4-1994

French Optical Telegraphy, 1793-1855: Hardware, Software, Administration

Alexander J. Field
Santa Clara University, afield@scu.edu

Recommended Citation

Field, Alexander J. 1994. "French Optical Telegraphy, 1793-1855: Hardware, Software, Administration," Technology and Culture 35 (April 1994): 315-47.

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ALEXANDER J. FIELD

The relatively stable contribution of technological change to aggregate growth masks technological trajectories which are, at the sectoral level, often highly discontinuous. For decades, even centuries, the capabilities used to produce a particular good or service may continue essentially unchanged or with relatively minor evolutionary modifications. Sometimes without much warning a breakthrough innovation will create a new technological paradigm, along with an accompanying "gale of creative destruction," which is then followed by a period of consolidation within a maturing framework.

From this perspective, one of the more remarkable aspects of the 19th century was its simultaneous experience of an unprecedented and as yet historically unique breakthrough in the technologies of moving both goods and information. The railroad and the telegraph were, in the words of H. D. Estabrook in 1913, the "Siamese Twins" of commerce.[1] Mutually dependent on each other, together they made possible enormous increases in the speeds with which materials and information moved through national and international distribution and production systems. These increases both required and made possible new managerial organizations and philosophies, and, at the enterprise level, increased the demand for middle managers in transportation and communication, in wholesale and retail distribution, and, selectively, in manufacturing.[2]

DR. FIELD is the Michel and Mary Orradre Professor of Economics and associate dean of the Leavey School of Business and Administration at Santa Clara University. He gratefully acknowledges research support from National Science Foundation grant SES-8910985, as well as comments from the *Technology and Culture* referees and seminar participants at Harvard University, Stanford University, Northwestern University, and the University of California, Davis.

[1] H. D. Estabrook, "The First Train Order by Telegraph," *Baltimore and Ohio Employees Magazine* 1 (July 1913): 27–29, cited in Robert Luther Thompson, *Wiring a Continent* (Princeton, N.J., 1947), p. 204.

[2] Alfred Chandler, *The Visible Hand: The Managerial Revolution in American Business* (Cambridge, Mass., 1977); Alexander J. Field, "Modern Business Enterprise as a Capital Saving Innovation," *Journal of Economic History* 47 (June 1987): 473–85.

0040-165X/94/3502-0003$01.00

Whereas the economic impact of the railroad has received extensive attention, that of the telegraph has not. The "new economic history" was, if not inaugurated, then launched into self-sustained flight by the appearance in 1964 and 1965 of landmark volumes by Robert Fogel and Albert Fishlow.[3] Fogel's and Fishlow's use of the counterfactual to place a numerical value on the contribution of the iron horse to growth has done little to remove the railroad from the center of the 19th-century historiographical stage, in spite of the fact that their quantitative conclusions moderated the more grandiose claims of their qualitative predecessors.

The telegraph, in contrast, has largely vanished from that stage. Economic history textbooks written in the three decades from 1960 to 1990 make few references to the device, its inventors or implementers, or its economic impact.[4] In the view of authors of these texts, the invention and diffusion of the electromagnetic telegraph was apparently not crucial for the understanding of 19th-century growth and development.[5] This was not the verdict of contemporaries or of a previous generation of historians. In *The Transportation Revolution,* published in

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[3] Robert W. Fogel, *Railroads and American Economic Growth* (Baltimore, 1964); Albert Fishlow, *American Railroads and the Transformation of the Antebellum Economy* (Cambridge, Mass., 1965).

[4] See, e.g., Lance Davis, J. R. T. Hughes, and Duncan McDougall, *American Economic History* (Homewood, Ill., 1965); Louis M. Hacker, *The Course of American Economic Growth and Development* (New York, 1970); Lance Davis, Richard Easterlin, William Parker, et al., *American Economic Growth: An Economists' History of the United States* (New York, 1972); Gerald Gunderson, *A New Economic History of America* (New York, 1976); J. R. T. Hughes, *American Economic History,* 3d ed. (New York, 1990). The index of each of these volumes is innocent of references to the telegraph. Gary Walton and Hugh Rockoff devote one paragraph to it in *History of the American Economy,* 6th ed. (New York, 1990), p. 190, but this passage is a carryover (and reduced in length) from the third edition (New York, 1973; p. 136) of the Ross Robertson text of the same title, responsibility for which they had assumed. The neglect is not unique to American economic history. In the *Histoire économique et sociale de la France,* ed. Fernand Braudel and Ernest Labrousse (Paris, 1976), there is nary a mention of the telegraph; the same is true in François Caron, *An Economic History of Modern France* (New York, 1979). In David Landes, *The Unbound Prometheus: Technological Change and Industrial Development in Western Europe from 1750 to the Present* (Cambridge, 1969), Landes mentions the telegraph once, in a footnote on p. 284. Earlier texts, such as J. H. Clapham, *The Economic Development of France and Germany* (Cambridge, 1936), contain multiple references. See also the more extensive recent discussion in Joel Mokyr, *The Lever of Riches: Technological Creativity and Economic Progress* (Oxford, 1990), pp. 123–24; as well as pp. 126–32 in the latest edition of Sidney Rattner, James Soltow, and Richard Sylla, *The Evolution of the American Economy* (New York, 1993).

[5] One of the few American scholars in recent years to focus on the economic impact of the telegraph has been Richard DuBoff. See his "Business Demand and the Development of the Telegraph in the United States, 1844–1860," *Business History Review* 54 (Winter 1980): 459–79, and "The Telegraph and the Structure of Markets in the United States, 1845–1890," *Research in Economic History* 8 (1983): 253–77.

1951, George Rogers Taylor ranked the telegraph as an even more significant break with the past than was the railroad: "In an age of revolutionary developments in transportation and communication, perhaps the most drastic change resulted from the magnetic telegraph."[6] And to contemporaries, the innovation appeared every bit as remarkable, indeed perhaps even more remarkable, than its Siamese twin. This was especially true with respect to the completion of the transatlantic cables.[7]

While the telegraph has been neglected recently by economic historians, it figures prominently in Alfred Chandler's *The Visible Hand;* indeed Chandler accorded it an importance more in line with Taylor's assessment.[8] And political historians have been struck by its significance as a mechanism for political control. Daniel Headrick's studies of the technological underpinnings of the New Imperialism and the interconnections between telecommunications and international politics place considerable emphasis on the role of the telegraph.[9] The lack of interest in the telegraph among late-20th-century students of long-run growth may well be explicable and justifiable. But this lack of interest is nonetheless intriguing, particularly in the context of continuing interest on the part of business and political historians. It is at least possible that economic historians have overlooked important channels through which telegraphy contributed to long-run economic growth. This possibility underlies my interest in the consequences of investment in electromagnetic telegraphy in the 19th century.[10] Out of this enterprise emerged my interest in alternative technologies.

Evaluating an innovation's contribution to growth requires identifying the sectors which used it and identifying, within that group, those sectors or uses for which its services were most valuable from a macroeconomic perspective. Identifying which sectors made use of the

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[6] George Rogers Taylor, *The Transportation Revolution* (New York, 1951), p. 151.

[7] See Henry M. Field, *History of the Atlantic Telegraph* (New York, 1866), pp. 217–20; Vary T. Coates and Bernard Finn, eds., *A Retrospective Technology Assessment of Submarine Telegraphy: The Transatlantic Cable of 1866* (San Francisco, 1979).

[8] See Chandler (n. 2 above). Writing in part to counter the claims of progressive historians who criticized big business on the grounds that its sole raison d'être was the search for monopoly power, Chandler argued that modern business enterprises performed socially valuable as well as privately profitable functions. DuBoff, in contrast, emphasized the contradictory role of the magnetic telegraph in both breaking down and fostering monopoly power.

[9] Daniel R. Headrick, *The Tools of Empire: Technology and European Imperialism in the Nineteenth Century* (New York, 1981), pp. 157–64, and *The Invisible Weapon: Telecommunications and International Politics, 1851–1945* (New York, 1991), chaps. 1–6.

[10] Alexander J. Field, "The Magnetic Telegraph, Price and Quantity Data, and the New Management of Capital," *Journal of Economic History* 52 (June 1992): 401–13.

new technology, and to what degree, is not by itself sufficient, because that pattern will not necessarily reflect where a technology contributed most to growth. There are two distinct reasons for this. First, some utilizing sectors will reap extraordinarily high incremental levels of consumer surplus, whereas for others the additional surplus may be negligible.[11] The contribution to growth of a new technology is likely to be greatest where one observes a combination of extensive use of the new technology *and* large increments to consumer surplus. Second, usage, per se, is not an infallible guide to contribution to growth because, in some applications, the private gain to the first adopters of a new technology may substantially exceed the social (and private) return when access has broadly diffused. In such cases individual competition will generate high demand and high usage but, in the long run, relatively little net benefit to society.[12]

The study of alternate technologies is of little direct help in identifying instances of this latter type. In such cases, whether the service could have been provided by other means at slightly increased cost is of relatively little interest. The very existence of positive net benefits may be in question, and the more fundamental issue is likely to be whether society would have been better off had the invention not been available at all for that application and had the resources absorbed in its diffusion been otherwise deployed.[13] In most other applications, however, where society (and individual adopters) are better off as a consequence of wide diffusion, knowing whether the service could have been supplied by other means and at what increase in cost and/or degradation in performance is central to estimating the increment to consumer surplus made possible by a new innovation. Here, knowledge of alternate technologies is crucial. If we can identify available substitutes that would have been used had the new technology not been available, we can conclude, for example, that comparatively little additional consumer surplus was being reaped by users in that application.[14]

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[11] Whenever customers are willing to pay more for a good or service than they are actually charged, they reap consumer surplus.

