughout Europe and in eastern Canada and was in use for both civilian shipping and aviation. After the United States blocked its adoption as an international standard for aviation, it nevertheless continued to expand for helicopter and maritime use. The U.S. military even used Decca to guide its helicopters in Vietnam. (Sources: Map by the author; station locations from a database maintained by Jerry Proc, derived mostly from *Decca Navigator News*, available at http://jproc.ca/hyperbolic/decca_chains.html. For coverage diagrams of Europe, Canada, and the Persian Gulf, see International Hydro-graphic Bureau, *Radio Aids to Maritime Navigation and Hydrography*, section II.3. For Japan, see Kazuo Taguchi and Kazuo Sao, "Errors of Decca LOP Due to the Metal Structure of a Ship," 59. Other coverage bubbles from Jerry Proc, at website above. Dectra tracks from Thomas D. Johnson, "Status of Dectra," 305.)

during the same time. Together the major systems ended up offering massively duplicated coverage, especially in those areas with the most international traffic.[63]

This logic was only reinforced by the development of ever more new systems in the 1950s and 1960s. Most of these were developed by private companies and offered only incremental improvements in heavily traf-

63. For use of Consol by fishing fleets, see J. C. Farmer, "Survey of Long-Range Radio Navigation Aids," 219. For stations, see Ernst Kramar, "Consol and Consolan," 31, and Geoffrey Edward Beck, *Navigation Systems*, 113. The U.S. stations were slightly different in design and were known by the name "Consolan."

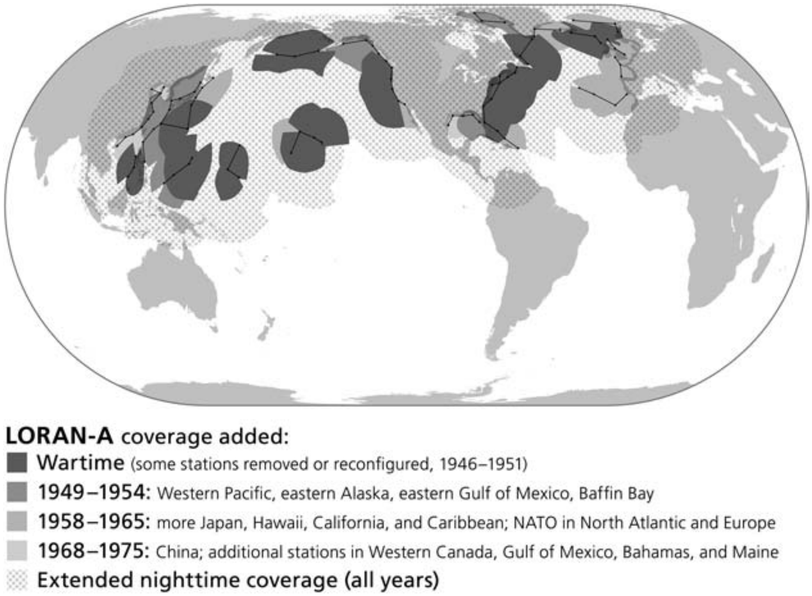

FIG. 15 Expansion of Loran coverage after World War II (known as Loran-A to distinguish it from later versions, especially Loran-C). Coverage in North America and the Pacific did not change much after the war, except for new stations near Japan added in the early 1950s. The biggest expansion was in western Europe, sponsored by NATO. (Source: Map by the author; station locations from a database maintained at http://loran-history.info/Loran-A/Loran-A.htm; coverage following International Hydrographic Bureau, *Radio Aids to Maritime Navigation and Hydrography*, section II.2; coordinates for the 1970s Chinese stations, which were independent of any U.S. or NATO plans, from "Loran-A Is Alive and Well," 47.)

ficked areas. By the early 1960s, for example, there were six separate aids in use by aircraft flying across the North Atlantic, with other, more experimental proposals presented regularly at ICAO.[64] At the same time, military sponsorship led to systems with much wider geographic reach. The U.S. Navy developed two systems with fully global coverage, both of which were eventually opened to civilians: a satellite system known as Transit (designed for Polaris submarines) and a terrestrial system called Omega.[65]

64. These experimental systems included Navaglobe, Navarho, Dectra, Delrac, Radio Mailles, Radux/Omega, and Loran-C. They were presented widely in navigation journals and discussed in "Report of the Sixth Session," October 1957, doc. 7831, in ICAO, box "COM-6, 1957."

