The Surveying Revolution of 1550–1650: An Examination and Implications for the Current Geospatial Revolution — Part I

N.W.J. Hazelton *

Coolgardie LLC,
2925 Wendys Way,
Anchorage, AK, 99517.

E-mail: nwjh@coolgardie-llc.com

Abstract

The historical development of surveying technology and techniques is briefly reviewed and discussed, with an emphasis on the period 1550–1650 AD. Changes during this time were revolutionary, because technology and techniques, as well as practitioners' worldviews and most theory, were completely changed. The evidence of the rapidity and completeness of that change is still with us today, especially in North America.

The pattern of the change, examined in the larger historical context, shows that the revolution of 1550–1650 has the characteristics of many historical revolutions, such as the Industrial Revolution. A long period of stasis, where little change is apparent over short periods of time (decades); an acceleration of change, culminating in a brief period of very rapid and deep change, which quickly spreads; and a return to a very different stasis. The revolution is not just a technological change, but is a major change in the worldview of the profession as a whole. During the hundred-year period of the revolution, surveying changed from being a local practice to having a global model of its world; from using simple arithmetic and rectangular measurement systems to driving mathematical theory in geodesy and error analysis; from being largely pictorial to being largely computational.

The ideas developed in this paper (Part I) lay the foundation for the discussion in Part II, where the current revolution in surveying and mapping is examined and placed into a similar context.

An earlier version of this paper was published in *SaLIS* (Hazelton, 2012).

Introduction

Throughout history there have been long periods of relative stability, and fairly short periods of rapid change. This process was termed 'punctuated equilibria' in biology (Eldridge and Gould, 1972), but appears relevant to the history of surveying, as well as larger tracts of history. Searching for causes of these periods of rapid change tends to reveal changes in technology that enabled a different approach, or changes in techniques or systems of organization that enabled the rapid changes to occur.

For example, the invention of the plow enabled the development of crop-based agriculture, which in turn ended the hunter-gather lifestyle and economy for much of the world's population, and ultimately propelled humanity on a path to the current high levels of urbanization. Similarly, the Roman Empire was able to expand rapidly and spread Roman culture and control across much of

Europe because it had developed highly efficient military and organizational systems, which enabled rapid conquest and control of areas, without dependence upon a single person in charge.

The surveying profession and the wider geospatial industry are currently in the midst of massive and rapid change. To help with understanding these changes, there may be benefits in examining previous periods of rapid change, to see if there are similarities and lessons that can be drawn from these earlier times.

Such an examination relies upon two important points. The first is that 'human nature,' i.e., the underlying emotions and drives of individuals and groups, remains largely unchanged over time. While people will use different tools and methods, they will still do things for fundamentally the same reasons: self-preservation, fear, a need for security, greed, altruism, self-aggrandizement, and the like. The second point is that the historical record is incomplete and largely written by the 'victors' in any clash of groups or ideas. As a consequence, both sides are hard to see, but the evidence of a struggle at one level may reasonably indicate struggles at other levels. If the constancy of human nature is accepted, some appreciation of human characteristics can be applied to fill gaps in the historical record. This may appear speculative, but may also give insights into deeper processes.

The discussion in this paper focuses on European developments in surveying and mathematics. This is because modern international surveying tends to be derived from these traditions, rather than those of Asia. There has been much cross-fertilization between cultures, especially in mathematics. There have also been significant developments in surveying in Asia, but the European developments of 1550-1650 have dominated the subsequent history of surveying internationally, so it is upon these developments that this paper is focused.

Because the primary focus of this paper is an analysis of the changes to surveying caused by the changes in 1550–1650, there is not an exhaustive examination of the traditional historical sources. There is general consensus in the literature about the details of the changes themselves, and they are summarized well by Werner (1966-1968), Kiely (1947), Richeson (1966) and other authors. What is important to the present discussion are the professional changes and what can be learnt to help understand the current geospatial revolution.

This author is certainly not the first to consider the period 1550–1650 a time of revolution in surveying. For example, Schmidt (2008) uses the same term, although his article focuses mostly on technology.

At the start of his seven-part 'Calendar of the Development of Surveying,' Werner (September 1966, p. 866) divided the history of mathematics for surveyors into three stages.

"1. 4,500 BC to 500 AD (approx.): Land and astronomical surveys were holy trades. Offices were held by priests in Babylonia, India, China, Latin America and on the Pacific Islands. Observations and computations were done by the same men.

2. 500 BC to 1,300 AD (approx.): Astronomy was a dominating influence; philosophers and mathematicians developed cosmological theories, but left the surveys of cities and engineering works to others. Geographers emerged and joined the great thinkers in an attempt to construct world maps.

3. 1,300 AD (approx.) to 1,800 AD: Social reforms accompanied by land re-distributions required cadastral surveys, hence maps. Geographers, mathematicians and surveyors combined their efforts. Finally surveyors produced their own mathematicians."

There is an overlap between stages 1 and 2, as cultural change happened at different rates in different parts of the world. But a shift in surveying from being part of a holy occupation to it being 'out-sourced' to specialists can still be discerned. It is at this time (500 BC to 500 AD) that surveying starts to become an independent profession, although professions (in the modern sense) had not been developed at this time.

