The Quest for the True Figure of the Earth

Ideas and Expeditions in Four Centuries of Geodesy

Michael Rand Hoare

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Science, Technology and Culture, 1700-1945

THE QUEST FOR THE TRUE FIGURE OF THE EARTH

In the 1730s two expeditions set out from Paris on extraordinary journeys; the first was destined for the equatorial region of Peru, the second headed north towards the Arctic Circle. Although the eighteenth century witnessed numerous such adventures, these expeditions were different. Rather than seeking new lands to conquer or mineral wealth to exploit, their primary objectives were scientific: to determine the Earth's precise shape by measuring the variation of a degree of latitude at points separated as nearly as possible by a whole quadrant of the globe between Equator and North Pole.

Although such information had consequences for navigation and cartography, the motivation was not simply utilitarian. Rather it was one theme among many in an intellectual revolution in which advances in mathematics paralleled philosophical strife, and reputations of the living and the dead stood to be elevated or destroyed. In particular the two expeditions hoped to prove the correctness of Isaac Newton's prediction that the Earth is not a perfect sphere, but flattened at the poles.

In this study, the 'Figure of the Earth' controversy is for the first time comprehensively explored in all its several dimensions. It shows how a largely neglected episode of European science that produced no spectacular process or artefact – beyond a relatively minor improvement in maps – nevertheless represents an almost unique combination of theoretical prediction and empirical method. It also details the suffering of the two teams of scientists in very different extremes of climate, whose sacrifices for the sake of knowledge rather than colonial gain, caught the imagination of the literary world of the time.

About the Author

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The Quest for the True Figure of the Earth

Ideas and Expeditions in Four Centuries of Geodesy

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Author's Preface

The purpose of this book is to explore the rich history of that branch of the art and science of land-surveying which for more than three centuries has been devoted to determining the precise shape of 'our terraqueous planet'. This speciality, that of determining the 'Figure of the Earth' ('Figure de la Terre') as it early became known, gave rise to the subject of *geodesy*, or *geodetics*, and with it a step-change in the accuracy previously required in the more quotidian process of map-making. At the same time it embraced the related activity of *gravimetry*, which is to say the measurement of the force of gravity and its subtle variation on, and eventually even above and below, the surface of the Earth. In striving for ever increasing precision through improvements in instrument design and measurement practices, geodesy aspired to the exactness of astronomy, which until the late seventeenth century had been the lone cynosure of quantitative science.

If the content of this narrative were simply a recital of technical innovation and occasional virtuosity, it would be of lesser import and more marginally related to the broader history of science and ideas which has remained my principal interest throughout. In fact the Figure of the Earth controversy brought to focus an extraordinary contest of philosophies and led to ongoing strife within the academies in which the names and reputations of the greatest of their age, Descartes, Newton, Voltaire and Maupertuis among many others, were put to test along with, one can almost say, the very honour of nations.

The second aspect that sets the Figure of the Earth problem apart from better known scientific achievements is the remarkable investment of human courage and ingenuity that it demanded of its devotees. That this courage was in large part physical as well as intellectual is underlined by the prominent part played by the expeditions that at intervals set out for some of the most inhospitable parts of the Earth and which entailed suffering and fortitude on a scale previously only associated with conquests by land and sea, the latter as likely of a mercenary nature as driven by geographical curiosity. This element of sacrifice in the name of science rather than domination and wealth was not lost on the literary world, particularly at the height of the French Enlightenment, and can be seen as a rapprochement of Science and Letters that has rarely since proved as intimate.

Certain compromises have been inevitable in the writing of this book. In particular I have decided not to burden the text with more than a smattering of mathematics. The theory of geodetics is both technically and conceptually complex; in the case of early work such as that of Newton and Maupertuis, it must be painstakingly deciphered, while the modern subject has become one of such complexity as to be baffling even to the experienced mathematician. Suitable references are given for those who wish to penetrate further in this direction. Nevertheless some relevant astronomical concepts are explained in detail in Chapter 3, much of which will be only optional reading for those well-versed in the subject. Another decision has been necessary regarding the use of foreign language quotations and translation. While it would burden the text to reproduce both originals and translation in every instance, it would have been a pity to deny more linguistically aware readers the pleasure of reading some of the more striking quotations in French and Spanish. I have therefore given more routinely descriptive passages in translation only, but kept the originals for spirited items of literary interest, especially personal letters and poetry. Where such are quoted I have, except in minor detail, retained the often quaint and inconsistent orthography of the eighteenth century for additional flavour. Translations are my own responsibility throughout.