65. For introductions to Transit, see R. B. Kershner and R. R. Newton, "The Transit System"; Thomas A. Stansell Jr., "The Navy Navigation Satellite System"; Stansell Jr., "The Many Faces of Transit"; Helen Gavaghan, *Something New under the Sun*, 47–126. For Omega, see Eric R. Swanson, "Omega"; J. A. Pierce, "J. A. Pierce and the Origin of Omega," in HUARC, HUG(B)-P461.4; J. A. Pierce, "Memoirs of John Alvin Pierce";

Similar geographic freedom was made possible by the maturation and subsequent civilianization of so-called "self-contained" aids—namely Doppler and inertial navigation—that did not rely on ground installations or outside signals at all. These were a radical alternative to traditional radionavigation, and they were especially useful for intercontinental travel.[66]

The appeal of combining signals from multiple systems was thus both technological and political, and the geographic result was additive rather than fragmentary. Combining radionavigation with self-contained aids was especially appealing, and soon after commercial Doppler first appeared in the late 1950s, several companies (especially Decca) developed special equipment that could give pilots their location as a line traced on a map, with the navigation systems themselves—along with any hyperbolic grids or radio beams—rendered invisible. By 1970, this kind of "integrated navigation" was commonplace.[67] The political payoff came very quickly. In 1965, for example, the promise of combining Doppler, Loran, and Consol led to détente at ICAO, where the United States and the United Kingdom signed a joint resolution stating that there was now "no requirement for a world standard" for these long-distance systems.[68] In 1969, a Norwegian military officer put this in more straightforward terms, explaining his country's simultaneous endorsement of both Decca and Consol by arguing that "there is not any real need to limit the number of systems, as long as each system adds something valuable."[69]

These sentiments were echoed throughout Europe and North America, and at ICAO they formed the backbone of a new "underlying philosophy"

Walter F. Blanchard, ed., "Technical Extracts from the Memoirs of Dr. J. A. Pierce"; Peter B. Morris et al., *Omega Navigation System Course Book*.

66. For the history of self-contained navigation, see Jones, "Navigation and War," 21–23, R. B. Horsfall, "Stellar Inertial Navigation," 106; William J. Tull, "Doppler Navigation"; H. Hellman, "The Development of Inertial Navigation"; Donald MacKenzie, *Inventing Accuracy,* chapter 2. For its commercialization, see reports on Doppler by the United States and United Kingdom in "Report of the Sixth Session," October 1957, doc. 7831, in ICAO, box "COM-6, 1957," pp. VII-103 to VII-148; Richard Witkin, "Aviation"; "Navigation—Inertial Portents"; "Doppler in Practice"; Joseph F. Galigiuri, "SGN-10 First Commercial Inertial Navigator"; Alexander B. Winick, "Air Navigation Trends," 79.

67. For early map interface development, see E. R. Wright, "The Use of the Flight Log." For integration in general, see A. Stratton, "The Combination of Inertial Navigation and Radio Aids." For Decca systems in particular, see Claud Powell, "An Elementary Compound System"; M. G. Pearson, "The Use of an Airborne Digital Computer in a Compound Navigation System"; "Decca Developments"; Blanchard, "Another Look at the Great Area-Coverage Controversy of the 1950's," 357. For similar solutions for Loran, see Loren E. De Groot, "Loran-Inertial Navigation Systems for Long-Range Use." For ubiquity by the early 1970s, see P. M. Grindon-Ekins, "The Impact of Digital Computing," or R. A. Severwright, "The Impact of Special-Purpose Computers on Aircraft Equipment."

68. "Report of Committee C to the Conference on Item 9," 19 November 1965, doc. AN Conf/4-WP/75, in ICAO, "box AN-Conference 4," page 9-2.