The discussion in this paper is focused on the 1550-1650 revolution, while Part II focuses on the current (fourth) revolution. This division is purely a matter of convenience, to keep the papers to a more reasonable length.

Before 1550 — The Greek and Roman Influences

There have been several surveying revolutions through history. Depending upon how they are counted, there are at least four. The first was the creation of surveying, as an arm of the religious orders of early societies that needed to deal with taxes, land ownership and the general good order of society. This role allowed surveying to be a key part of the shift from a Neolithic culture to agricultural and artisanal societies. Notice the inter-connection between the development of a very specific discipline and changes in society. The worldview of people before this change was hunter-gatherer, with a possible interest in navigation and tribal boundaries, while afterwards there is a formalism to the process of measuring and marking out land for various purposes. 'Individual ownership' is a new concept that takes root in societies, especially as villages and towns start to appear.

Surveying and mapping had developed along with agrarian society in ancient history. Surveying provided means for taxation of land, construction of buildings, roads, towns, irrigation schemes and monuments, determination of sea routes for trade, and was closely associated with the development of the calendar. Morley and Renfrew (2010) discuss the development of the concept of measurement in ancient societies, through examination of the archaeological record. Often a function of priests and other religious figures, surveying concepts like 'boundary stones' were commonly used as a metaphor for boundary lines between groups of people, and between various types of behavior (e.g., Hosea 5:10). Clearly, the role of surveying in ancient societies was well understood throughout the culture.

The second revolution occurred over several centuries as the Ancient Greek approach to mathematics via geometry was driven, in part, by surveying issues. The codification of geometry allowed surveying to move forward with a sound foundation for solving spatial problems. Ancient Greek culture introduced many major shifts in how a civilization should operate, and surveying was part of these shifts, tied up in the Ancient Greek worldview of comprehension through ordered knowledge. The structure that surveying brings to land and building was also brought to society as a whole, through the medium of Greek thinking in mathematical terms.

Surveying and mapping techniques developed in the Mesopotamian and Egyptian cultures as much through solving practical problems (often by trial and error) as by theory. The Greeks provided surveying with a strong theoretical foundation, as for them geometry was the foundation of all the sciences. Further, Greek mathematics is characterized by deductive reasoning, where logic is used to derive conclusions from definitions and axioms. Previous mathematical work was largely based on inductive reasoning, where a series of observations are used to find heuristic solutions.

Greek mathematical investigations were often based on finding general (i.e., universal, rather than case-specific) solutions to problems of topographic and construction surveying, as the works of Hero (or Heron) of Alexandria indicate (e.g., *Metrica*, *Geodesia*). Hero's work also discusses the use of a simple angle-reading instrument known as a dioptra, able to measure both horizontal and vertical angles (*On the Dioptra*), although whether this instrument was ever constructed is unknown. Hero's surviving writings also seem to indicate a definite connection to the practical solutions of Mesopotamia and Egypt, and an attempt to fuse them into the Greek tradition of deductive mathematics (Boyer, 1968).

The Roman Empire was notable for its engineers and surveyors, who were able to accomplish many major construction works. The presence of straight roads and rectangular town plans, as well as extensive aqueducts, sewerage and drainage systems, indicate their skills in this field. It is noticeable, however, that the Roman culture produced no notable mathematicians, and that once a certain level of practical skill had been achieved in surveying, subsequent development was very slow.

This is not to say that surveying was not an important part of the culture. The Romans established cadastral surveying as a distinct occupation or profession, and general surveying was one of the practical subjects taught in Roman academies. In 540 AD Cassiodorus of Rome reported on land surveying that "The professors of this science [of land surveying] are honored with a more earnest attention than falls to the lot of any other philosophers. Arithmetic, theoretical geometry, astronomy, and music are discoursed to listless audiences, sometimes to empty benches." (Kiely, 1947, pp. 43-44.) Surveying at the time apparently had little need for arithmetic, theoretical geometry and astronomy.

By around 150 AD, surveying had a solid mathematical foundation, courtesy of the Greek mathematicians, as well as an extensive body of application, courtesy of the Roman surveyors. After the major advances of the Greek mathematicians (c. 600 BC to 150 AD), very little happened over the next 1,400 years to change either theory or methods. As Werner notes about the period from the 7th to the 15th centuries AD: "The so-called 'lull' period in the development of surveying in Europe probably occurred because surveying was highly developed and satisfied the given circumstances." (Werner, March 1967, p. 29.)

Surveys were done largely using the gnomon or similar triangles to set out right angles, as the dioptra appears to have been lost in antiquity. Distances were measured using simple techniques, cords and ropes, and the largely orthogonal arrangements meant that simple addition and subtraction covered most of the computations. As a consequence of the limitations on distance measurement, surveys tended to be local in extent. Mapping was as much pictorial as cartographic, and showed what you could see, usually without the benefit of perspective. In summary, surveying and mapping were locally-focused, used arithmetic rather than mathematics for much of the work, and based the field and office techniques around the technology of the day, largely the gnomon and knotted rope.