[12] In extreme circumstances the net benefit may be negative. Military adversaries, e.g., are often worse off when they have all acquired a new weapon system, and the search for competitive advantage can sometimes produce the commercial equivalent of an arms race. Yet we must bear in mind these differences between war and commerce: in most instances competitive pressures to adopt new technologies lay the foundation for price wars, from which consumers benefit, in contradistinction to their fate in military conflicts.

[13] Economists have long maintained that, if the social rate of return exceeds the private return, government subsidies or other encouragement may be warranted. The logic of taxation or other restriction in the reverse case is simply the flip side of this argument.

[14] Market valuation reflects willingness to pay, but it does so only at the margin. Broccoli production valued at $100,000 must by definition be "worth" as much to the economy as

An examination of alternate technologies is therefore an important part of evaluating the economic impact of an ultimately triumphant innovation. From this perspective, the study of the contribution of electromagnetic telegraphy to economic growth leads inexorably to an examination of optical or aerial telegraphy. Where speed mattered, optical transmission was the closest available substitute for the electromagnetic telegraph. European technology and in particular the proven record of the French Chappe system lay behind the serious proposal put before the U.S. Congress in 1837 to build a semaphore system from New York to New Orleans. The motivations for this system were in part commercial, and many thought the project feasible and desirable. One of those objecting was Samuel F. B. Morse, at the time lobbying for a subvention to finance a demonstration of what he hoped would be a superior and more versatile device.[15]

Resistance must be overcome in thinking about optical systems as possible substitutes for those that were in fact built. Extinct or near-extinct technologies recede from our historical consciousness because that potential has, in the event, not been realized.[16] Optical systems could have and in fact were servicing some of the applications in which electromagnetic technology enjoyed its greatest commercial successes, implying on first consideration that the additional surplus reaped by customers on account of the availability of electromagnetic technology might have been relatively small. Nevertheless, the applications in which optical telegraphy was most competitive, including the transmission of financial market data, happened to be those in which the contributions to economic growth of faster transmission time (by whatever means) were most limited. These were applications in which the private return to first adopters far exceeded the social return when wide diffusion had occurred. In contrast, where electromagnetic technology contributed most to economic growth, in making possible the tight logistical control of complex transportation and distribution systems, optical telegraphy was a poor substitute. These conclusions, and their implications, are addressed in more detail at the end of this article. They represent a

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$100,000 worth of molybdenum, and the market tells us that there is no gain to be had from taking the resources used to produce the broccoli and redirecting them toward production of the mineral. If there are no close substitutes for the molybdenum, however, its purchasers may enjoy much greater consumer surplus from its availability than is the case for broccoli consumers, and the social saving from its availability may be much larger.

[15] U.S. House of Representatives, *Telegraphs for the United States: Letter from the Secretary of the Treasury Transmitting a Report upon the Subject of a System of Telegraphs for the United States*, 25th Cong., 2d sess., 1837, H. Doc. 15.

[16] Both Fogel and Fishlow had to overcome incredulity when they proposed canal and river transport as (imperfect) interregional alternatives to the railroad. See n. 3 above.

mixed verdict on the viability of optical systems as alternatives in electromagnetic applications and thus a mixed verdict on the commercial potential of optical telegraphy in the absence of Morse and his fellow innovators.

Electromagnetic telegraphy represented a qualitative breakthrough in long-distance communication, and it would be wrong to claim that we should study optical telegraphy because it was a close substitute across all economically relevant applications. From the standpoint of technological history, the significance of optical telegraphy appears to lie less in its obvious limitations than in the performance levels it did manage to achieve and, perhaps more important, in how it managed to achieve them. These systems deserve attention in their own right from the standpoint of information theory—in particular as a case study of how software and administrative design can overcome, at least in part, fundamental limitations in hardware.

Optical Telegraphy

If economic historians have devoted little attention to the electromagnetic telegraph, their attention to aerial or optical telegraphy has been almost nil.[17] Few American scholars are aware of the U.S. coastal lines, the British Admiralty telegraphs,[18] or, of more significance, the existence and capabilities of a communication network in France operating continuously from 1794 to 1855, a network which in the 1840s covered almost 5,000 kilometers, comprising over 530 relay stations within the current geographic borders of France. Born in the tumultuous years of the French Revolution and extended under Napoleon, the French optical telegraph system, unlike its British and other European counterparts, did not fade with the coming of peace. It continued to grow through the Restoration and under Louis Philippe. New lines were still being constructed in the 1840s when electromagnetic devices appeared as serious alternatives.

The transmission of messages over long distances was based on a system of relay stations, 8–10 kilometers apart, situated at high points on mountains, specially constructed towers, and church belfries. Manned by one or two operators (*stationnaires*) armed with telescopes, a station was topped by a strange assemblage of three movable arms connected to each other, and by brass wires, pulleys, and rods to controls below, such that each arm could be rotated freely through a

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[17] The French use the terms interchangeably; "optical" is the more common English term. Within these categories, my interest is principally in telescopically assisted semaphore systems.

[18] Geoffrey Wilson, *The Old Telegraphs* (London, 1976), chaps. 2 and 3.

common vertical plane.[19] These devices and their accompanying software made it possible, during daylight hours and under favorable atmospheric conditions, to send complex messages across France with a speed that was unrivaled by contemporary communication technologies.[20] Optical telegraph systems were also operated by the British Admiralty and by the Prussians, Russians, Swedes, Finns, Norwegians, Danes, Spanish, Portuguese, Australians, South Africans, and Americans in the first half of the 19th century.[21] But the French system—the Chappe system—was by far the most extensive and persistent, a coordinated achievement in the areas of hardware, software, and public administration.

During wartime, its reach was international: at the height of the Napoleonic period (1810), lines ran west from Paris to Brest, north to Amsterdam by way of Lille and Brussels, east to Mainz in Germany by way of Metz and Strasbourg, and southeast to Lyons and then across northern Italy to Venice by way of Milan.[22] Although confined within French territorial boundaries after 1815, the system continued to expand. The Paris-Brest line was extended north to Cherbourg and

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[19] Michel Ollivier, "Le mécanisme du télégraphe Chappe et son évolution," in *Proceedings,* Third International Colloquium on Aerial Telegraphy (Toulouse, May 1983, mimeographed).

[20] On the basis of evidence (ca. 1840) from the written record of transmission kept at various points on the lines (*procès verbal*), Étienne L'Hôpital concludes that twenty seconds is a reasonable approximation of the time required to compose and finalize (assure) an individual signal at a given post and that a half second is a reasonable approximation for the propagation of information from one station to the next. These conclusions are consistent with Edouard Gerspach's remark that "under exceptional conditions, with top flight operators, one could send three signals per minute" (Edouard Gerspach, "Histoire administrative de la télégraphie aérienne en France," originally published in several issues of the *Annales Télégraphiques,* Publiés par un comité composé de fonctionnaires de l'Administration des Lignes Télégraphiques, vol. 4 [May–June 1861]: 245). They permit one to estimate the time required, under favorable circumstance, for signals to move over a given line. The Paris-Lille line, e.g., had (eventually) twenty-two stations and therefore required approximately thirty-one seconds to send one signal (20 + 22/2). A transmission of thirty-five signals between Paris and Lille would, according to these assumptions, have taken approximately eighteen minutes. Comparisons of transmission times for complete messages are meaningless unless one specifies the number of signals and the number of stations on the line. Such estimates must also recognize the performance limitations associated with the likelihood of atmospheric disturbance, as well as limited daylight hours. For more detailed justification for the assumptions used above, see Étienne L'Hôpital, "Les messages Chappes et la théorie de l'information," in *Proceedings,* Sixth International Colloquium of the FNARH (Fédération Nationale des Associations de Personnel des Postes et Télécommunications pour la Recherche Historique) (Montpellier, 1989): 2:10–11.

[21] Wilson provides an international survey of optical telegraph systems including, but not limited to, these. I am unaware of another survey of optical telegraphy comparable in scope.

[22] Ignace Urbain Jean Chappe, *Histoire de la télégraphie* (Paris, 1824), p. 129.

south to Nantes, and the Lille line to Boulogne. Toward the southwest a line was built to Bordeaux in 1823 and from the Atlantic to the Mediterranean from Bordeaux to Toulon via Montpellier between 1832 and 1834, thus beginning (and, in the event, ending) the provision of alternate routes between the periphery and Paris.[23] A line connecting Lyons with Strasbourg was under construction in the 1840s when the arrival of electromagnetic technology brought it to a halt. Slightly modified equipment continued to be operated in Algeria even after the system's demise in metropolitan France—the absence of potentially disruptable wires in a politically and militarily unstable environment was deemed an advantage. The system was also extensively used during the Crimean War.

In conjunction with its new software and administrative support systems, the Chappe system provided performance levels far beyond any which had previously been achieved through visual means. For the first time complex messages, the contents of which had not necessarily been anticipated, could be sent at speeds, over distances, and with a reliability with which neither smoke and fire—nor horses—could compete. Although much prior optical telegraphy had been at night, thereby facilitating the recognition of lights or flares over fairly long distances, the Chappe system was throughout its history principally a daylight system, sacrificing some interstation distance for the more complex informational units (and messages) that could be sent by manipulating the telegraph's three articulated bars, painted black to maximize contrast against a bright horizon and louvered to prevent high winds from destroying them.[24]

Even after the towers and equipment had been abandoned, the laws and organizations to which the telegraph service gave rise continued to influence the implementation of electromagnetic telegraph and telephone service in France. Although other nations, including the United States, used optical systems of one form or another in the first half of the 19th century, nothing elsewhere on the globe approached the French system in terms of its extent, performance levels over long distances, and persistence. An understanding of the capabilities of this inferior yet clearly practicable alternative for sending information with high time value can help differentiate between the truly revolutionary uses of the electromagnetic device and those which were of less economic importance or for which substitutes could more easily have been procured.