69. Bjørn A. Rørholt, "Electronic Aids to Navigation for Fishing Vessels and Other Open Sea Users," 248.

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of navigation known simply as the "systems approach"—an approach soon taken up in marine circles as well. As explained by an American engineer in 1969, its basic lesson was that "no one piece of equipment is the answer"; what mattered was overall navigational capability, not the geography (or materiality) of any specific system.[70] Urban helicopter pilots and nuclear submarine captains could each have their own custom solution, and yet together these could be combined to create a relatively seamless, invisible global infrastructure. This was not the smooth homogeneous space of GPS, but it was technologically robust, politically legitimate, and geographically expansive.

The postwar use of radiosurveying followed a similar logic, but without any lengthy battles over standards or the same need to amortize wartime investment. Although radio continued to support the kind of aerial photography and hydrographic surveys pursued during the war—Decca, for example, was used for difficult surveying everywhere from the Sahara to Greenland, and surveying quickly became the *only* use for Oboe and the related H systems—its postwar significance lies more in the advent of two major new strategies, both of which extended traditional surveying well beyond the edges of continents.[71]

The first technique was high-accuracy geodetic measurement, and here the American Shoran was unique among the new systems. Shoran continued to be used as a blind-bombing system—especially during the Korean War, where it knocked out dams, rail lines, and other precision targets—but it had a much longer life as a survey tool.[72] It was especially useful for measuring the distance between widely separated ground stations; as long as both ground stations could see the same airplane at the same time, their spacing could be measured within a few feet. By measuring the distances between a large network of points, Shoran could thus be used for high-precision surveys in areas where traditional triangulation would have been either instrumentally or economically impossible. (Because this technique relies on distances rather than angles, it is known as "trilateration.") Shoran was used to map the vast expanse of northern Canada in the late 1940s and 1950s, and its later, even-higher-accuracy cousins Hiran and Shiran became the preferred tool for connecting the previously separate surveying networks of North America and Europe. Figure 16 shows the extent of these projects through the 1960s.[73]

70. For ICAO, see "Report of Committee C to the Conference on Item 9," page 9-1; for marine "systems approach," see Nicholas S. Christopher, "Marine Integrated Navigation System," 419.

71. For use of Decca, see Powell, "Early History of the Decca Navigator System," 208, and Claud Powell, "Radio Aids to Surveying," 91. For Oboe and H-systems, see note 41.

72. Conrad Crane, "Raiding the Beggar's Pantry," 909, 917. For a discussion of some of the problems associated with Shoran in Korea, see Daniel Kuehl, "Refighting the Last War," 95–100.