Somewhat against present trends I have adhered to convention in not referencing any Internet material, whether seemingly ephemeral or not. It should be pointed out, nevertheless, that the fund of information available there under the key words *Figure of the Earth* and *Geodesy* is immense, as is the coverage of biographical material for personalities that appear in this book. Adepts will have no difficulty in delving deeper and in more varied directions than I have been able to follow in this work; but equally I believe they may search cyber-space in vain for the kind of considered historical synthesis that can be found in this and other volumes in the present series.

Although research for this work has not been financially supported, I am greatly indebted to a variety of individuals and institutions for both information and encouragement. Most numerous are the often anonymous librarians and archivists, principally of the British Library, the Bibliothèque Nationale, the Muséum d'Histoire Naturelle and the Paris Observatory , the Royal Society in London and the University of London Library. Particularly outstanding, however, have been Florence Greffe of the Académie des Sciences Archives and Annie Accary of the Observatory of Paris, who went out of their way to point me towards valuable documentation. Closer to home, I am also indebted especially to Anita McConnell, Professor John Barker, Professor. John Rowlinson, James Smith, Vivian Salmon and Larrie Ferreiro all of whom, not to mention the members of my immediate family, provided invaluable stimulus and encouragement.

Michael Rand Hoare
June 2005

Chapter 1

A Dispute in the Making

In the 1730s two expeditions set out from Paris for what might well be termed the ends of the Earth. The first, under Louis Godin was destined for the equatorial region of Peru; the second, led by Pierre-Louis Moreau de Maupertuis headed north to the Arctic Circle. Several factors set these adventures apart from better-known tales of exploration and conquest. Though under royal patronage, they were initiated by the *Académie Royale des Sciences* , with a common purpose; moreover their members were neither ruffians in search of adventure, nor prospectors after mineral wealth, but rather, for the most part, distinguished scientists, sensitive men, already famous in their fields and with further distinction ahead of them. Both parties suffered great hardships in opposite extremes of climate and were lucky to escape with their lives, the Arctic team nearly shipwrecked, the equatorial party risking fever and assassination. Both, when they struggled back to Paris, found themselves in a sea of back-biting and controversy, such as only the high Enlightenment could provide.

The purpose of the twin expeditions was to determine the Earth's precise shape by measuring the variation of a degree of latitude at points separated as nearly as possible by a whole quadrant of the globe between equator and North Pole. Though some would urge its importance for navigation and cartography, the need for such measurement was not primarily utilitarian; rather it was one theme among many in an intellectual revolution in which advances in mathematics paralleled philosophical strife, and reputations of both the living and the dead stood to rise and fall in the general ferment. Central to this was the newly deceased figure of Isaac Newton, the mathematical giant who, among others, had made a crucial calculation of the shape conformed to by a revolving planet, a prediction which, significantly, had excited far more attention in the volatile intellectual climate of France than in the more staid, to a degree complacent, *Royal Society of London.* Thus the reputation of the English genius of the previous century was tied to a tangible measurement, a matter of *finding out*, and moreover in a manner ironically 'down to Earth', in contrast to the celestial mechanics on which his reputation, and the theory of universal gravitation, had largely turned.

When the results of the two surveys were collated, and Newton's prediction confirmed, French literary circles were as much impressed as the world of Science.

Voltaire, a partisan of Newton since his brief exile in England, went into raptures at the return of the northern expedition, declaring with characteristic hyperbole: 'If your undertakings are those of Archimedes and your courage that of Christopher Columbus, your description of the snows of Tornea is that of Michaelangelo, and those of the aurora borealis are those of Alban...', while more soberly averring that: 'Never have experiment and reason come together in such agreement to prove a truth.'[1] When, in later life, La Condamine, a mainstay of the southern expedition, became one of the few scientists to be admitted to the *Académie Française*, his contemporary Georges Buffon eulogized him for having done: '...par le seul motif de la gloire des Lettres, ce que l'on ne fit jamais pour la soif de l'or: voilà ce qu connaît de vous l'Europe, et ce que dira la posterité...'[2] ['...from the simple motive of the glory of Letters, that which were never done for the glory of gold: this is what Europe knows of you, and what posterity will come to relate'].