The European Renaissance

The earliest sparks of the Renaissance appeared in northern Italy, perhaps as early as the 12th century. More conventional starting dates are centered around 1400 AD. This places it after the plague of the Black Death (1348–1350), which had a major effect on political and social structures of the day, and allowed the flourishing of new approaches to art and, later, science. The fall of the Byzantine Empire in 1453 brought scholars from Constantinople with Ancient Greek works that were new to Western Europe, which helped spark changes that were both scientific and humanistic.

The discovery of the New World by Columbus in 1492 changed European ideas about geography and consequently their thinking about the world. The focus on Europe and something towards the East shifted to a more global perspective. In 1543, Vesalius published one of the first modern works on human anatomy (*De humani corporis fabrica*), and Copernicus' book on the heliocentric solar system (*De Revolutionibus orbium coelestium*) was published posthumously. Galileo, Tycho Brahe and Kepler made major advances in astronomical and scientific understanding. But perhaps the greatest advance of this time was the development of 'the scientific method.' This was a major cultural change for Europe.

"Rapid accumulation of knowledge, which has characterized the development of science since the 17th century, had never occurred before that time. The new kind of scientific activity emerged only in a few countries of Western Europe, and it was restricted to that small area for about two hundred years. (Since the 19th century, scientific knowledge has been assimilated by the rest of the world.) This assimilation has not occurred through the incorporation of science into the cultures and institutions of the different societies. Instead it has occurred through the diffusion of the patterns of scientific activity and scientific roles from Western Europe to the other parts of the world." (Ben-David, 1984, p. 21.)

Ben-David (1984, p. 26) noted that the mechanicians (engineers) of the day resisted the development of science, as did the academics, the clergy, and various metaphysical philosophers. However, many of the developments in surveying came from both the scientists and the mechanicians. Surveying encompassed both theoretical and practical problems, so developments in one area led to a need for developments in the other.

By 1550 AD the Renaissance was in full swing across Europe. From Russia and Hungary to Portugal, from Italy to England and the Netherlands, changes in politics, arts, sciences, mechanics, religion, thought and everyday life were happening very quickly, compared to previous times. The advent of the printing press and cheap paper made the dissemination of ideas and knowledge quick, cheap and easy, and changed the way that learning occurred. Travel around Europe became easier, especially between universities and cultural centers, which helped the rapid spread of new ideas and knowledge.

When there are major changes in some of the various systems in society, it is hardly surprising that changes occur in other social systems. No part of a social organization can be isolated from the other parts; every part influences the rest. So it was impossible that surveying, largely unchanged since the days of the Roman Empire, should remain unchanged amid these society-wide changes.

Werner (March 1967, p. 33) noted that there were four primary reasons for the advances in surveying that started occurring at this time:

1. Disintegration of feudalism and changes in agriculture;
2. Discovery of new lands, navigation, astronomy, cartography, and printing;
3. Warfare, as the artillery that was coming into use needed bearings and distances; and
4. The need to resolve the dispute between the heliocentric and geocentric planetary systems, which required more precise instruments.

Richeson (1966) notes that advances in learning in general and science in particular, especially mathematics, the introduction of the Hindu-Arabic numbering and related calculation system, the interest in astronomy at Merton College, Oxford (and their need for more precise instruments), together with the standardization of the units of land measures, were critical steps leading to the advances of the sixteenth century. "By the close of the fifteen century, the accumulated effects of these factors were having their effects on land surveying. Likewise, the rise in the economic level of the country brought about an increase in the value of the arable land which, in turn, produced greater demands on the land surveyor." (Richeson, 1966, p. 28.)

This indicates that there were several areas of change in the larger social structure that had a significant effect on surveying. In fact, these changes accelerated the rate of change in surveying, as well as the degree of completeness of the changes in surveying.

Another critical change happening in Europe was the rise of professions. The growth of knowledge, as well as the acceleration in the growth of knowledge, had left the older apprenticeship system of educating the next generation of professionals unable to keep up. Further, the guild system was based on closed systems of knowledge, while the new ideas driving science were based on open access to knowledge. The guilds became less relevant to the growing areas of professional practice, and universities (now becoming centers of open knowledge and knowledge creation) began to focus on educating professionals. While law and theology had been regular subjects, a greater focus on the sciences, especially related to medicine, also occurred. In time, engineering and surveying became a larger part of universities' professional focus.

The general upswing in scientific knowledge, together with the growth of the European population, meant that there were larger markets for all manner of commodities and products. As professions grew, offering wider services, there was a need for increased production, which pushed the need for manufacturing as a large-scale enterprise. What was needed was a large workforce that could support large-scale production. This was achieved in Britain through enclosure of common land, which had the effect of removing a large proportion of tenant farmers from agriculture, and allowed extensive grazing of sheep. The conversion of arable land to pasture reduced the agricultural workforce required, while improving the landowners' profits.

At the same time as lands were enclosed, Britain experienced major population growth: a 280% increase from 1550 to 1820, while the rest of Western Europe grew 50% to 80%. 70% of European urbanization happened in Britain, 1750 to 1800. Urban populations flourished, and so did their need for food, shelter and other materials. Britain was in the fortunate situation to have substantial reserves of coal, iron ore and other raw materials close to urban centers, as well as coastal shipping and rivers to enable easy supply by water (at the time the only viable means of transport for large volumes of materials).