73. Shoran work in Canada was very well publicized within the survey profession;

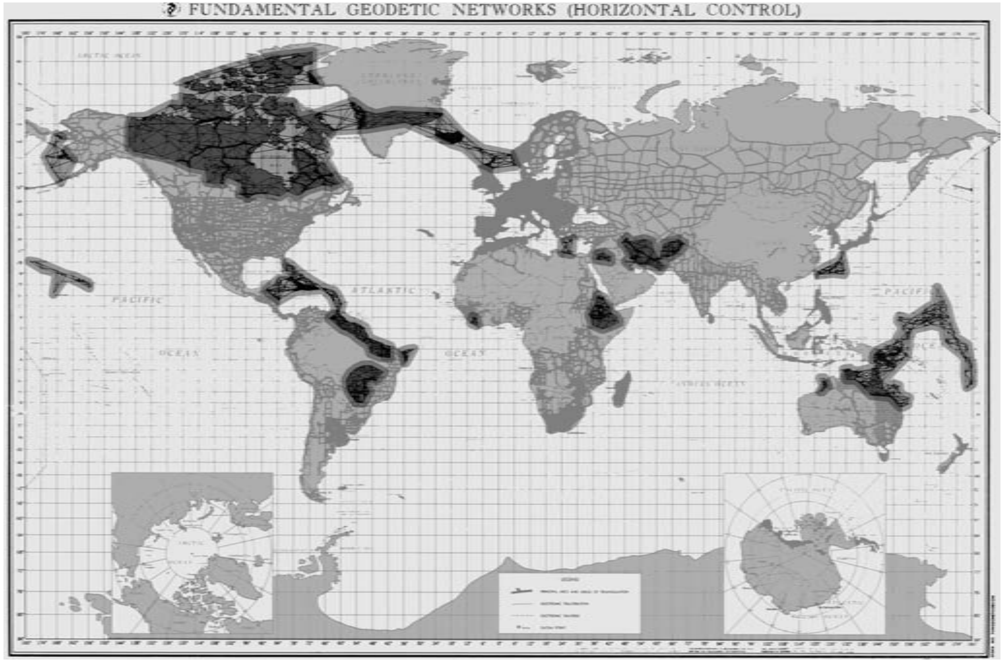

FIG. 16 Radio trilateration performed in the 1950s and 1960s, shown with dark shade. Trilateration was at times used for domestic surveying —as in Canada, Brazil, and Ethiopia—but it was mostly used to bridge gaps between existing survey systems and to connect far-flung islands to the mainland. The majority of this work was either performed or supervised by the United States. The connections in the North Atlantic and Caribbean were especially important for the recalculation of the shape of Earth for long-range missile guidance. Locating small Pacific islands was also important, since these islands were home to radionavigation transmitters. (Source: Map dated 1971 from Defense Mapping Agency, *Geodesy for the Layman*, 18; shading added.)

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The politics here were a blend of domestic consolidation and U.S. military globalism. Although some countries sponsored trilateration surveys for purely internal reasons, the majority were undertaken with the support of geodesists at the U.S. Army Map Service, who were engaged in constructing a unified global coordinate network for aiming long-range guns and intercontinental ballistic missiles. The army supported not just obviously transnational projects like the link across the North Atlantic, but national ones as well, since these national projects often filled conspicuous holes in the larger international network. (The double-edged nature of this support did not go unnoticed by the countries receiving help. At a survey conference in 1951, for example, a British official working in Africa noted that in the era of "atomic war-heads and guided missiles . . . happy is the country" whose surveys cannot be rectified to fit the American system.[74])

The second technique was the smaller-scale application of radio to offshore exploration. Throughout the 1950s and 1960s, various companies in the United States, France, and the United Kingdom (including, again, Decca) developed specialized systems for hydrographic mapping and oil prospecting on the continental shelf. These systems were portable, affordable, and much more accurate than their wartime predecessors: they could locate (and re-locate) points within a few meters, even well out of sight of land.[75] Taken together, the overall effect of these systems was that the oceans ended up being treated as simple extensions of continental territory, in both a rhetorical and a political sense. Rhetorically, these systems were seen as creating fixed, durable landmarks in the otherwise featureless ocean, similar to the electronic grids of World War II. This materiality was often quite explicit, as in the surveying advertisements shown in figures 17 and 18.[76] The new systems also allowed much faster collection of reliable depth soundings, and this huge increase of underwater data meant that the

see J. E. R. Ross, "Shoran Triangulation in Canada"; Ross, "Shoran Operations in Canada"; Ross, "Canadian Shoran Effort, 1949–1953." On the use of Hiran and Shiran, see Carl I. Aslakson, "The Influence of Electronics on Surveying and Mapping"; B. B. Hunkapiller, "Aerial Electronic Surveying"; Richard B. H. Shepherd, "Shoran and Hiran in Geodetic Surveying," 4 September 1958, *Notes of the Week*, Tokyo: US Army Map Service, Far East, manuscript papers in NOAA library; Simo H. Laurila, "Across the Jungle by Hiran"; E. M. Salkeld Jr., "Development of a Precise Geodetic Survey System."

74. H. H. Brazier comment in Floyd W. Hough, "The Universal Transverse Mercator Grid," 69.

75. Sea-Fix and Hi-Fix were developed from Decca, and EPI was a cross between Shoran and Loran; see Clarence A. Burmister, "Electronics in Hydrographic Survey." The new systems (Raydist, Lorac, Rana, and Toran) were derived from a 1934 French patent that finally found life in the late 1940s. For details, see Charles E. Hastings, "The Application of Raydist to Hydrographic Surveying"; Seismograph Service Corporation, "Lorac"; Étienne Honoré and Émile Torcheux, "Les radionavigateurs Rana"; P. Laurent, "Toran."

76. For geodetic control at sea, see A. G. Mourad and N. A. Frazier, "Improving Navigational Systems through Establishment of a Marine Geodetic Range," or Andrew C. Campbell, "Geodetic Positioning at Sea."