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[23] Alternate routes expanded capacity as they brought new cities into the network and made connections between Paris and the periphery more reliable. They did so by reducing the vulnerability of a connection to disruption by localized fog or other disturbance.

[24] On the (infrequent) use of the Chappe system during nighttime, see Chappe, pp. 118–22.

Although the leap from Chappe to Morse was arguably more revolutionary than that from canal to railroad, the French network must still be seen as the world's first modern telegraph system. Catherine Bertho has argued that the Chappe system was closer to ancient systems of signal transmission used by Greeks or Romans than to those we use today.[25] From the standpoint of the scientific principles underlying its operation she is perhaps right. But the creative use of software and administrative structures broke new ground and made the network qualitatively different from anything which had preceded it. Even more so than was true of its electromagnetic successor, the achieved performance of the optical telegraph cannot be understood in purely technical terms, at least not those which apply to hardware alone.

The principles underlying the Chappe system represent an excellent illustration of the French adage "*Reculer pour mieux sauter.*" Technological search mixes periods of breakthrough with periods of evolutionary change, stagnation, and dead ends. Sometimes these dead ends are absolute, the consequence of fundamental limits imposed by properties of energy and matter. Other times they are historically conditioned, reflecting the absence of necessary complementary knowledge. At the end of the 18th century, scientific frontiers lay in the exploration of electricity and magnetism. Claude Chappe, as did many inventors of his time, wrote scientific papers in the area of electricity and experimented with an electric telegraph.[26] Poor insulation rendered his efforts (and those of others) nugatory, and he ultimately chose to work with optical/mechanical technologies whose principles, if lacking in novelty, were better understood.

The military use of optical telegraphy had a long history predating Chappe. In the Peloponnesian Wars soldiers raised their torches to the right to signal the arrival of friends and to the left to signal that of enemies,[27] and at the onset of the American Revolution Paul Revere used a simple nighttime visual code to announce the mode of arrival of the British. The Romans constructed an immense circular signaling system stretching from Rome west into France and Spain, crossing south into Africa at Gibraltar, and returning east across north Africa to Egypt to the valleys of the Tigris and Euphrates and then back through the Danube Basin. Towers from this system can be seen in paintings of Pompeii and in relief on Trajan's Column in Rome; the ruins of some can still be

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[25] Catherine Bertho, *Télégraphes et téléphones: De Valmy au microprocessor* (Paris, 1981), p. 9.

[26] J. J. Fahie, *A History of Electric Telegraphy to the Year 1837, Chiefly Compiled from Original Sources and Hitherto Unpublished Documents* (London, 1884; reprint, New York, 1974), pp. 94–95.

[27] Thucydides, cited in Alexis Belloc, *La télégraphie historique, depuis les temps les plus reculés jusqu'à nos jours* (Paris, 1888), p. 7; see also Chappe, p. 21.

explored in the Midi of France. These towers were located about 10–12 kilometers apart—slightly more than the average separations of the Chappe system. But all operational visual systems prior to the Chappe system were limited to sending simple messages whose content had been anticipated by both sender and receiver. These systems could not announce unforeseen events or respond to unexpected developments.[28]

The contribution of the Chappe brothers lay in designing and implementing a practical system that could do so, and, although its mechanical components and the scientific principles underlying their use were not new, they displayed a kind of genius in rejecting simpler, more obvious, and more elegant approaches for one that was complex, far from intuitive, and inelegant. Their system used a large set of *chiffres primitifs* (basic transmission elements) in conjunction with a coding system in which short sequences of signals were associated with phrases and proper names. Given the inherent limitations of its hardware, the Chappe system achieved remarkable performance levels. From the standpoint of information theory, it can be understood as having done so by complementing its hardware with relatively sophisticated software and administrative procedures. Present-day communication technologies, although more advanced from the perspective of hardware, are, in other respects, less complex.

Optimization under Constraint

Modern information theory, pioneered by Claude Shannon and others, provides systematic means for measuring the information, or uncertainty-reducing, content of a communication channel.[29] For a system that sends sequential signals along a noiseless channel, let S be a basic transmission set consisting of n possible signals, and p_i the probability that the ith element of the set appears. Information per signal H can be measured, using the binary digit (bit) as the fundamental unit of information, as

$$H = -\sum_{i=1}^{N} p_i \log_2 p_i.$$

In the case of equal and independent probabilities, this reduces to

$$H = \log_2 n.$$

If N is the number of signals per unit time, channel capacity can be measured as

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[28] Chappe, p. 29.

[29] Claude E. Shannon, "A Mathematical Theory of Communication," *Bell System Technical Journal* 27 (1948): 379–423, 623–56.

$$C = N \cdot H = N \cdot -\sum_{i=1}^{N} p_i \log_2 p_i.$$

These equations provide a framework for understanding how the French system achieved the performance levels it did. The capacity of a communications channel of this type, be it of the Chappe, Morse, or modern binary digital variety, depends on n, the number of elements in the basic transmission set; the p_i's, the probabilities with which each of these elements appear; and N, the number of elements which can be transmitted and received within a given time period. Channel capacity can be increased by raising n (thus expanding the size of S), reducing disproportionalities in the p_i's, or increasing N.

The hardware, software, and organizational structure of the French optical telegraph network influenced each of these variables. Because signals had to be visually recognized and manually recomposed at each relay station, optical telegraphy faced, relative to its successors, severe limitations on how much it could increase N, the number of signals per unit of time. Within these limits, management and training protocols reduced amplification lags. Because the system relied not on a crude electromagnetic device but rather on the remarkable (telescopically assisted) pattern-recognition capabilities of the human eye, it could employ a complex set S of basic transmission elements (high n). Finally, its stylized *vocabulaires* (codebooks), which associated short sequences of basic transmission elements with entire phrases or proper names, counteracted the extensive redundancies normally present in natural language text. This drove the p_i's closer to equiproportionality. Careful operator training protocols, the selection of a complex repertoire of signals, and the unique mapping of language onto these signals were all essential in expanding channel capacity to the point where the system was practicable for long-distance communication.

The trade-offs and the optimization reflected in the Chappe system design can best be appreciated by comparing it with its modern counterparts. Whereas the French system used ninety-eight distinguishable signs (ninety-two for text transmission), modern digital communication uses two—the simplest possible set. (A transmission set with one element transmits no information [$H = 0$] and removes no uncertainty.) A set with two equiprobable states has the capability of transmitting 1 bit per signal ($H = 1$). Each Chappe transmission sent more information per signal, but its channel capacity was much lower than those of modern systems because of its limited number of signals per minute (N).

To move closer to equiproportionality, Chappe precoding broke text into phrases or words and mapped these directly onto sequences of two signals drawn from a relatively large ($n = 92$) signal set. In contrast, digital communication, using ASCII coding, breaks text into letters and then maps letters onto sequences of 8 bits drawn from a two-element signal set ($n = 2$). Thus, a phrase consisting of twenty-one spaces and letters could be sent with two signals (page number and line number) by using the Chappe software. When ASCII is used, the same phrase requires 168 signals, a total of 189 including the error-checking parity bits.[30] Today signals are sent so quickly and so cheaply that their use is characterized by what is, from a 19th-century perspective, incredible profligacy. Chappe did not have this luxury. Direct transmission by letter using a signal set coextensive in size with the alphabet ($n = 27$) or precoding by letter and transmission by sequences of signals drawn from a smaller signal set ($n = 4$ or 2) is an inherently more flexible means of transmitting the subtleties and nuances of written language than the precoding by phrase which characterized the French system. But when the average cost per signal (in time and resources) is high, as it was in optical telegraphy, precoding by letter is entirely impractical.

The electromagnetic telegraph was the first technology to reduce cost per signal sufficiently to make precoding by letter economically viable for general communication. Morse transmissions are based on a quaternary (not binary) code, consisting of four basic elements (dot, dash, short pause, long pause); signals are indexed by both state and duration (but not intensity). In the equiprobable case, each signal sends the equivalent of two binary digits of information ($H = 2$), because a sequence of two binary digits, having the potential to generate any of four sequences (10, 01, 11, or 00), could communicate the same information.

The French system, which precoded by word or phrase rather than letter, did not use a binary or quaternary code, exploiting instead a transmission set with a much larger number of elements. The larger the transmission set, the higher the potential bits per signal, although the increase is not proportional. For example, a thirty-two-letter signal set can send substantially more information per signal than a bit, but not sixteen times as much. Such a set would, for each equiprobable signal, transmit the equivalent of 5 bits of information, because a sequence of 5 bits could, as a substitute, be used to represent any of thirty-two different states. In order to maximize channel capacity, Chappe in fact

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[30] Unlike Morse code, ASCII signal sequences are of uniform length (eight signals). They can be sent so quickly that it is scarcely worth trying to conserve on them, although modern data-compression technology is essentially concerned with squeezing the waste out of this system. Error frequency could be reduced by simply retransmitting the same data several times. But it is much cheaper to include a 9th bit, chosen so that the sum of the digits is always even. An odd sum signals to the receiver a transmission error. A reverse convention could of course achieve the same result.

used a transmission set forty-six times larger than that used in digital communication, which increased potential bits per signal and channel capacity, although it did not do so proportionally.[31] This was still well within the range of the visual recognition capabilities used in his amplifiers (repeaters).