The rapidly growing urban population, joined by displaced agricultural people, provided a cheap workforce for large-scale manufacturing. The presence of flowing water allowed water-powered factories (known as 'mills') and the rapid movement of raw and finished materials. The development of manufacturing machinery expanded to encompass agricultural machinery, forcing even more people from agriculture to the urban areas, as agricultural efficiency improved dramatically.

Enclosure of land in Britain had not been a smooth process. At times it was outlawed, and at others encouraged by Parliament. There were several peasant uprisings against the practice, beginning around 1549 with Kett's Rebellion, while the last was the Newton Rebellion of June, 1607, where a pitched battle left some 40 to 50 dead (Greenall, 1979). The claims by the peasants of traditional and constitutional rights granted to the free and sturdy English yeoman were to have a significant impact on the Enlightenment thinking that was to help develop the modern era.

While the period 1550–1650 pre-dates the Industrial Revolution by at least a century, there are changes happening during this time that set up the conditions for the massive changes from an agrarian economy to a manufacturing economy in Britain. While it can be argued that the fence was the critical piece of technology that really started the Industrial Revolution, by forcing the movement of people from rural to urban areas, there was a convergence of technologies and ideas that established the scene for rapid change. The same process also fed the idea of rights for all people into the philosophical discussions of the time, including both scientific and philosophical components into the Enlightenment.

Surveying and Mapping Inventions and Developments

After 1500 AD there was a rising tempo of developments in surveying and mapping. Even using older techniques, there was growing interest in mapping entire kingdoms, Germany and Russia being two regions that started such mapping efforts. In 1512 Waldseemüller of Germany introduced the *polimetrum*, apparently the first modern European instrument for measuring angles, which was further developed by Leonard Digges of England (the *theodolitus* of 1571) and many others. Interestingly, there seem to be several simultaneous and independent 'inventions' of the theodolite, which suggests that the need for such an instrument was becoming apparent across much of Europe. What is also fascinating is speculation about the inter-communication that may have led to these parallel development, as well as bringing ideas from Chinese, Indian, Greek and Mesopotamian scholars and surveyors through the ages to Europe through contacts with the Mongol and Muslim cultures pressing into Europe from the east after 1100 AD.

Fitzherbert (1523) published the first surveying textbook in English (although it was focused on land management, rather than land measurement), and the Pynson company published many such textbooks up to 1700. Leonard Digges published his first book on surveying in 1556, after studying at Oxford and being influenced by continental surveying practices. Agricola of Chemnitz, Germany, included a chapter on mining surveying in his mining text of 1530. Frisius, a professor of medicine at Louvain University in Holland, gave the first detailed description of triangulation in 1529. Nunez, professor of mathematics at Coimbra, Portugal, designed a forerunner of the vernier (developed in 1631), allowing angular measurement to fractions of 30 minutes of arc. Nunez also determined how to find a rhumbline (or loxodrome) for direct navigation. In 1547, the first of a series of improved designs for levels appeared, and development continued for over the coming 150 years in Italy, France, Germany and Poland.

Around 1500, indexing was introduced into libraries, allowing easier searching, and became a critical technology for open knowledge institutions. Logarithms were first discussed by Burgi in a publication of that name in 1607, and extended by Napier in 1614. Napier's bones were developed in 1617 as a means of tabular arithmetic calculation (a form of abacus), and were soon augmented by the slide rule (developed in 1620): a mere 13 years took calculation from being totally by hand to the introduction of the slide rule. Ciermans suggested the design of an adding machine in 1640, and Pascal built one in 1642. Gethaldi developed algebraic geometry in 1630, and Descartes (1637) and Fermat (1640) developed analytical geometry. This allowed the use of co-ordinates for plane surveying computations.

Foullon of Versailles, France, described a plane table with a complex but versatile alidade in 1551. In 1574, Reinhold of Saalfeld, Thuringia (Germany) wrote in his book on proper surveying methods that using a wire for measuring distances was preferable to hempcord. Meanwhile, various developments of rods for distance measurement were occurring, and by 1600 a chain of 100 links was introduced in England for distance measurements.

In 1616, Rathborne's textbook *The Surveyor* called for "proper education of English surveyors and not just to teach them tricks and make jugglers out of them; he described the 'theodelite, the playne table, the circumferentor and the peractor' (a segment of a circle covered with sine lines for the reduction of slope distances)." Werner, March, 1967, p. 38.) Rathborne also discussed traverses, their measurement and computation, the first description of the tripod, and the concept of backsights (Richeson, 1966). Units of length were standardized in several countries to facilitate commerce and measurement in general.

The telescope was developed during this same period and early experiments with lenses for surveying appear to have been undertaken by Digges prior to 1571. Bourne in England wrote about convex lenses in 1585, and Della Porta of Naples discussed compound lenses in 1589. Kepler produced an astronomical telescope for surveyors in 1610, and Huygens refined lens making to reduce spherical and chromatic aberration around the same time. Snellius (Snell) published the sine law of refraction in 1621, and Descartes demonstrated the limitations of spherical lenses in 1637. By 1638, telescopes fitted with crosshairs of various materials had been developed, and in 1639 Gascoyne of England developed a movable crosshair, allowing the eventual development of self-reducing tacheometers. In 1640, he used fine spider web for the crosshairs.