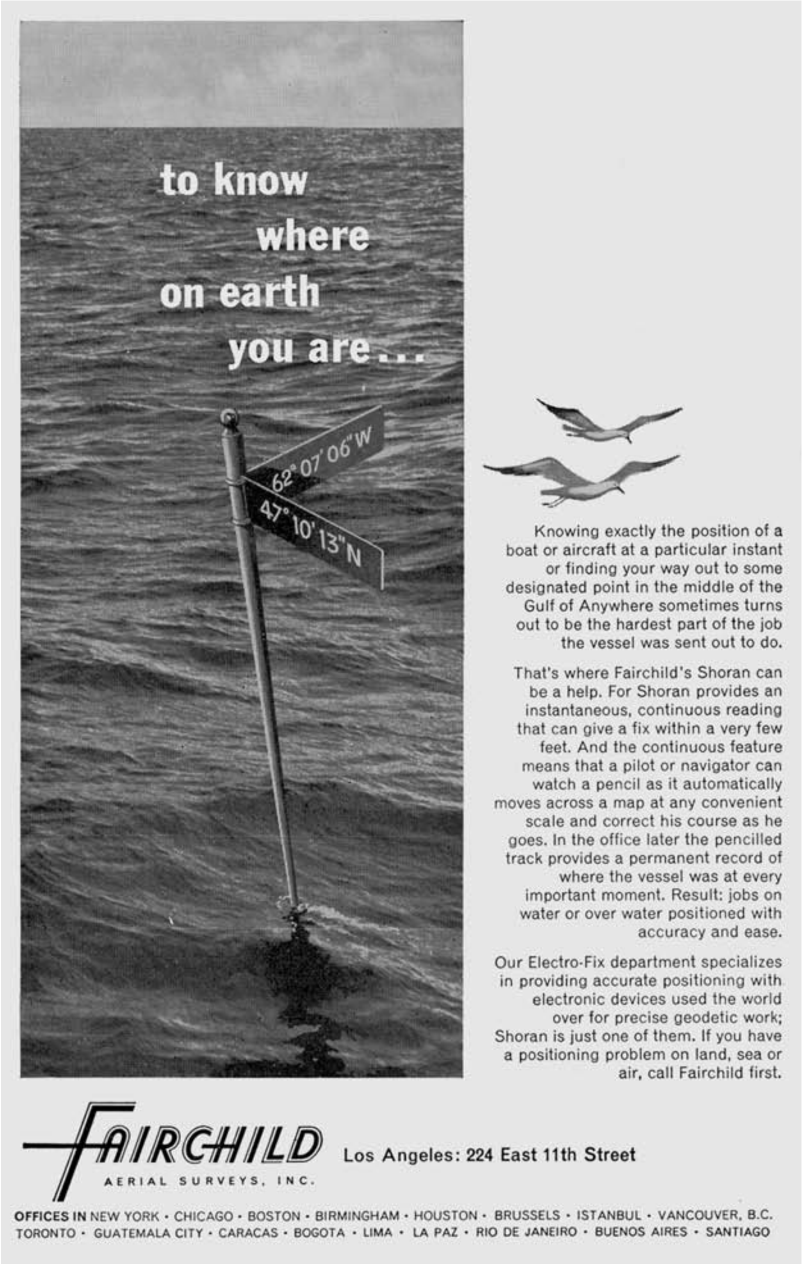

FIG. 17 The featureless oceans become as legible as the intersection of two city streets. This advertisement for offshore Shoran surveying promises instantaneous and continuous accuracy "within a very few feet," as well as automatic plotting of a ship's position on a map. (Source: *Surveying and Mapping* [March 1959], 141.)