Not all were so impressed with Newton's laurels, however, and the controversy over the true shape of the Earth that had bridged the seventeenth and eighteenth centuries would rumble on well into the nineteenth. At its height passions were raised almost to the point of duels being fought, and more than once the dignity of the French nation was held to be at stake. Yet, however interpreted, the achievement of the two expeditions entered deeply into the Enlightenment consciousness; in the great *Encyclopédie* of d'Alembert and Diderot, published in 1751, the entry FIGURE DE LA TERRE ran to no less than twenty-five quarto columns with myriad cross-references, one of the longest articles in that monumental work. The quantitative precision that had hitherto been the preserve of astronomy was given a terrestrial dimension; the previously humdrum profession of the surveyor acquired global significance; and as the new science of geodesy emerged the perfection of measuring instruments was fruitfully paralleled by new mathematical methods far extending Newton's primitive version of the infinitesimal calculus.

In this volume I shall describe the Figure of the Earth controversy in its several dimensions, not neglecting the human actors and its impact on the development of the Enlightenment world-view. I hope to show that this relatively little-known episode in European science, while producing no spectacular process or artefact, beyond a relatively minor improvement in maps and safety at sea, represented an almost unique combination, for its time, of theoretical prediction and empirical method, the latter of a painstaking character worthy of celebration in itself. That it was, as Buffon said, 'for the glory of Letters rather than that of gold' is, moreover, a marker of poignant contact in the sometimes troubled relationship of Science and Literature, no less important for its remoteness from our present-day perceptions.

The history of concern for the geometry of the Earth presents us with a number of stages. Leaving aside the fantastic models of the Ancients – the cylinder of Leucippus, Democritus' hollow disc, the column of Anaxiamander, not to mention

Hercules and the supporting elephants of Hindu tradition – we can discern a progressive refinement of interest paralleled by mathematical sophistication. First, there is the topological conception of the Earth as a three-dimensional ball, assumedly spherical, as reason and aesthetic alike seemed to demand; secondly, the quantitative concern with its dimensions, the measure of the circumference, or equivalently the length of the degree, a matter of more than just maritime interest; thirdly, the raising of doubts as to whether the perfection of the sphere might be perturbed into other forms with rotational symmetry; finally, the onset of doubts as to whether even this element of symmetry might be flawed by the existence of long-range irregularities, beyond those of its superficial mountains and valleys.

The focus of this book is on the third of these stages, and its emergence from the second. The scene is set at the turn of the eighteenth century, in the politically fraught atmosphere that attended the early years of the Académie Royale des Sciences, the prized creation of Louis XIV and his equivocal concession to modernity. But if the focus of events is to be found in France, their range of influence was considerably wider and touched on many orders of national sensibility across Europe, where frequently pride and philosophical tradition conflicted with the unyielding regime of the mechanical world-view, with its respect for reason and measurement over speculation, and its healthy disregard for national boundaries.

To approach the subject from its origins it is necessary to go back over two thousand years. The idea that the spherical Earth was a discovery of the first circumnavigators is, of course, a literary conceit which ignores the whole classical tradition of investigation. Leaving the purely fantastic aside, the first serious moves towards a realistic depiction of the Earth belong to ancient Greece and it was the Greek spirit of geometry that led to an ingenious measurement, in effect the prototype for the modern survey methods almost two millennia later. In the third century BC it was common knowledge in the Egyptian city of Syene that the mid-day Sun at the summer solstice stood precisely at the zenith, and would directly illuminate even the bottom of a deep well. The philosopher Eratosthenes noted that in Alexandria, some distance to the north, this was not the case, and that simultaneously the Sun stood at an angle of some 1/5th of a revolution towards the south. Assuming the rays of sunlight to be parallel, and the two cities to lie on the same meridian, this angle must equal that subtended by the arc between them, just over 7°. (See Figure1.) If the distance between the cities were known, then the length for one degree could be found, and from this the radius, R, of the Earth.[3] Eratosthenes estimated the distance between Alexandria and Syene to be 5,000 'stadia' and this led him to a circumference of 50 x 5,000 stadia for the Earth. Unfortunately we have no precise knowledge of the length of the 'stadium'. Some inspired guesses, perhaps with a suspicion of working backwards from modern units, put the value at about 185 metres.[4] If so, this would make Eratosthenes' estimate some 15 per cent high.