These calculations of bits per signal presume, however, that each signal appears with equal and independent probability. The main reason communicating text information by letter is so inefficient is that the letters of an alphabet do not occur randomly. Shannon's work permits us to say exactly how much information per signal would be carried by a twenty-seven-element alphabet (twenty-six letters and a space), when it is assumed that the letters occur with equiprobability. In this instance $H = \log_2 27 = 4.75$. Because of disproportionalities in conditional probabilities, however, the actual information (uncertainty-reducing) content in a letter of a natural language such as English or French has been estimated to be closer to 1 bit. Most text, for example, can be recovered by a representative reader even with all vowels deleted or with every other letter or space deleted.[32]

The frequencies of letters are disproportional because the probability of a symbol appearing is not independent of the symbol(s) which precede it. A natural language has many of the properties of a Markov process, with an implicit matrix of transition probabilities.[33] Samuel Morse's business partner, Alfred Vail, was not indifferent (as is ASCII) to relative letter frequencies. He wanted the most frequent letters to have the shortest codes, and he began counting letters in text before realizing that typesetters at the local newspaper could answer his question more quickly. Contemporary data collected from professional printers on the basis of the processing of hundreds of thousands of words in a wide range of printed matter show that, for English, *E* is the most common letter, occurring approximately 10 percent of the time, followed by *T*

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[31] If in the equiprobable case, each signal from a two-element set sends 1 bit of information, a sixty-four element signal set sends 6 bits; a 128-element set sends 7 bits, etc. Rapidly diminishing returns set in quickly as the size of the signal set increases. Moreover, the larger the signal set, the greater the challenge in distinguishing one signal from another.

[32] The Franklin Institute in Philadelphia experimented in the early 19th century with English-language communication based on a twelve-letter alphabet. To say that each letter contains only 1 bit of information rather than 4.75 bits does not mean that 75 percent of the letters can be deleted at random for the text to remain recoverable; deletions would have to be carefully considered. Indeed, studies have shown that text cannot be consistently recovered if the probability of random deletion rises much above .25. See Dominic Welsh, *Codes and Cryptography* (New York, 1988), p. 101.

[33] The concept of a Markov process emerged as a result of Andrei Andreevich Markov's development of statistical procedures for predicting the sequence of letters in Aleksandr Sergeevich Pushkin's novel *Eugene Onegin.*

(7.1 percent), *A* (6.4 percent), *I* (6.3 percent), and *N, O,* and *S* (5.6 percent each). *Q, J, X,* and *Z* bring up the rear of the rankings, each occurring less than .4 percent of the time. Vail chose a single dot for *E* and a single dash for *T*.[34]

The statements made above about letters in a natural language also apply to words. Not only do words appear with vastly unequal probabilities, but the frequencies also bear a striking empirical relationship to each other. In 1935 the linguist G. K. Zipf observed that, if words were ranked according to their frequency, this frequency could be expressed almost exactly as a function of rank by using the following formula: $p_n = \mathrm{A}/n$, where A is a language-specific constant (.1 in English), n is the rank of the word, and p_n is the probability that a word of rank n will appear.[35] Thus, in English "the" (rank 1) appears about 10 percent of the time (.1/1), "of" (rank 2) appears about 5 percent of the time (.1/2), and "at" (rank 3) appears with a frequency of 3.3 percent (.1/3), and so forth. This relationship illustrates the clear violation of word equiproportionality in a natural language.

The disproportionalities in the conditional probabilities reflected in implicit transition matrices can be illustrated by constructing a text passage in the following manner: open a book at random, pick a word, search elsewhere in the book for the same word, and select the word which follows it. Repeat the process. This gives a first-order word approximation of English. A second-order approximation keys each new word on the two previously selected. In the absence of disproportional conditional probabilities, these approximations should remain as unintelligible as a zero-order approximation. But by the third or even the second approximation, constructed text begins to appear to take on meaning.

To increase the channel capacity of a system that could send only a limited number of signals per minute, Chappe had to increase the information content of each transmission by designing hardware and software that took maximal advantage of the visual recognition capabilities that were the key links in the system of relay stations. Thus, the French system was principally a daylight system, and the semaphores were painted black in order to stand out against an illuminated horizon. The system operated with a set of ninety-eight basic transmission elements, ninety-two of which were used for text transmission.[36] The

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[34] Welsh, app. 2; G. R. M. Garrat, "Telegraphy," in *A History of Technology,* vol. 4, ed. Charles Singer et al. (Oxford, 1958).

[35] George Kingsley Zipf, *The Psycho-Biology of Language* (Boston, 1935; reprint, Cambridge, 1965), pp. 44–47.

[36] This is in contrast to the two elements used in modern systems or the four elements used by Morse.

transmission of an individual signal therefore had the potential to send approximately 6.5 ($\log_2 92$) bits of information.

But that theoretical potential could be approached only if the mapping from language to the basic transmission elements was such as to reduce disproportionalities in the conditional probabilities of one signal following another. Letter- or even word-based precoding was unsatisfactory in this regard, for the reasons noted above. Instead, the French distinguished words from proper names and grouped the former into phrases (groups of words commonly appearing together, i.e., with high conditional probabilities of following each other) and the latter into names of individuals and names of places. The phrases were listed in a *vocabulaire* consisting of ninety-two pages with ninety-two entries on each page, or 8,464 precoded groupings communicable with a sequence of two signals. Similar *vocabulaires* were developed for places and proper names.[37]

The French system almost completely eschewed precoding by individual letters (it was, in extremis, possible to switch to this, but at a prohibitive cost in terms of increased transmission time). Some loss of flexibility in expression is the price paid for a greatly reduced number of signals per line of text, a trade-off that made eminent economic sense given the implicit costs imposed by the available hardware. The trade-off is almost the same one made in American Sign Language, and for many of the same reasons. Sign language is, in a sense, optical telegraphy over short distances, with hand, arm, and finger signals the analogue to the positions of the Chappe apparatus. Both systems use a large and complex transmission set, since both can rely on the acuity of visual recognition; both are constrained by the time required to compose individual signals.[38] Sign language transmission becomes excruciatingly slow whenever the signer must switch to precoding by letter as opposed to word or phrase, laboriously spelling out each component of text that has not been "precoded." A sign language based in general on the transmission of individual letters would be impractical, just as optical telegraphy would have been, had it been based on this principle.

Precoding and/or direct transmission by letter are natural and obvious solutions to an analytical mind but are not practical when

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[37] Even after the advent of electrical telegraphy, the high cost of transmission led to the extensive use of commercial codes to overcome the inefficiencies of natural-language text. See Headrick (n. 9 above), pp. 45–46.

[38] American Sign Language is in fact an offshoot of, and linguistically similar to, a code originally developed in France in the 18th century. See *Recent Perspectives on American Sign Language,* ed. Harlan Lane and François Grosjean (Hillsdale, N.J., 1980), esp. chaps. 1 and 6.

composition and amplification lags are high.[39] In 1690 Guillaume Amontons demonstrated a system that placed giant letters on the sails of rotating windmills. The chosen letters were gradually raised by the windmill to a height from which they could be perceived with a telescope from a distance of several kilometers. While windmills could transmit simple messages (and were in fact so used during the Vendée rebellion), the Amontons system was unsuitable for transmitting complex communications whose content had been unanticipated because of both the slow speed of transmitting individual letters and problems of differentiating among letters visually at a distance.[40]

An optical communication system proposed by the Greek philosopher Polybius suggested precoding by letter and using banks of torches, five on the right and five on the left, to transmit the letters.[41] Distributing an alphabet within a five × five square, a row and a column signal was sufficient to send an individual letter. Because of the time required to code, transmit, and decode messages in this format, however, such software is inadequate for optical systems except where distances are short and messages are simple. Ship-to-ship communication using flags or louvered lights is one application where optical transmission by letter can persist, but this application satisfies the requirements of short distances (no relay stations) and simple messages.

Early proposals for static-electric and electrochemical telegraphs envisioned both precoding by letter and the use of a basic transmission set coextensive in size with the alphabet, apparently the obvious thing to do.[42] The result in these implementations was typically a plethora of wires, rendering even more cumbersome systems already vitiated by a poor understanding of conductivity and insulation. Electromagnetic telegraphy finally reduced composition and retransmission lags sufficiently that *precoding* by letter became practical for long-distance communication. Interestingly, the move to single- or dual-wire systems led to a shrinkage in the size of the basic transmission set from several times that of an alphabet (in the Chappe case) to a small fraction of its size (in the Morse case).

Communication over the French system sacrificed some complexity of discourse in order to increase the information content of each signal transmitted and coupled this with a large and complex basic transmission set in order to maximize channel capacity given the inherently high

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[39] Modern systems precode by letter but transmit by using sequences of a basic transmission set significantly smaller in size than an alphabet.

[40] Gerspach (n. 20 above), *Annales Télégraphiques* 3 (January–February 1860): 49.

[41] Belloc (n. 27 above), p. 12; Chappe (n. 22 above), pp. 26–27, and pl. 2.

[42] Static-electric proposals included one described in a February 17, 1753, letter to *Scots Magazine,* as well as Don Francisco Salvá's attempts in Barcelona between 1795 and 1798. See Fahie (n. 26 above), pp. 68–71, 101–8, 220–49.

composition and reamplification lags. Under the constraints of his technology, it made no sense for Chappe to push in the modern direction of a significantly smaller and less complex basic transmission set. One of the advantages of his repeaters was that they embodied visual recognition technology, giving him the ability to distinguish cheaply among a larger transmission set. Nor could Chappe afford the somewhat greater flexibility associated with precoding by individual letters, or even words. Where channel capacity is limited, such coding is too costly given the extensive redundancies inherent in the structure of natural languages.