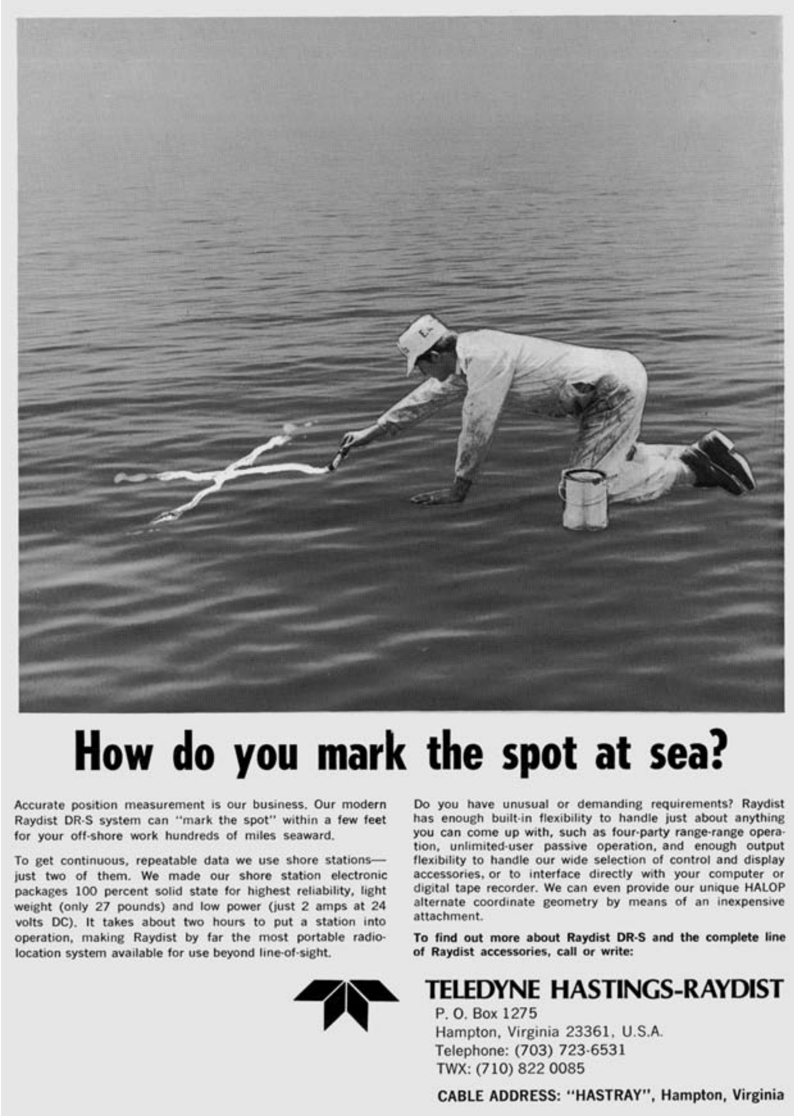

FIG. 18 The surface of the sea made solid and ready for inscription. More than a decade after the advertisement shown in figure 17, the novelty and importance of extending precision surveying beyond the sight of land had not lost its appeal. The promise is again for accuracy to "a few feet." (Source: *Navigation* (U.S.) 18, no. 3 (fall 1971), inside cover.)

seafloor could often be shown on maps with the same detail and visual language used for land. Not only did mariners compare the contours and coloration of their updated charts explicitly with topographic maps, but the 1950s also saw the advent of new scholarly projects that showed underwater features using the kind of hand-drawn relief typically used for mountain ranges. The most famous of these, the shaded-relief map by Marie Tharp and Bruce Heezen that ended up being used to support the theory of plate tectonics, was co-sponsored by the U.S. Navy and AT&T.[77]

Politically, radio coordinates were closely connected to the aggressive postwar expansion of national territorial claims to the ocean. President Truman was the first to flaunt the traditional three-nautical-mile limit of a country's territorial sea when he declared sovereignty over the American continental shelf in 1945; a few years later several countries in South America made similarly ambitious claims to fishing rights within 200 nautical miles of shore.[78] These grand claims did not necessarily require radiosurveying, but as they became codified in the UN Convention on the Law of the Sea—first in the late 1950s, then more aggressively in the early 1980s—reliable electronic coordinates became crucial for policing fishing zones and partitioning oil and gas discoveries (especially, as it turned out, in the North Sea).[79] The terrestrial logic of precisely surveyed, hard-edged boundaries was thus extended deep into the ocean, provoked by a political-geographic synergy between offshore coordinates and offshore revenue.