Triangulation had been discussed by several people, and Tycho Brahe had used a simple version to connect Denmark and Sweden across the Öresund (through the island of Hven) in 1579. Snellius of Holland developed the baseline extension net and resection, and started serious triangulation surveys around 1615. Norwood measured an arc between London and York by chain in 1633, and probably used thermometers, microscopes and telescopes as part of the work.

Isaac Newton postulated around 1665 that the Earth was an oblate ellipsoid or spheroid, based on the rotation of a liquid Earth at some point in the past, but did not have a good value for the radius to do more detailed computations. Picard supplied a reasonable value in 1671, allowing improved calculations in Newton's *Principia* (1687). Subsequent extensions of Picard's arc of a meridian across France by G.D. Cassini (1683) and La Hire, J. Cassini and Maraldi (1700–1716), as well as J. Cassini's re-measurement of Picard's arc in 1710, gave a figure of the Earth as a prolate ellipsoid. This led to a major controversy between the French (supporting the Cassinis) and the English (supporting Newton) that lasted until more accurate measurements in Peru (now in Ecuador) and Lappland (1734–1742) confirmed Newton's model of the oblate ellipsoid and, as was said at the time (in England), flattened both the Earth and the Cassinis at the same time. After this, debate continued as to the exact shape and size of the Earth, as measurement precision continued to improve.

Also developed during this time period were methods for simplifying calculations. Trigonometric tables were developed using the angle as the argument, whereas they had formerly been calculated using the lengths of the sides of triangles, or tabulated using chord lengths. Some early theodolites were graduated so that they could be read directly in tangent and cotangent values, rather than angles, to simplify calculation. Surveyors were encouraged to use logarithms and trigonometric tables for calculation by Rathborne in 1616.

The above are a sample of the more critical developments around the period 1550–1650. Comparing the technology available at the end of this period with the technology and techniques available at the beginning shows the rapidity of change that had occurred.

An interesting piece of confirmation of the rapidity of the change can be seen in surveying in North America. In the various collection of surveying equipment from the North American colonial era, one can find all manner of interesting instruments, but nothing seems to exist of the instruments in common use prior to around 1550 AD. Successful settlement north of Florida by European powers other than Spain began after 1600, and early surveyors brought their instruments with them from Europe. There is apparently no evidence that colonial era surveyors used equipment that pre-dated the 1550–1650 surveying revolution, so it can be reasonably surmised that the new methods and instruments had quickly swept through surveying practitioners in Europe, so that no pre-1550 surveying equipment made it to North America during the period of settlement after 1600 in the northeast.

As a further indication of the rates of change in surveying equipment, which continued with on-going development and refinement after 1650, one of the reasons given for retaining Mason and Dixon in 1763 to resolve the boundary between Maryland and Pennsylvania was that they had more modern surveying equipment than could be found in the colonies. However, by 1784 local surveyors had equipment capable of extending the boundary with the same precision (Hicks, 1904, p. 32). It should be noted that this more modern equipment varied from the earlier instruments developed during the 1550-1650 period in refinement and precision, rather than major differences in function.

As a further indication of instrument development, Alder (2002) discusses the methods and instruments used by Delambre and Méchain in the survey of the Paris meridian, 1792-1799, from Dunkerque to Barcelona. The Borda repeating circle, used for both horizontal angles in the triangulation and vertical angles for astronomical observations, was capable of producing reduced angles to around 1.5 seconds of arc, a significant improvement over the best instruments of the 1770s, which could do no better than 15 seconds of arc. The English theodolite made by Jesse Ramsden in 1785 could work to about 2 seconds of arc, but weighed about 91 kg, compared to the 9 kg of the Borda repeating circle. Surveying angle measurements to consistently better than one second of arc would have to wait for glass circle theodolites in the early 20th century, in particular the Wild T3, first produced in 1927.

Consequences of the Changes 1550–1650

An examination of surveying prior to 1550 reveals a general pattern of work. Instrumentation was primarily knotted ropes for distance, similar triangles (occasionally the groma) for setting right angles, and sketching materials for local maps. Basic leveling was possible with squares and plumb bobs, and sometimes water levels. Surveying was very much local, and while there was some interest in mapping larger areas, most work was as much pictorial as representational. Very little had changed since the height of the Roman era, over a thousand years before, as materials, methods and worldview were largely unchanged.

After a period of slow development of supporting technologies and methods between about 1400 and 1550, the hundred-year period 1550–1650 saw a rush of technological change in surveying and mapping. The means to undertake traverses, triangulation, resection and quality distance measurements were introduced across Europe. At the same time, computational capabilities expanded rapidly, with logarithms, slide rules and trigonometry tables based on angles being introduced. With the development of co-ordinates and higher precision measurement, it became possible to develop high quality maps. Triangulation and the plane table allowed massive expansion of high precision mapping that could cover entire countries and soon continents.