Hardware

Chappe's search for a means to optimize channel capacity given the range of hardware to which he had access can be seen in reviewing his initial experiments. His first prototype consisted of synchronized clocks, with a sweep arm rotating through divisions on the clockface, each of which corresponded to a numeral.[43] The sending station banged two saucepans together to transmit a signal. Saucepan signaling effectively limited transmission between stations to a maximum of 400 meters, making the system impractical for long lines. Chappe tried to solve the problem by replacing the sound signal with an electrical pulse sent over a wire, but, as noted, he was hampered by the absence of an effective insulator.[44]

His second system was demonstrated on March 2, 1791. Two clocks were again harmonized, driving sweep hands through divisions of a clockface. At the height of a 4-meter pole was a 1.65 x 1.33-meter rectangle, one side white, the other black. When the sweep hand moved to the desired symbol, the axis of the pole was turned; this could be noted through telescopes at the receiving station. Thus it was possible to transmit a message between two stations, one at Parcé, the other at Brulon, 15 kilometers apart.[45]

Chappe and his brothers were then given authority to construct a demonstration project in Paris, which they proceeded to do on the Étoile. In September 1792 the apparatus was destroyed by a mob convinced that this was part of a nefarious plot to communicate with Louis XVI. The destruction apparently persuaded Chappe to abandon synchronized clocks and focus more on shutter signals, but his apparatus was destroyed again. Chappe concluded, unlike the designers of the British Admiralty system that operated from London to Plymouth, that shutter systems were too vulnerable to confusion at long distances; elongated forms would be easier to differentiate.

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[43] Chappe, pp. 123–24.

[44] Fahie, p. 95.

[45] Chappe, pp. 123–25, 234–42.

Chappe's engineering trials cycled through then-known principles of long-distance communication. The Greeks had used synchronized and identical clepsydras to transmit simple messages long distances: a flare would signal to start the water draining; as the water drained, a float marked with different messages would descend. A second flare would indicate which message to read.[46] Sir Robert Hooke, in a discourse to the Royal Society on May 21, 1684, outlined a system that employed many of the principles settled on by Chappe, who acknowledged his debt to Hooke. Hooke envisioned single letters corresponding to words and phrases and stressed the desirability of locating stations at high points, so that the telegraph would be clearly visible against the sky and so that the disruptions of fog and the refraction of warmer air could be minimized. He also envisioned the use of telescopes to increase the distance between stations; indeed, it was in part improvements in telescope design that stimulated his reflections. All three of these principles eventually found their way to the Chappe system.[47]

The design of the telegraph required a form that not only had enough surface to be visible at a distance but that was also light enough to be easily carried up mountains or towers and strong enough to resist wind.[48] The device had to be relatively easy to operate, and the signals had to be repeatable, easily distinguished from one another, and unambiguous. Chappe discovered that black was preferable to white, provided that the devices were so situated as to be silhouetted against the sky, because visibility depended more on contrast with background than with the actual surface area of the object. He discovered that longer lines were more visible at greater distances than were shorter lines or disks of the same width; thus the long rectangular arms of the Chappe apparatus.[49]

Although the fundamental design of the system used in metropolitan France changed only modestly through its six decades of usage, it is useful to speak of an initial period of "debugging" from 1793 to 1805, of the Milan system (named after the design used throughout the Paris-Milan line completed in 1808), and of a final stage running from 1840 to its demise.[50] The basic telegraph settled on by Chappe after the

[46] See description in ibid., pp. 25, 26, and illustration in pl. 1; the source again is Polybius.

[47] Garrat (n. 34 above), p. 645.

[48] Chappe, p. 98.

[49] Ibid., pp. 100–1. Indicators were added initially because the addition of end pieces made the position of a rectangle easier to discern at a distance.

[50] I follow here the excellent research of Ollivier (n. 19 above). One must take note of the extraordinary recent interest in the Chappe system on the part of both scholars and a wider public in France. Since 1979, "international" conferences have been held biennially, and in 1984 the FNARH was founded. Much of the scholarship engendered has an antiquarian flavor and is not motivated by the larger issues that might concern an

experiments with synchronized clocks and shutters was designed with the assistance of the clockmaker Abraham Louis Bréguet. The device, initially quite heavy because it was made almost entirely of metal, was mounted on a ladder-like frame holding at its top the signal and at its bottom the control apparatus and measuring usually about 7.5 meters, 4.5 meters of which extended above the building in which the operator(s) were situated. Subsequently, wood was substituted for much of the metal.[51]

The hardware defies simple description, and the intent here is only to give a sense of its main components and principles of operation. A Chappe telegraph consisted of three main assemblies: the signal arms, a vertical (and immobile) ladder/frame, and the controls. The signal assembly was attached near the top of the ladder/frame, the controls were attached near the bottom, and the two were connected vertically by rods, pulleys, and cables.[52] Figure 1 shows the basic relationships.

Signal assembly.—The signal assembly (fig. 2) can only be understood sui generis—it is unlike anything those unfamiliar with the French system will have encountered. Picture a folding yardstick composed of three pieces: a long middle section, at the ends of which are attached two shorter pieces, each of which rotates 360 degrees around its hinge or connecting point. By manipulating these end pieces, one could imagine forming (ignoring the serifs) an *L*, a *Z*, an *N*, a *Γ*, a straight line of any of three different lengths, or any number of innumerable other shapes. The Chappe signal arms were narrow rectangles about a foot wide. The long middle section was called the *régulateur* (henceforth, regulator), and the shorter pieces at either end, *indicateurs* (henceforth, indicators). The midpoint of the regulator was attached to an axle near the top of the stationary tower.

The regulator measured externally 4.59 × .35 meters (approximately 15 feet × 1 foot). Its frame had interior crosspieces consisting of angled parallel blades (its sections resembled a half-open Venetian blind). This design reduced weight, but more important, it lessened wind resistance by permitting air to pass through the frame. A potential drawback was that at certain times of the day or year the sun might shine directly through the blades or cause reflections, making it difficult for the next station on the line to distinguish the configuration of the signal. To

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economic historian. But research such as that of Ollivier, L'Hôpital, and many others is invaluable in understanding how the system operated and what it achieved.

[51] Gerspach (n. 20 above), *Annales Télégraphiques* 3 (July–August 1860): 361.

[52] The hardware descriptions that follow refer specifically to the "Milan" design, introduced in 1805. By this time wood had replaced much of the metal used in the original machines; the basic design principles remained unchanged.

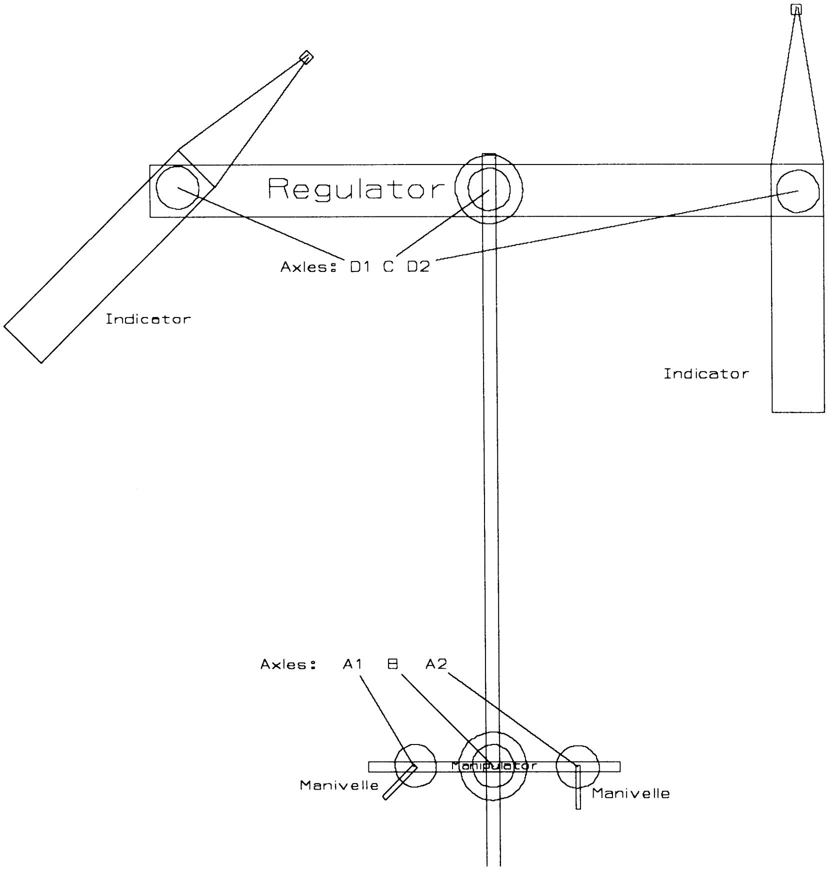

Fig. 1.—The main hardware components of the Chappe telegraph. Circles indicate pulleys; cabling is not shown. When the operator rotated the manipulator on axle B, the regulator rotated on axle C. Rotating the left *manivelle* (handle) on axle A1 caused the left indicator to rotate sympathetically on axle D1. Drawing is not to scale.

address this problem, the bar was divided into four segments, and the angles of the blades in two of the segments were offset 90 degrees. Thus, at worst, the sun shone through only two of the segments and the orientation of the frame could still be perceived at a distance.[53]

The indicators were constructed along similar lines, but were less than half as long (1.96 meters) and slightly narrower (.324 meters) (approximately 6.5 feet × 1 foot). An iron weight mounted on a V-shaped bracket counterbalanced each indicator, permitting it, when rotated, to rest freely in any position. Small axles had an indicator on one end and a

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[53] Chappe (n. 22 above), pp. 105–8.