Taken together, geodetic trilateration and offshore surveying were pursued by very different actors for very different reasons, but all these projects shared a common goal: connecting new surveys to existing networks. Offshore oil surveyors connected the continental shelf to national land-based networks; national governments connected their coordinates to their neighbors'; and the Army Map Service bridged continents. Unlike tradi-

77. For comparison of nautical charts and topographic maps, see G. D. Dunlap, "Major Developments in Marine Navigation during the Last 25 Years," 76. For underwater relief, see Ronald E. Doel, Tanya J. Levin, and Mason K. Marker, "Extending Modern Cartography to the Ocean Depths," or Naomi Oreskes, *The Rejection of Continental Drift*, 267f (the cover of which shows a very similar shaded-relief map).

78. See S. N. Nandan, "The Exclusive Economic Zone"; Lewis M. Alexander, "The Expanding Territorial Sea"; FAO Legislation Branch, "Limits and Status of the Territorial Sea, Exclusive Fishing Zones, Fishery Conservation Zones and the Continental Shelf." For the continental shelf in particular, see A. D. Couper, "The Marine Boundaries of the United Kingdom and the Law of the Sea."

79. At the 1958 United Nations Conference on the Law of the Sea meetings, radio location was seen as sufficient grounds for initiating "hot pursuit"; see comments by Denmark in UNCLOS Document A/CONF.13/5 (5 August 1957), 81, and the United States in A/CONF.13/C.2/SR26-30 (8 April 1958), 80, in volumes 1 and 4 of *United Nations Conference on the Law of the Sea*. In the late 1970s, every meter of error in the maritime boundary between the United Kingdom and Norway was said to translate to two million dollars of natural gas; see T. C. Haile, "Political Aspects of the Charting of the Seas," 66.

tional municipal or national surveys, these projects did not end at jurisdictional boundaries and did not create stand-alone survey systems. (The translation of different surveys into the universal language of latitude and longitude also erased the metaphorical scaffolding of yardsticks, street signs, and paint.) The geographic result, again, was not a perfectly homogeneous global space; it was instead a hierarchical space with a relatively smooth continuity between the U.S. military's global project and the smaller geographic reach of other groups' interests.

Radionavigation and radiosurveying can thus be seen as two parts of the same geographic transformation. The expansion of radionavigation created a new kind of transnational transportation infrastructure, while radiosurveying expanded the reach of precision mapping (and thus territorial legibility) into that same transnational space. In both cases, previously unbridgeable or ungovernable spaces became concrete, calculable, and claimable. At the same time, radio was also changed, as the previously distinct technological frames of railroads, grids, and yardsticks all ended up blurring into a diffuse soup. Characteristics like permanence and political neutrality were still important, but radio itself was increasingly dematerialized.

Comparing the radio landscape of the 1960s to the later logic of GPS, the point is not to say that GPS added nothing new, but to be precise about what GPS did in fact represent. It is no surprise that GPS was not the first radio-location system that was global, hyper-precise, or useful for both surveying and navigation. And the fact that GPS combined all these things into one user-friendly technological apparatus is of course terribly important, especially when considering the economies of scale that allowed GPS receivers to become so cheap, ubiquitous, and culturally visible. The difficulty, however, is that GPS is often seen as inaugurating a new geographic politics, and these politics are seen as self-evidently related to its American military origin. But the history—and politics—of things like transnational legibility and invisible infrastructure are more profound than implied by this easy association. The kind of geographic system associated with GPS emerged in the decades after World War II as a complex mix of purposeful design, messy compromise, and the physical properties (and changing interpretations) of radio. This radio landscape was not just an instrument deployed for certain clearly defined military ends; it was instead a reconfiguration of geographic relationships of all kinds—economic, political, and military alike.

Conclusion: Intangible Artifacts and Geographic Power

How, then, should we understand the geographic significance of radionavigation? And what lessons does radio hold for other intangibles? A list of intangible artifacts would be a diverse array indeed. It would include not just electromagnetic radiation of all kinds (from X-rays and radio to light pollution and nuclear fallout), but also a wide range of gases, toxins, and other miscellaneous invisibles—everything from soot, carbon dioxide, or microbes to electric and magnetic fields, urban noise, and noxious odors. What distinguishes these intangibles from their more material cousins, and what do their common qualities imply about their politics?