At the end of this hundred years of major change, surveying was mathematical and becoming more so, computations were highly complex, measurement was far more precise, and methods were totally different to a mere century before. Mapping had shifted from local and approximate to continental and precise.

Around 1650, a major question that was starting to be asked was: What is the exact size and shape of the Earth? Debate would rage for another eighty years before the general shape was settled. Such a question was almost inconceivable in 1550: the Earth was known to be a sphere of uncertain size, and that was the extent of what was known. There were no instruments that could produce sufficiently precise measurements to improve that knowledge. Little had changed from the Ancient Greeks' state of knowledge 1,500 years before. But by 1750 geodesists were investigating gravity anomalies, and soon after were considering tri-axial ellipsoids as a better approximation to the figure of the Earth.

Not all of the major changes happened in the period 1550–1650, but this period saw the changes with the most profound impact on the surveying profession, as well as the world in which it worked. Of course, not everyone changed how they worked when new types of equipment were introduced, but word spread and as the dissemination of knowledge had also sped up dramatically, so new technology and techniques moved into use far faster than they ever had before.

The changes were not simply technological. The new technology enabled new methods, which enabled a different approach to surveying and mapping. The power of the new technologies was such that they totally changed the surveyor's worldview: from local to planetary in scope; from a purely practical trade to a highly mathematical profession.

There could be no going back to the old technology and methods. Demand for new services in location and mapping meant that it was impossible to consider abandoning the new technology. Given human nature, who would want to go back to more difficult, slower, limited and less precise techniques? The new technologies would be continuously improved and new techniques added, but the fundamental situation remained largely unchanged from about 1650 to 1950. Traverses and triangulation using theodolites, tapes and chains would remain the core tools of surveying and the backbone of surveying control across the world. The plane table would remain the primary mapping system, and logarithms and slides rules the primary computational tools.

Upon this foundation, generations of surveyors, mappers and geodesists were able to attempt work that could not be imagined before 1550. It was possible to create the meter unit, based on precise measurements of the planet (Alder, 2002). It was possible to move huge tracts of land into private ownership in North America and Australasia, based on cadastral surveys, a move that created modern economies and modern democracies. The possibilities kept expanding, limited only by human imagination and ingenuity.

In summary, over a 100-year period there was a total change in the nature of surveying. This change encompassed:

- Changes in technology;
- Changes in techniques;
- Changes in scale of operations (from local to global);
- Changes in methods of working (great increase in mathematics); and
- Changes in focus areas (mindset).

The specific characteristics of these changes were as follows:

- A slow build-up of various technologies in parallel, then the introduction of a small number of integrated technological changes in a short period of time, creating a 'tipping point,' followed by a rapid series of fundamental changes, transforming the entire discipline;
- Complete change or transformation, across the entire discipline, once the technological tipping point was reached;
- An initially accelerating rate of change, followed by the rapid transformation of the discipline after reaching the tipping point;
- Key technologies that together with larger societal change drove fundamental transformations in the discipline.

In the 1550–1650 surveying revolution, the combination of powerful computational tools, triangulation, resection and the plane table, together with changes in political, economic and social systems, drove increasing precision in measurement, global mapping, radical changes in land distribution, and a totally changed role and mindset for practitioners in the discipline.

These changes were rapid (compared to the prior rate of change) and comprehensive: almost nothing remained of the prior methods and equipment. This speed and completeness are characteristic of the changes that revolutions bring. Revolutions change history; indeed "revolutions are the locomotives of history." Therefore the term 'revolution' is properly applied to this period in the history of surveying.

The changes in surveying and mapping were largely complete by around 1650. Combined with other social changes, the surveying and mapping professions were able to help set the scene for the massive changes brought by the Industrial Revolution. With the changes brought about by the application of water power, and later steam, to run large-scale machines, combined with a large workforce that could be paid cheaply and the ready availability of suitable raw materials, the Industrial Revolution was getting moving by 1750 in Britain.

What is of importance to note is that the technological change happens first. It is gradual and piecemeal, but related changes allow its spread. The technological changes drive theoretical changes, which then drive mindset and organizational changes. As an example of a scientific and technological revolution, it is interesting to note that it is largely complete a century before the Industrial Revolution begins in earnest.

With the Industrial Revolution came the change from agrarian economies to manufacturing economies, together with the rise of economics as a science, and massive changes in how people lived. It has been pointed out that: "For the first time in history, the living standards of the masses of ordinary people have begun to undergo sustained growth.... Nothing remotely like this economic behavior is mentioned by the classical economists, even as a theoretical possibility" (Lucas, 2002, pp. 109-110). The economic systems of the previous agricultural age were totally replaced by the economic systems of the industrial age. The Industrial Revolution started a period of economic growth in human society that was unprecedented in history, and continues to spread across the globe.

Discussion

Looking at the 1550–1650 surveying revolution, it can be seen that there is a definite progression that forms ahead of the moment when the revolution takes off. There is an existing solution to existing problems that seems adequate, but there is a slow introduction of some small piece of new technology, which triggers other new technologies, techniques and theory. This builds to a critical mass, whereupon there is a sudden change brought about by collections of these technologies working together. This is the tipping point of the revolution, accompanied by a rush of new concepts and a burgeoning of new ideas. Eventually things settle down into the new pattern, but there has been a total change compared to before the revolution.