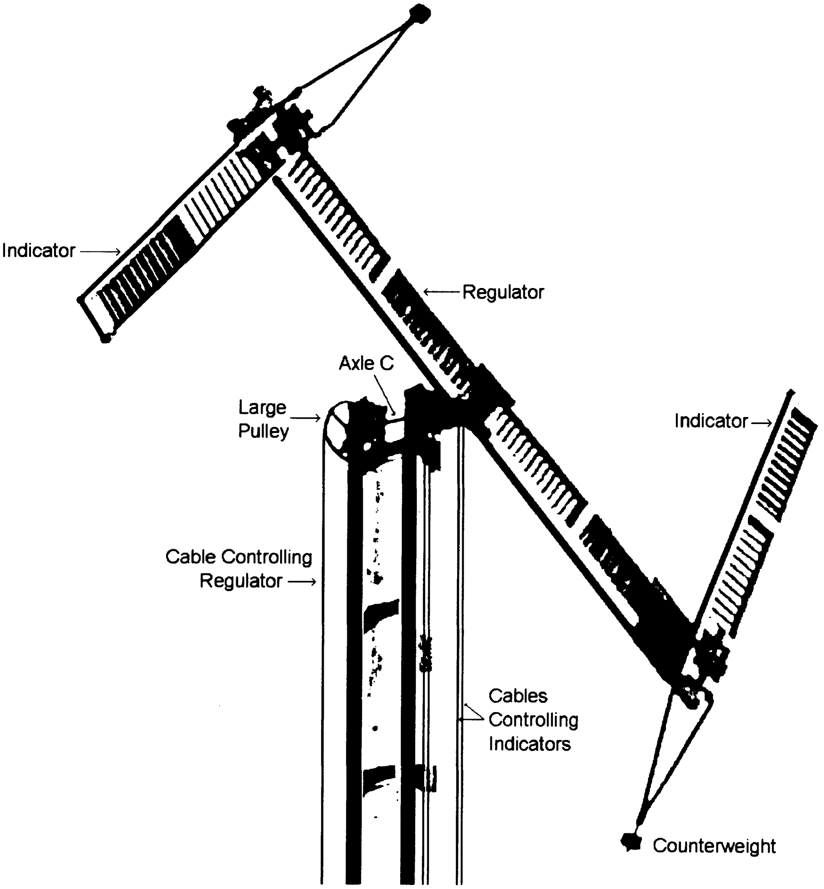

FIG. 2.—Signal-arm assembly. This enhanced image, based on a photograph of a full-scale reconstruction, shows the cabling permitting the operator to control the orientation of the regulator and each of the two indicators.

pulley on the other end and rotated within reinforced crosspieces at the extremities of the regulator. All three rectangles were painted black to ensure strong contrast with the sky, thus maximizing daytime visibility.

Control assembly.—The control assembly (fig. 3), a miniversion of the signal arms, was mounted on the ladder/frame, about a meter above the floor on which the operator stood. To rotate the regulator the operator turned a control bar called the *manipulateur* (henceforth, manipulator), which was almost 5 feet (1.37–1.45 meters) long and which was thus about one-third the length of the regulator, whose movements it controlled. To turn the left or the right indicator, the operator turned the corresponding *manivelle* (henceforth, handle). These handles (to be

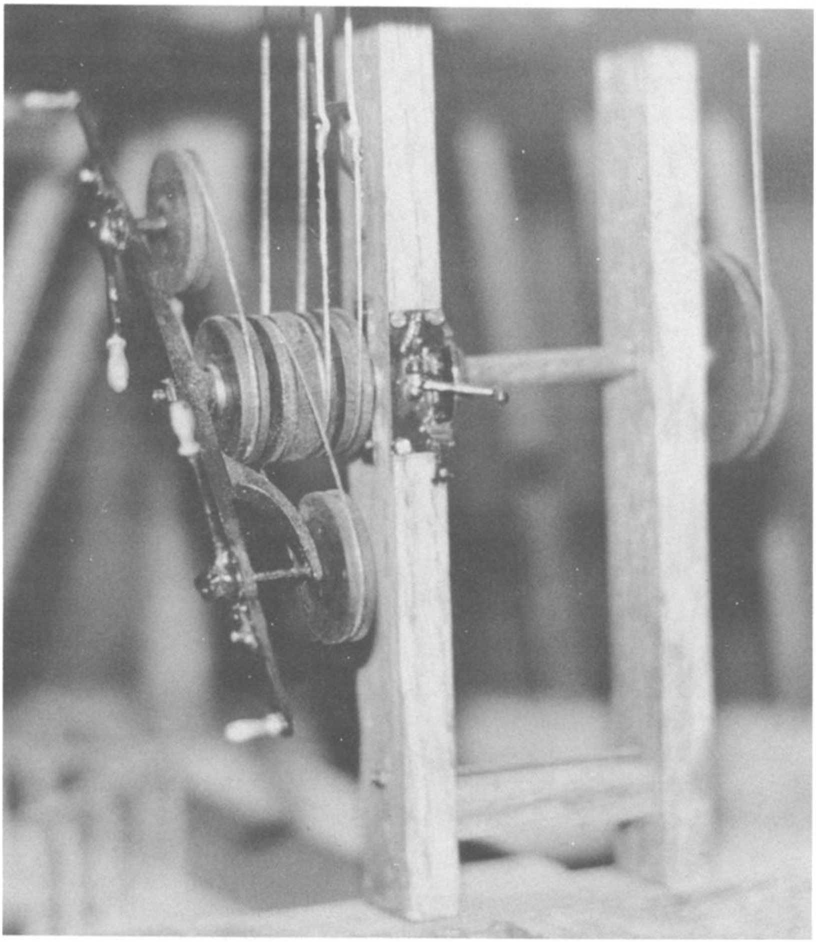

FIG. 3.—Model of the control-arm assembly. Photograph by author of model in the Centre national d'études des télécommunications.

distinguished from the fixed grips mounted at each end of the control bar) rotated in a common vertical plane around the points where they connected with the manipulator. The manipulator rotated freely in the same plane because it was attached to an axle running through the stationary tower.

Ladder/frame and connecting hardware.—The stationary tower resembled a 7.5-meter (25-foot) wooden ladder. A ladder consists of side rails and rungs. The regulator's axle took the place of a rung about 15 centimeters from the ladder's top, and the manipulator's axle replaced a rung about 1 meter from the ladder's bottom. The back of each of these axles (away from where the operator stood) connected to large pulleys measuring half a meter in diameter. The bottom pulley, attached to the manipulator's axle, can be seen on the right-hand side of figure 3. Both pulleys are represented by large circles in figure 1, where we have the benefit of X-ray vision; the ladder is seen in profile here. Two smaller pulleys rotated freely on the front end of the top axle, and two rotated on the manipulator's axle, although in this instance one of the two pulleys was nested inside the other. Immediately to the left of the "ladder" in figure 3, on the main axle one can see pulleys with four grooves (1, 2, 3, 4, from left to right), each of which contains a belt. Loop 1 and loop 4 are attached to the same spool and move together. Loops 2 and 3 are attached to the nested pulley, which rotates around the first spool, which in turn rotates freely on the manipulator's axle. Finally, the regulator was attached to the front end of the top axle, and the manipulator was attached to the front end of the lower axle. Cords and rods formed a belt connecting the two large pulleys such that when the bottom axle turned, so did its counterpart on top. Part of this belt, stretching upward, can be seen on the right side of figure 3. Since the large pulleys were rigidly attached to the regulator on the top and to the manipulator on the bottom via their axles, when the operator moved the former, the latter moved sympathetically.

The eight smaller pulleys and belts permitting the left and right handles to control the indicators formed a more complex mechanical system. Small axles pierced the manipulator near its left and right side (see fig. 3; points A1 and A2 in fig. 1). On the front of these axles, facing the operator, were mounted the left and right handles; on the back of each was a small pulley. When the operator turned a handle, the small pulley on the other end of the axle turned. A belt connected this pulley to one of the two freely rotating pulleys on the main control-arm axle (point B in fig. 1). Rods and cords formed a belt carrying the motion vertically to one of the two freely rotating pulleys on the main signal-arm axle (point C in fig. 1). In the last segment of the journey, a belt carried the motion to a pulley at the extremity of the regulator (point D1 or D2 in fig. 1), mounted on the same axle on which the indicator turned. Thus, when the operator rotated the left handle relative to the manipulator, the left indicator rotated relative to the regulator in the same fashion. The right handle was linked in an analogous fashion to the right indicator. Finally, a set of ratchet stops permitted the controls (and signal) to be locked at 45-degree intervals, giving for each handle (and indicator) eight possible positions.

The hardware design had a number of advantages, perhaps the most important of which was the transparency of its controls. The operator could tell at a glance what the position of the telegraph was simply by observing the position of his control apparatus. It was also very easy to repair: all the moving parts could be easily accessed through the partial disassembly of one of the axles. Its major design defect was the heavy weight of the signals and the need to move all three of the articulated arms as a single assembly around a central pivot point. The device consequently had considerable inertia and required strenuous efforts on the part of the operator.

The Chappe system did not dominate completely in France. In 1804 a semaphore for shore-to-ship communication was introduced on the French seacoast. The signaling device, which had three arms, each mounted separately on a stationary vertical post, had a similar complexity of signals, but was simpler mechanically and required less effort to operate.[54] Chappe and his brothers, however, strenuously rejected even the slightest comparison of this semaphore with their telegraph. Modifications in materials and design for the Chappe telegraph did occur, but the basic mechanism remained largely unchanged until 1840. At that point, a new design which mounted the three arms horizontally with three separate pivot points was experimented with on the Dijon-Strasbourg line, which never reached beyond Besançon. In Algeria and the Crimea, the regulator was suppressed entirely, reducing the size of the basic transmission set, but permitting more signals to be transmitted in a given time period.