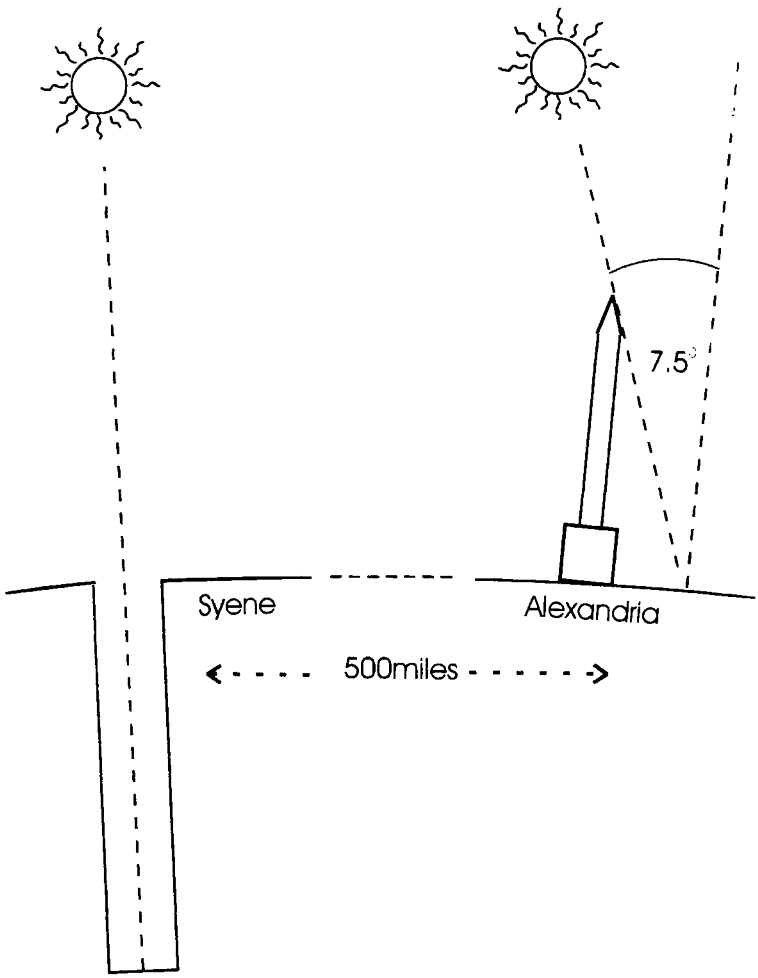

Figure 1 Eratosthenes' method for determining the radius of the Earth

In the first century BC another Greek, Poseidonius, performed similar observations at a greater distance, between Alexandria and the island of Rhodes. He observed that, while the star Canopus lay on the horizon at Rhodes, its elevation at Alexandria was 1/48 of a circle (7°30'). His estimate of the distance, based on the sailing time between the two can hardly have been reliable, and his result, some 11 per cent too high, depending on the stadium, can only be a historical curiosity. Other observations were made in the Chinese and Arab worlds. In the year 724 in the Tang dynasty, the Buddhist astronomer Yixing (一 行) measured the shadows of a standard gnomon along a meridian of some 11,400 Chinese *li* (approximately 5000 km). (Although it is possible to derive an Earth radius from these results,[5] these results,[5] Yixing most certainly did not do so, since the idea of a spherical Earth was inconceivable to the Chinese until suggested nearly eight centuries later by the Jesuit missionaries).[6] A little later, in the year 883, in the time of the caliphs Al-mansur and Al-ma'mum, the Arab astronomer Al-Hâçan ben Schaker measured a meridian of over two degrees, though again the translation into modern units remains doubtful.[7] There matters would appear to have rested, until the first tentative surveys of the sixteenth century. Not surprisingly, interest in the geometry of the Earth was not confined to land surveys, for in practical terms maritime concerns were probably the greater. One of the most succinct reviews of the reasons for believing in the spherical Earth is to be found in Richard Norwood's *Seaman's practice* of 1659. Though the conclusions may be obvious, the simplicity of the arguments can hardly be bettered, and they touch usefully on the astronomy and history involved. This little-known and charming work deserves quotation *in extenso*. Norwood's argument in his original words runs as follows:

> First, the Eclipses, especially of the Moon, which are caused by the shadow of the Body of the Earth being interposed between the Sun and the Moon, and as much as this shadow doth fall upon the Moon, alwayes and on every side circular, and so appears to us, it is manifest by the Optiks, that the Earth from whence it proceeds is a Spherical body.
>
> Secondly, likewise the Eclipses of the Sun, which are caused by the interposition of the Moon beteen the Sunne and those places where it appears Eclipsed; I say it could not be determined when and in what place such an Eclipse should appear, and where not, if the form of the Earth were not known; but seeing the places where such Eclipses happen, and where not, may be and are usually determined, and that upon this ground; that the surface of the Earth is spherical, it is thence also ratified to be a truth.
>
> Thirdly, the Sunne, Moon, and Starres do rise and set, and are upon the Meridian sooner to those that are resident in the Eastern parts, then to others more Westerly, and that in a proportion answerable to the roundnesse of the Earth, as the Planets and stars are up upon our Meridian at *London* sooner by almost four houres, then they are to those that inhabit *Summer Islands*, and the confines of *Virginia* and *New England*; And so in *East-India*, and other Eastern Regions, the Sunne and Starres are sooner upon their Meridian then upon ours, which is manifest to be so, as by other reasons, so especially by the Eclipses of the Moon: for an Eclipse of the Moon hath not in it self any diversity of time, being at one and the same instant without respect of places, yet because in the Eastern parts the day is begun, and it may be far spent before it begin in places farre Westerly, therefore such an Eclipse may appear to the Eastern Inhabitants towards the end of their night, which to the Western appears in the beginning or middle of the same night with them, and so the difference will be more or lesse, according to the different distance of those places in Longitude.
>
> Fourthly, furthermore we see, that going or sayling to the Northwards, we have the Artick Pole and the Southern Stars more elevated, and the Antartick Pole and Northern Starres more depressed, the Elevation Northerly increasing equally, with the depression Southerly, and either of them proportional to the distances we goe: the like happeneth in going to the Southwards. Besides the Oblique Ascensions, Descensions, Occultations, Emersions, and Amplitudes of Rising, and Setting of the

Sunne and Starres, in every several Latitude, agreeing with the *Hypothesis* of the Earths Sphericity.

Fifthly, so if we stand upon the Sea-shore, and see a Ship farre off under sail making towards the Land, at first we see only the Top-sails or highest parts, and withall doe manifestly behold the convex Superficies of the Sea, as it were raised and interposing itself between our sight and the Hull or the lower parts of the Ship, till she approacheth neerer, and this uniformely, every wayes alike, and proportionately to the several distances which evidently demonstrate the Spherical roundnesse thereof.

Sixthly, And lastly, (to adde no more) the Navigations of these later times make it apparent, those especially that have been made around the World, as those two voyages by our famous Countrey-men Sir *Francis Drake*, and Mr. *Thomas Candish*, both which severally sayling from our Coasts to the *West Indies*, and passing the straights of *Magellans*, continued their course Westerly till they came into those parts, which are from us to the Eastwards, namely the *East Indies*, and so sailed still Westerly till they came to *Cap bon Esperance*, and thence returned into *England*, having sailed about the whole Terrestrial Globe, they found nothing by their Observations or reckonings dissonant from the uniforme *Sphericity* thereof in all its parts. That they came short in the number of dayes, one, and reckoned the time of their absence lesse by one day and a night then they which remained at home, this further confirms the thing in hand.[8]

To this we need only add, seventhly, that the Earth when seen from a distant spacecraft is most certainly spherical in appearance, and can be seen to rotate, while finally the rotation of the Earth can now be detected not only by the classic Foucault's pendulum experiment, but even on the laboratory bench using low temperature quantum phenomena.[9]

While in the annals of Science the dramatic locus must pass through the progression Copernicus, Galileo, Kepler and Newton, who between them elucidated the mechanics of planetary motion, concern for the geometry of the heavens was paralleled throughout by a more muted interest in that of the Earth. This showed itself not only in the improvement of instruments and measuring techniques, but also, more subtly, in the ideological shift that followed the abandoning of a geocentric Ptolemaic Universe and acceptance of the heliocentric solar system of Copernicus. None of these trends can be separated from the philosophical forces that contended along the increasingly convoluted frontiers of Religion, Natural Science and secular Philosophy.