In surveying, we see a fairly steady pattern for over a millennium prior to about 1500. Then there is a slow development of new technologies and ideas, in parallel with other new ideas and technology appearing in the wider society. By around 1550 there is the technology to measure angles over large distances starting to be developed, and with it comes changes to trigonometric tables. This slowly improves, and is joined by plane tables and better distance measurement equipment over the next 60 years. While it seems slow today, it is reasonable to suppose that many surveyors during the period c. 1550–1610 were caught in the changing and improving technology of the period, along with the development of improved theory and techniques to support the technology. The presence of early textbooks indicates a growing need to disseminate knowledge in ways foreign to the closed system of the guilds, as well as a growing audience with both interest and the funds to buy books. Printing with moveable type was started by Gutenberg in the mid-1450s, so the rise of surveying textbooks began within 80 years of the creation of the technology to create them.

Up to this point, development was of the ‘better, faster, cheaper’ form, but still undertaking similar work as had been done for the previous millennium. Then in a fairly short period, between about 1610 and 1620, there is a succession of rapid changes. Triangulation is developed to the point where continental-scale networks are possible, telescopes are included in angle-measuring instruments, calculation is made far faster and easier using logarithms, and soon after analytical geometry is introduced.

This period of rapid change, occurring after an accelerating period of technological change, altered not only what was possible for the surveying and mapping industry, but also its entire worldview. The change is rapid and apparently complete, as emphasized by the absence of any pre-revolution surveying equipment in North America.

After the rush of 1610 to 1620, there is still more to come, but the big change occurred in that decade. It occurred not just in the technology and theory, but also in the hearts and minds of the practitioners. The changes after 1620 were probably far more acceptable to practitioners, as they helped build out the new model of surveying and mapping as activities that could, and should, occur at a planetary scale.

After 1650, there were still major changes coming. Least squares adjustment and calculus were still to come, but they were able to fit into the new model and extend it, rather than change it.

How does this fit the concept of punctuated equilibria discussed in the Introduction? ‘Punctuated equilibria’ is the idea that a species stays in a relatively static state (stasis) most of the time, but that occasionally there will be periods of very rapid change, leading to the development of a new species. This is not to say that there is no change during the periods of stasis, merely that there are no major changes from one generation to the next. Gradual change and development can happen all the time. In surveying, there was little change over the millennium prior to about 1500.

Eldridge and Gould (1972) were concerned with periods of geological time, so a 'rapid event' in their context could be tens of millennia. In the historical context, the 'rapid event' would be measured in decades, and the larger the group concerned, the longer the 'rapid event.' So the surveying revolution, occurring among a fairly small segment of society, took about a century, with perhaps one to two decades of the most frantic change. The outcome of this change was a new 'species,' the modern surveyor. With this new species came new social organizations and rituals over time, e.g., professional bodies, state registration, and university programs.

By contrast, the Industrial Revolution started around 1750 and is still occurring in many countries, when considered on a global scale. But the Industrial Revolution, considered on a national scale, has also created a new 'species:' the industrial economy. This new species also generated new social organizations and rituals over time, e.g., unions, the nuclear family, economics, and MBAs.

Both these new species have been so successful that they have largely replaced the previous species. With surveying, the changes can happen over one person's working life, a few decades. As the rapid changes in equipment and techniques suggest, supported by the technology used in North America in the colonial era, the previous species went extinct in Western Europe very quickly. By contrast, industrialization may take over a century to become fully established.

One last point to note is that in the same way that the creation of a new species cannot be reversed, so major historical changes cannot be undone. Once the light of a new model of the world has been revealed, it cannot be shut off again. The analogy of the Garden of Eden is relevant here: once the fruit of knowledge has been consumed, it is impossible to go back to the 'blissful ignorance' of the past situation.

Conclusions

An examination of the progress of the surveying revolution of 1550–1650, placed in its historic context, indicates a very specific pattern of development. The long, slow build-up of new technology and ideas, accelerating in its last few decades, culminate in a decade of revolutionary change. The primary indicator of the change is not the technology, but the mindset and worldview that run with it. After the brief peak of revolutionary change, there is a period of continued rapid change, as the entire body of practitioners shifts to the new model of the world.

Viewed in the context of the 1500-year period between c. 400 AD to 1900 AD, there was a period of stasis up to around 1400 AD. Technological change started very slowly around this time, but was almost unnoticed until around 1550 AD, when technology, technique and theory started to change collectively and symbiotically. The rate of change began to accelerate, and the changes began to spread across societies and nations, aided by improvements in the communication of ideas and the movement of people.

The accelerating rate of change continued to throw up new technologies, techniques and theories, which culminate in a brief period around 1610 to 1620 AD, when the critical technologies, techniques and theories come together. At this point, the possibilities become manifest. Suddenly, the world is different, because the collective worldview has changed. Surveying has suddenly moved from local to global, from pictorial to computational, from arithmetic to mathematical.