Software

While the hardware has some fascination from a purely mechanical standpoint, the software design is more interesting from the standpoint of information theory. As noted, had the Chappe telegraph chosen precoding by letter, it would have failed, because the time required to compose, transmit, recognize, and retransmit each signal would have rendered the sending of complex messages impractically long. Chappe's cousin, Léon Delaunay, had been French consul in Lisbon, whence came the idea of using something equivalent to a diplomatic code. The first set of basic transmission elements, used on the Paris-Lille telegraph line, consisted of ten configurations, each corresponding to a decimal numeral. These signals used only horizontal and vertical placement of the three arms, with at most one (right) angle. Odd numbers were built

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[54] One should also mention the 1826 device of Sir Home Popham in England: it had a revolving post, permitting the direction of telegraphic transmission to be varied. There is some evidence that the British semaphores were inspired by the French coastal devices, which were used for ship-to-shore communication in France, although the Chappe device continued to hold sway internally. Arguably, this is one area in which the Chappe system had not successfully optimized, although the rotating regulator may have offered some advantages in the area of signal recognition.

around the vertical: completely vertical signified 1, and a vertical regulator with the top or the bottom indicator pointing right or left signified 3, 5, 7, or 9. Even numbers were built around the horizontal: completely horizontal signified 2, with right indicator down, left down, left up, or right up signifying 4, 6, 8, or 0, respectively. A *vocabulaire* of 9,999 words, phrases, and places was composed. A sequence of one to four signals corresponding to a numerical code transmitted each phrase or unit.[55] To mark the conclusion of signal sequences, which were of variable length, one of the indicators moved to a 45-degree angle. In addition to the ten numerical codes, an additional fifteen signals regulated traffic flow, signaling the beginning or end of a transmission session, suspension due to rain or fog, break for one or two hours, the priority status of a message, the cancellation of the previous signal, or the fact that a station was receiving and would be transmitting signals in both directions.

The codes were secret, so none of the operational personnel had the slightest idea what information was being transmitted. Nor would the interception of the signals be of the slightest use to anyone not armed with the codebooks. Still, under this system, 90 percent of the coded words or phrases required a sequence of four signals to send—a considerable expenditure of transmission time for a single word, phrase, or place, and the Committee of Public Safety complained about the speed of transmission. Typically, for example, only two or three messages per day could be sent from Paris to Lille.

Obviously, transmission speeds could be improved somewhat by limiting or rearranging the vocabulary. Use of the first 100 places in the code (which required two or fewer digits) for the most frequently used transmissions could result in some improvements.[56] Cutting the vocabulary from 9,999 to 999 (one-tenth its original size) could ensure a maximum of three signals; cuts to one-hundredth of its original size would mean a maximum of two signals per unit. Any improvements in communication speeds, however, would be purchased with substantial losses in the range and complexity of possible transmissions. At the limit, one approached a vocabulary not much richer than that available through smoke signals or flares.

Performance improvements therefore required that some software constraint other than the size of the *vocabulaire* be relaxed. This was done by drastically expanding the number of *chiffres primitifs* from ten to ninety-eight. In principle, since all three of the articulated arms rotated, an infinite number of signals could have been defined, depending on

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[55] Gerspach (n. 20 above), *Annales Télégraphiques* 3 (January–February 1860): 55–56.

[56] This is analogous to hard-disk rearrangement programs which improve access time by placing the most frequently used files in the most favorable position relative to the disk head.

the precise angle of one or another of the arms. For the signals to be useful, however, they had to be distinguishable at distances of 10 kilometers or more. Experiments using protractors superimposed on telescope lenses convinced the Chappe brothers that 45 degrees was the smallest interval that could practically be utilized. This meant eight positions for each indicator. But they also discovered that it was difficult to differentiate between the situation where the indicator was fully extended along the axis of the regulator and that where it was folded inward along the same axis, so they deleted the fully extended position, reducing the number of possible positions for each indicator to seven. Thus, for a given position of the regulator, there were forty-nine possible signals.

Limiting the system to 45-degree angles, there were four possible positions for the regulator to take, implying 196 possible signals. The basic transmission set was restricted, however, to configurations where the regulator assumed a horizontal or vertical position, implying a set of ninety-eight signals, of which six were reserved for information other than the content of the message itself.

The operator composed a signal with the regulator in a diagonal position (on the "right" oblique), on the basis of the telescopically observed position of an upstream signal. He positioned the indicators relative to the regulator, on the observation of which the upstream signal would be finalized, and a new one would be composed. When the operator confirmed by telescope that the downstream station had successfully copied his positioning of the two indicators relative to the regulator, he too would finalize or "assure" the signal by rotating the regulator (with the indicators temporarily locked in place) to either the vertical or horizontal. Thus did signals ripple down the line. Each station not a terminal was downstream to one station and upstream to another, the relationship depending on which direction messages were moving. Operators monitored telescopes pointing in both directions, watching upstream for the "composing" of a new signal and the subsequent movement of the regulator which "assured" and finalized it. They looked downstream to confirm successful replication of what they themselves had composed, before finalizing or assuring it. The "left" oblique was used to signal a forthcoming transmission regarding the administration or repair of the telegraph line.

With a basic transmission set of ninety-two signals, *vocabulaires* of ninety-two pages, with ninety-two entries on each, were developed, providing "storage space" for 8,464 phrases, words, or proper names, each of which could be transmitted with two signals only. Initially, as noted, there were three such codebooks: words, phrases, and names and places. As in American Sign Language, the system could shift in extremis to transmission of individual letters.

The increase in the size of the basic transmission set S roughly doubled channel capacity. A basic transmission set of ten elements can send a maximum of $\log_2 10 = 3.3$ bits per signal, whereas one of ninety-two signals transmits (in the equiprobable case) about 6.5 bits per signal. Expressed alternatively, to transmit messages based on one vocabulary of 8,464 units by using the original decimal system would have required an average of 3.87 signals per vocabulary entry.[57] The new system required only two signals per unit, for a reduction of over 48 percent in signals per phrase or proper name. This calculation gives approximately the same result: roughly doubling the number of bits per signal roughly halved the number of signals required per phrase or proper name.[58]

The telegraph network as it developed was principally a hub-and-spoke system, with Paris at the hub. And the lines were "single-track": while more than one message could run at the same time in the same direction, protocols were needed for dealing with "collisions" of messages going in different directions. There were two protocols: urgent messages (*urgences*) dominated regular transmissions (*activités*), and, within categories, a message from Paris (*grande activité*) dominated a transmission to the capital (*petite activité*). Every message was preceded by a code indicating whether it was a regular transmission or an urgent message. Although messages from Paris had priority, an *urgence* from the provinces dominated an *activité* from Paris. Similarly, protocols and codes had to be developed to deal with interruptions of transmission due to fog, or to signal a mutually agreed on break of a quarter-hour, half an hour, hour, or two hours.

Administration

The success of the French system, as noted above, was due as much to software and administration as it was to advances in hardware. The telegraph was a *service*, and, like a submarine or ship at sea, it was only as strong as its weakest link. One drunken or careless operator in a line of eighty-five stations would shut down the line.[59] The construction of the original line, from Paris to Lille, in the tumultuous years of 1793 and

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[57] This assumes the frequency of transmission of units 1–999 was similar to those for units 1000–8464. As noted, some reduction in transmission time could have been achieved within the constraints of the decimal code by packing more frequently used words or phrases in slots 1–999.

[58] More than a century before Shannon, the Chappes had an excellent intuitive understanding of the relationship between the number of basic transmission elements and bits per signal: "*Si l'on peut se servir de cents chiffres primitifs aux lieu de dix, on fera avec deux ce qu'on ne pourroit exécuter qu'avec quattre.*" See Chappe (n. 22 above), p. 138.

[59] Ibid., p. 110, n. 6; pp. 231–34.

1794, required considerable improvisation within a flexible organizational structure. Once the system became operational, it became more hierarchical. The operators, or *stationnaires,* numbered about 1,000 in 1833. Thirty-four *inspecteurs,* a few trained at the École Polytechnique, were stationed along the routes. Twenty *directeurs,* recruited from the inspecteurs and local notables, constituted the top echelon of the hierarchy.[60] The operators were recruited from the local population, with preference given to army veterans, who sometimes took the position in lieu of a pension.

Each post was manned by one or two *stationnaires.* With two present, one operator used the telescope to monitor the upstream station and called out the signal as it was composed. The second operator used the control assembly to replicate the signal, in some instances noting the finalized signal on a printed form (*procès-verbal*).[61] For the telegraph line to function well, communication between the spotter and the transmitter had to be quick and accurate. The main challenge was to develop a protocol for describing the positions of the two indicators, a protocol that was easily taught, remembered, and used by the operators. Operators were trained to refer to a 45-degree angle as "5 *ciel*" (sky), to 90 degrees as "10 *ciel,*" and to 135 degrees as "15 *ciel.*" An angle of 225 degrees was "15 *terre,*" 270 degrees was "10 *terre,*" and 315 degrees was "5 *terre.*" (*Terre* [earth, ground] reminded the operator to think "down.") The seventh position, folded in against the regulator, was simply *fermé* (closed). Finally, the position of the regulator had to be described. "*Perpen*" (perpendicular) meant "in vertical position"; the default was horizontal. Thus a string of a minimum of three and a maximum of five words sufficed to indicate any one of the ninety-eight basic signal units. Moreover, these three- to five-word strings were drawn from a list of only seven words, three of which were numbers: 5, 10, 15, *ciel, terre, fermé,* and *perpen.*[62] A signal could be reported as "*dix ciel quinze terre*" or "*cinq ciel quinze terre perpen.*" These voice communications were a potentially weak link in the telegraph system. The training and software necessary to make these links quick and accurate were important to the line's successful operation.[63]

[60] Bertho (n. 25 above), p. 31; Wilson (n. 18 above), p. 143.

[61] Wilson, p. 144, states that only the divisional stations (at Orléans, for example, on the Paris-Bordeaux route) wrote down the transmissions, where they were decoded and reencoded. According to Wilson, this permitted the French lines to operate significantly faster than those in Prussia, where every station kept a written record.

[62] Belloc (n. 27 above), p. 242.

[63] "*Ceux qui ont cru avoir inventé des télégraphes dont les agents pouvoient se servir sans instructions préliminaires se sont trompés.*" See Chappe (n. 22 above), pp. 111–12.

Twentieth-century fiber-optic systems utilize a digital transmission technology but must still have signals periodically amplified, or repeated. Each one of the relay stations on an aerial telegraph can be thought of as a repeater, but one that introduced friction into the movement of data. Although data moved at the speed of light from the signal arms through the telescopes and to the eyes of receivers, the signals had then to be called out to the sender and recomposed.[64] The French made an optical system practical by reducing reamplification lags through the development of operator protocols, by choosing a large and complex transmission set, and through coding that substantially increased the informational content of each signal.