In the late seventeenth and early eighteenth centuries, the decades in which the Figure of the Earth controversy became acute, two competing views of natural mechanics were in opposition, each tied to a thinker invested with great national renown. The earlier of the two, René Descartes (1596-1650), was revered in France both as philosopher of the Mind and as 'Geometer', which is to say 'Applied Mathematician' in modern terms. In his philosophical mode he was credited with bringing to an end the centuries of scholasticism and the almost unquestioned domination of Aristotle as the exemplary scientist and thinker. While the praise he received for his *Discours de la Methode* was certainly justified, its reputation served to deflect criticism of his eccentric excursions into physiology and geology and, above all, his theory of the solar system. For, while his enduring achievement in wedding algebra to geometry remains truly monumental, and the creative scepticism of 'Cartesian doubt' would become as though second nature to the modern scientist, his excursions into the phenomenology of the material world were far less secure. The centrepiece of Cartesian mechanics was his theory of *vortices* , the *tourbillons* in French, which he believed to be the key to planetary mechanics. The *tourbillons* were allied to the existence of the *subtle matter* , which Descartes believed to pervade the Universe and to negate any possibility of a *vacuum* in nature. The Aristotelian idea that bodies in motion needed to be pushed, had its validation in the *tourbillons* , which, he believed, were formed of the subtle matter circulating about the Sun, bearing the planets with it. Other minor *tourbillons* would exist to move the Moon in its monthly orbit, to cause the daily rotation of the Earth and account for meteors and comets. Descartes' theory of light was also imaginative, with transmission represented as an impulsive transfer of energy from particle to particle of the subtle matter until it impinged on the eye.

The eventual demise of the *tourbillon* theory was inevitable once Newton appeared in the field with his Laws of Motion and theory of universal gravitation. The First Law of Motion made it clear that a body would continue to move in a straight line, except in so far as it was acted upon by a force. Newton's *quantity of motion* , effectively our present-day *linear momentum* , was also without representation in Cartesian mechanics, but by far the greatest anathema was reserved for the postulate of action at a distance, as implied by the theory of universal gravitation. This was the aspect of Newtonian mechanics most vehemently attacked by the Cartesians, who regarded it as an appeal to occult forces of the kind that Descartes was supposed to have banished, along with the science of Aristotle. For more than a half-century after Descartes' death in 1650 the French scientific world virtually ignored the detail of Newton's achievement, even though the Académie Royale des Sciences did deign to make him an honorary Fellow. It is not unreasonable to say that the whole beauty of Newton's analysis of planetary motion – the prediction of an elliptical orbit in accordance with Kepler's laws, and its conditioning upon the inverse square law of gravitational attraction – was lost on the French science community until well into the eighteenth century. Long before it was finally abandoned, evidence against the *tourbillon* theory was building up, much of it quite independent of Newton's mechanics. There was the problem of explaining the Earth's rotation, which seemed to require a separate *tourbillon* acting in conflict with the main one keeping the Earth in orbit. Then there was the appearance of retrograde comets, cutting through the solar system, but in the opposite direction to the supposedly prevailing vortices. As the Cartesians struggled to explain one anomaly after another the *tourbillon* theory took on such a convoluted complexity that it would soon have collapsed under its own weight, even without the stimulus of Newton.

When Newton died in 1726, his body borne into Westminster Abbey on the shoulders of eight dukes, a remarkable Frenchman was present in the congregation. This was François-Marie Arouet, better-known as Voltaire, in temporary exile from Paris, having only recently adopted his illustrious *nom de plume*. Voltaire was to play a key part in the conversion of the French Academy from Cartesianism to Newton's world-view, a cause he took up with relish alongside his enthusiasm for the philosopher Locke, the Quakers, vaccination, and a whole series of things English that he admired. One detail of French attitudes would soon fuel his resentment and this was the *Éloge* on Newton pronounced before the Académie by its venerable Secretary, Fontenelle. While fulsome in Newton's praise, this managed to create the impression, much to the indignation of the Fellows of the Royal Society of London, that Newton was not quite of the order of Descartes, and moreover owed many of his ideas to the Frenchman.