There are two commonalities I want to highlight. First, all these phenomena are typically characterized as having a temporary, fleeting presence in the world. Indeed, their fleeting quality seems to be why, with only a few exceptions, they generally seem like poor candidates for thinghood. Gamma rays, toxic spills, and sonic booms are usually seen as *events* that happen to occur in a particular place, rather than as a defining feature of a landscape. There are certainly events so catastrophic or toxins so long-lasting that they scar a landscape for generations—Chernobyl, Bhopal, and Yucca Mountain, after all, are metonyms that conflate place, event, and hazard. But even less-lethal intangibles tend to have a remarkably persistent geography. Urban planners, for example, routinely treat the noise of a runway or the smell of a landfill as inherently spatial, since these features tend to last at least as long as buildings, bridges, or railroads. Unhappy citizens likewise do the same with late-night truck routes or high-voltage towers near schools. Yet the default tendency is still to enforce a conceptual division between a stable landscape of tangibles and an allegedly temporary configuration of sounds, smells, radiation, and so on. In particular, intangibles rarely appear on maps—certainly not on topographic maps that show "permanent" features—and simply revealing their "hidden" geography can be a subversive act in itself.[80]

The second commonality is that these intangibles are rather difficult to contain. They are promiscuous trespassers and boundary-crossers. It is almost cliché to say that problems like acid rain, CFCs, and nuclear fallout are "inherently international," and the ease with which radio could invade enemy territory was its primary advantage during World War II. But the boundary-crossing I have in mind is more profound. It is not just that intangibles cross boundaries, but that there is *always* misalignment between their fuzzy geography and more dominant forms of territoriality. From the scale of territorial states to the scale of individual property rights, our default spatiality is defined by clean edges and the promise of exclusive control. There are certainly legal mechanisms for addressing intangible artifacts—climate treaties, frequency-allocation rights, noise easements, etc.—but these exist exactly because of mismatches with standard legal geography. Again, intangibles are seen as the exception to the usual pattern, and they require special treatment.

It is these two qualities—one temporal, one spatial—that suggest a pol-

80. The definition of "permanence" used in topographic mapping is not only somewhat arbitrary, but can largely be seen as a reflection of the map sponsors' interests in military operations and civil engineering; see Denis Wood, *The Power of Maps*, 82–84.

itics of intangible artifacts. Their ambiguous permanence and incorrigible trespass allow an insidious kind of power: they are often a permanent occupation masquerading as a temporary event. Systems like Loran, Decca, or GPS can easily be seen as nothing but a spray of radio signals that leave no trace and violate no one's sovereignty. But even before a country's troops are on the ground or an international NGO starts distributing emergency aid, there is already a friendly infrastructure in place. The geographic power of radio waves—or gas, or noise—stems from exactly this tension: they can flicker between being invisible trifles and thick, thingy substance as the need arises, often inhabiting both states at once. And by *power* I do not mean just the ability to wield a new kind of spatial force, but the ability to reconfigure basic assumptions of geographic presence, occupation, and control.

What is the larger lesson here? It is certainly not that there is anything *inherent* about this clandestine mode of power. There is nothing that *requires* intangible artifacts to disrupt territorial control. The Radio Range, after all, was a strongly national project, and one of the main uses of offshore radiosurvey was likewise to stabilize national claims to the continental shelf. The lesson here is instead rather more historical. Analyzing radio is helpful not because it allows us to draw general relationships between intangibility and politics, but because it shows just how geographically present an intangible artifact can be, and also how malleable. Indeed, perhaps the main lesson is that referring to intangibles as things will always have a double resonance that evades any easy dichotomy. From one point of view, radio has always been a *thing*: it exists as a cultural artifact at the intersection of physical properties and human intentions. But we should also ask how intangible artifacts have (or have not) been *made thingy*—that is, visible, persistent, and obdurate—through language, law, or their entanglements with more conventional objects. The thingyness of most intangibles is usually suppressed, with invisibility often used as a convenient way to evade responsibility or to blur the line between accident and strategy. The thingyness of radio, however, was for many decades explicitly emphasized and exploited through analogies to railroads, grids, and yardsticks; only once radio systems began to overlap and merge did these railroads and grids cease to be discussed or shown on maps. Ultimately, one of the most important considerations with any intangible artifact is the possibility of ignoring its temporal and geographic presence altogether.

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