The attachment to the human and physical investments associated with the Chappe system is reflected in the initial French response to electromagnetic technology. At the request of the telegraph service, Louis Bréguet (grandson of the Bréguet who had assisted Chappe in the design of the original optical telegraph) successfully constructed a machine that electromechanically manipulated two miniature indicators on the face of a small, beautifully crafted receiving unit. The sender moved small *manivelles,* and could use traditional codebooks. This Foy-Bréguet telegraph required two wires for optimal performance (its transmission rate fell by 50 percent if only one wire was used) and was entirely replaced between 1854 and 1860 by Morse apparatus.[65]

Commercial Use

From an engineering standpoint, optical telegraphy could almost match the performance of early electromagnetic systems, *provided* that the atmospheric conditions were favorable and the distances moderate. Étienne L'Hôpital estimates a transmission rate of 24 bits per minute on the Paris-Lille line and 12.4 bits per minute from Paris to Bordeaux. This compares with approximately 30 bits per minute when a character-based dial telegraph is used, 60 bits per minute when Morse apparatus is used, or 18,000 bits per minute when a 300-baud (bits per second) modem is used.[66]

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[64] Bertho (n. 25 above), p. 25, indicates that the *stationnaires* did not need to be literate. An intelligent operator would not have needed to know how to read and write in order to learn the various positions for the signal-arm assembly, how to call them out, or even how to record the positions (using angled-line segments) in the *procès-verbal.* However, article 2 of the *réglement* (regulations) for operators does state that "*ils savent lire et écrire et doivent répondre à toutes les questions relatives au mécanisme et aux passage des signaux.*"

[65] *Histoire des télécommunications en France* (Toulouse, 1984), p. 23; Belloc (n. 27 above), p. 222. Bréguet was also instrumental in designing a character-based *télégraphe à cadran* in which a dial at the sending station caused a needle at the receiving station to point to individual letters of the alphabet.

[66] L'Hôpital (n. 20 above), p. 14.

Given this capability, optical systems could and to some extent did satisfy some categories of the revealed demand for electromagnetic service. These categories, particularly in the United States, consisted principally of the transmission of "public" information: quotations on stock and commodity exchanges, information on the impending arrival of ships, and political news. Such information flows possessed two qualities: first, because they involved "public" data, there existed a broad population willing to support the costs of transmission either directly or indirectly (e.g., by purchase of newspapers). Second, "Better late than never" applied: compared with other types of data, information value at a distance deteriorated relatively slowly with the passage of time. Both factors meant that the higher cost and technical limitations of optical telegraphy would not have choked off, and in fact did not choke off, the demand for this type of use.

Commercial optical systems operated in Britain, Germany, and the United States, not only to announce the arrival of ships but also in some cases to transmit financial data. As electromagnetic technology matured and came closer to commercial viability, more optical applications of this sort were under consideration. An 1836 plan proposed to transmit stock market information from Paris to London in one-and-a-half hours. This system would have involved nine British and fourteen French stations, with one or more telegraph ships anchored in the Channel.[67] And, as noted, a serious proposal to build an optical system along the coast from New York to New Orleans was under consideration by the U.S. Congress in 1837. The arrival of electromagnetic technology forestalled these plans, just as the development of the steam railroad forestalled plans in the Massachusetts legislature to drive a canal through the Berkshires to Albany.[68]

Commercial Possibilities in France

The French optical telegraphy system was developed as an instrument of war and diplomacy. With the coming of peace, it became an instrument of governmental administration. Collecting its revenues indirectly from the public through taxes, it received funding intermittently from the ministries of war, interior, and public works. Chappe, painfully ill with cancer of the ear, threw himself down a well in 1805. Before ending his life, however, he recognized and enumerated ways in which additional revenues might be gained from commercial use. First, he proposed that the apparatus be put at the disposal of private business and commerce. He knew that merchants would pay for advance

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[67] Wilson (n. 18 above), p. 82.

[68] Taylor (n. 6 above), p. 36.

information on the arrival of ships and that bankers wished to know the course of the foreign exchange. Second, he proposed to publish a newspaper in Paris and send bulletins (approved of course by the government) to the provinces. Third, he suggested that results of the national lottery be telegraphed.

Only the latter proposal proved acceptable to the French state, and this was because doing so recaptured revenues that were otherwise lost in the interval between the moment the government betting office closed and the results arrived, during which local speculators continued to take bets on their own. Still, the government for a short time allowed a private line organized by Alexander Ferrier to carry bourse quotations from Paris to the port city of Rouen. In 1834, in the aftermath of a scandal involving the corruption of telegraph operators by speculators in Bordeaux attempting to get early access to the same type of data, this private line was shut down.[69] Both the line's operation and the scandal, however, indicate the intensity of individual demand for this type of data. Consumers and investors had (and have) an almost insatiable appetite for more timely news and a financial incentive to get stock- and/or commodity-price data before other local traders. In Britain, optical telegraphy was not limited to its use by the Admiralty. Barnard Watson operated a number of commercial semaphore lines, including one from Holyhead to Liverpool. In Germany in the early 1840s, Johan Schmidt constructed a commercial line from Hamburg to Bremen using private capital.[70]

In the United States a series of lines linked coastal outposts to commercial centers and announced, as Chappe had suggested, the impending arrival of ships. Jonathan Grout built a line from Martha's Vineyard to Boston, which opened in 1801 and closed in 1807, apparently the victim of overpricing. John Parker established a more successful telegraph from Nantucket to Boston in the 1820s.[71] Christopher Colles was instrumental in setting up a semaphore from Sandy Hook to Coney Island to New York City. Colles published a pamphlet in 1813 that discussed a system from Maine to New Orleans. Roughly the same proposal was picked up again in 1837 by Parker and Samuel Reid, who pressed for a line from New York to New Orleans that would use proven European technology.[72] In 1840 a Philadelphia broker set up a

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[69] Gerspach (n. 20 above), *Annales Télégraphiques* 4 (May–June 1861): 247. An 1837 law established a government monopoly on telegraph service in France (Wilson, p. 139).

[70] Wilson, pp. 159–60, 213.

[71] Ibid., p. 211.

[72] Reid was harbormaster of the Port of New York and had specialized knowledge of French and English systems. See Richard John, "Samuel F. B. Morse and the Origins of Commercial Telegraphy in the United States," unpublished paper (Chicago, University of Illinois at Chicago Circle), July 1988, particularly pp. 8–10.

line between Philadelphia and New York to carry stock prices and lottery information.[73]

Had electromagnetic technology not appeared, the commercial application of optical telegraphy in areas similar to those identified by Chappe would have increased. But we now reach a somewhat paradoxical conclusion. These areas were *not* (in my judgment) the applications of telegraphy—optical or electromagnetic—which contributed most to long-term economic growth. The individual willingness to pay for stock- or commodity-price data or political news ahead of, or at least at the same time as, the next person reflected a perceived private return to telegraph use that far exceeded the social return (in this application) to the incremental improvement in the speed of information flow when all had access.

In contrast, applications of electromagnetic technology that had greater payoffs from the standpoint of long-term growth involved the private use of the telegraph by individual firms to implement tight systems of logistical control, particularly in an era of fast and reliable overland transportation inaugurated by the railroad. The use of a telegraph for logistical control required not only that data move faster than the goods or vehicles being controlled but also that such data move reliably, regardless of the weather or time of day. Under optimal conditions the optical telegraph could move data faster than railroads, but it could do so only during daylight hours and in the absence of fog, warm-air refraction, or other obstacles to visibility. Even had reliability not been an issue, the limited channel capacity of an optical network—and its associated high price per message—could not have accommodated the volume of messages associated with its large-scale use by private businesses for purposes of logistical control.

By making possible the cheap transmission of real-time "private" data—sometimes of direct interest to only one or at most two firms—the electromagnetic telegraph enabled the coordination of input and commodity flows so as to increase capacity utilization rates on fixed capital and increase the turnover rate of inventories. It did so in a manner that in certain sectors saved hundreds of millions of dollars of real physical capital.[74] Because of high cost, low bandwidth, and vulnerability to interruption by weather or darkness, optical systems could not have substituted for electromagnetic technology in these

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[73] Morse's invention put him out of business in 1845. See Wilson, pp. 216–17.

[74] The most compelling instance is the ability of the Americans to operate a largely single-tracked railroad system. The use of the telegraph in conjunction with the railroad by wholesalers, retailers, and dealers speeded rates of inventory turnover as they reduced the costs and time required to complete transactions. See DuBoff (n. 5 above); and Field, "Magnetic Telegraph" (n. 10 above).

applications. To implement tight systems of logistical control, one needed inexpensive real-time communication on a twenty-four-hour all-weather, all-year basis. Semaphores simply could not have provided that.

Conclusion

French optical telegraphy represented a highly refined blend of software and hardware generating performance levels in long-distance communication which were, given the limitations of its hardware, quite remarkable. Had the electromagnetic telegraph not become available, French optical technology, or a variant, would have served increasingly as an imperfect substitute for electromagnetic technology, particularly in the transmission of price data on commodity, stock, and bond exchanges. This affirmation of the commercial viability of optical telegraphy does not, however, significantly reduce our estimate of the contribution of electromagnetic technology to economic growth. Although the private demand for telegraph service manifested itself most intensely in these areas, the more substantial social payoff to the electromagnetic device came from its less publicized use by firms to reduce inventory holdings and raise fixed-capital utilization rates in sectors with large minimum efficient scales. Here, optical telegraphy's vulnerability to disruption by the weather, limited channel capacity, and restriction to daylight use would have made it a very imperfect substitute in an age of rail-speed communication.