These changes did not happen only among a select few, such as the high-level theorists; they swept across the entire body of practitioners. Over the next few decades, a single working generation, there is nothing left of the old ways to transplant to the New World. The new species of surveyor has completely replaced the previous species, and European exploration carries that new species to all parts of the planet.

After things settle down into the new model, around 1650 AD, surveying enters another period of stasis. Major changes occur around surveying, such as the development of calculus, least squares and the Industrial Revolution, with relatively little change in the core worldview. The larger surveying profession was busy determining the exact size and shape of the planet, mapping in finer detail, supporting development, and aiding the explosion of private land ownership. Details and jobs changed, but the worldview remained largely unchanged from generation to generation.

Having established the general pattern of the change process, and the nature of the punctuated equilibrium of surveying's development in the period c. 400AD to 1900 AD, the question is: Can this understanding of one episode of revolutionary change help us understand the current changes affecting surveying, and the wider geospatial professions?

Part II of this paper will attempt to transfer that understanding to the period from 1950 AD. It is generally acknowledged that surveying has been undergoing major, if not revolutionary change since that time, and we may be able to understand this process better in the light of the third surveying revolution.

Acknowledgements

The original impetus for this paper came from the St. Cloud State University student team that competed at the ACSM Student Competition in Salt Lake City, UT, in January, 2009. In particular, Casey Crisp and Cole Kelleher focused my attention on the technological developments associated with surveying computations, and the broader context in which these changes occurred. The involvement of Tom Lambrecht, Matt Schoenrock and Travis Suedel, the other members of the team, was also invaluable in developing some of the initial ideas behind this paper. Some of the ideas in this paper were discussed at the Professional Land Surveyors of Oregon and GIS in Action Joint Conference in March, 2012, and the positive feedback from that presentation is appreciated.

Some of the ideas and connections discussed in this paper have come about from fruitful discussions with many colleagues over the years, in particular: Ian Williamson, the global cadastral systems expert; Frank Leahy and Sjef Bervoets, whose forward-looking approach to surveying and photogrammetry remains fresh and relevant decades later; John Bossler and Ivan Mueller, who have always been ahead of their time; and Dean Ringle, Bob Mergel and Willy Schmidt, who provided invaluable insights into US surveying.

References

Alder, K., 2002. *The Measure of All Things: The Seven-Year Odyssey and Hidden Error That Transformed the World*. New York: The Free Press.

Ben-David, J., 1984. *The Scientist's Role in Society: A Comparative Study*. Chicago: University of Chicago Press.

Boyer, C.B., 1968. *A History of Mathematics*. New York: Wiley.

Eldredge, N., and Gould, S.J., 1972. “Punctuated equilibria: an alternative to phyletic gradualism.” In: Schopf, T.J.M., (ed.), *Models in Paleobiology*. San Francisco: Freeman Cooper. pp. 82-115.

Fitzherbert, A., 1523. *The Boke of Surveying and Improvements*. London: Pynson.

Greenall, R.L., 1979. *A History of Northamptonshire*. Chichester, UK: Phillimore and Co.

Hazelton, N.W.J., 2012. The Surveying Revolution of 1550-1650: Implications for the Current Geospatial Revolution—Part I. *Surveying and Land Information Science*, Vol. 72, No. 3, pp. 129–139.

Hicks, F., 1904. “Biographical Sketch of Thomas Hutchins.” In: Hicks, F., *A Topographical Description of Virginia, Pennsylvania, Maryland and North Carolina, reprinted from the original edition of 1778*. Cleveland: The Burrow Brothers Company.

Kiely, E.R., 1947. *Surveying Instruments, Their History and Class Use*. New York: Bureau of Publications, Teachers College, Columbia University.

Lucas, R.E., 2002. *Lectures on Economic Growth*. Cambridge: Harvard University Press.

Morley, I., and Renfrew, C., (eds.) 2010. *The Archaeology of Measurement. Comprehending Heaven, Earth and Time in Ancient Societies*. Cambridge, UK: Cambridge University Press.

Rathborne, A., 1616. *The Surveyor in Foure Bookes*. London: W. Burre.

Richeson, A.W., 1966. *English Land Measuring to 1800: Instruments and Practices*. Cambridge, MA: The M.I.T. Press.

Schmidt, W.A., 2008. “Second Thoughts: The Earlier Revolution in Surveying circa 1600.” *Professional Surveyor Magazine*, Vol. 28, No. 2, February, 2008.

Werner, A.P.H., 1966–1968. “A Calendar of the Development of Surveying.” *The Australian Surveyor*, Vol. 21, No. 3, September, 1966, pp. 847-874; Vol. 21, No. 4, December, 1966, pp. 927-947; Vol. 21, No. 5, March, 1967, pp. 27-48; Vol. 21, No. 6, June, 1967, pp. 145-166; Vol. 21, No. 7, September, 1957, pp. 265-289; Vol. 21, No. 8, December, 1967, pp. 332-355; Vol. 22, No. 1, March, 1968, pp. 43-81; Vol. 22, No. 2, June, 1968, pp. 131-141. Also Letters, Vol. 23, No. 3, September, 1970, p. 212.