In 1728, shortly after Newton's death, while Voltaire was still in London, one of the younger, more internationally-minded members of the Académie, Pierre-Louis de Maupertuis, visited England with a growing interest in Newtonian physics. He carried letters of introduction to Sir Hans Sloane, current President of the Royal Society and himself an *associé étranger* of the French body. There are only scant records of Maupertuis' time in London, and it is not certain whether he met Voltaire there, but it seems likely that he was more interested in visiting Sloane's Chelsea Botanical Garden and Flamsteed's Royal Observatory than in keeping literary company. His most important contacts in the Royal Society, moreover, were the exiled Huguenot mathematicians Jean-Théophile Desaguliers and Abraham de Moivre, with whose work he was certainly familiar. De Moivre proposed him as a Fellow, and he was duly elected on 27 June 1728.

While Maupertuis was probably a partisan of Newton before reaching London, it seems certain that his visit turned him into an enthusiast, and removed any remaining sympathy he may have felt for Descartes. Prepared now to carry the cause back to Paris and fight his corner in the Académie with renewed conviction, he began the series of papers that would by stages undermine the Cartesian position and create the tension against which the events of this narrative would be set. Maupertuis would prove to be the *provocateur* who would, with a small band of sympathizers, like Voltaire, eventually turn French science away from Descartes and towards a grudging acceptance of Newton. In the course of this he would also play a leading part in the resolution of the Figure of the Earth problem, which would further breach the defences of the traditionalists. This would not prove an easily won victory, however, and before it was secured the scientific and literary worlds would witness human endeavour at a level that embraced mathematical virtuosity on the one hand, even as it called for extremes of physical endurance on the other.

Such is the train of events that this book will consider. Rather than distort what cannot be shaped into a linear narrative I shall examine the whole network of influence and initiative that feeds to the central theme, that is the problem of the Figure of the Earth and its place in the Mathematical and Earth Sciences in an evolutionary age. My concern is with the multiple trajectories of an idea, one that led to a flourishing of inventiveness ranging from precision instrumentation to mathematical techniques, while at the same time an irritant that would divide the sharpest minds of Europe and evoke chauvinistic animus hardly consonant with the splendid evolution of science that is often presented to us. That an apparently minor issue in the History of Science should have had such interesting repercussions is more than a curiosity; rather it testifies to the profound complexity of the physical world with its inescapable human dimension, and to the deceptive intricacy of what might wrongly be perceived as merely 'down to Earth' in character.

Though this work in no way presumes to be a comprehensive history of geodesy in all technicality, I have sought to provide at least an overview of progress as it developed beyond the early expeditions, through the refinements of the nineteenth century, towards the space age and the modern subject. Geodesy is nowadays a project of extraordinary complexity, employing as it does many thousands around the world and presenting an exemplar of international cooperation scarcely equalled in any other field. Nevertheless, although monographs on the subject are usually deferential to its past, and the international bodies have encouraged the formation of extensive historical data-bases, a truly definitive history of geodesy remains to be written.

Notes

1 Voltaire to Maupertuis, 22 May 1738. In *The Complete Works of Voltaire* (Ed. Besterman, T.) *Correspondence* Vols 85 et seq. (Geneva, Toronto, Banbury, Oxford, 1968-1977) Letter D1508.

2 Pronounced by George Louis Buffon on the occasion of La Condamine's reception into the Académie Française. 12 January 1761. *Choix de discours de Reception à L'Académie Française*, 2 vols. (Paris, 1808), p.344.

3 If θ is the measured angle in degrees for a distance, d, on the surface, then the radius of a spherical Earth follows from; $R = 360\, d/2\pi\theta$.

4 Other estimates have it in the region 148m or 158m. Mignard, F, in Lacombe, H., and Costabel, P. (Eds). *La figure de la terre du XVIIIème siècle à l'ère spatiale.* (Paris, 1988), p.283.

5 Smith, J.R. *An Introduction to Geodesy* (London, 1996). Smith derives a value of 128,300 Li or 56,700km for the Earth's circumference corresponding to a degree of 157km from Yixing's measurements.

6 See Beer, A., Ho Ping-yu, Lu Gwei-djen, Needham, J., Pulleyblank, E.G., and Thompson, G., 'An 8th-Century Meridian Line: I-Hsing's Chain of Gnomons and the Pre-history of the Metric system', *Vistas in Astronomy*, 1961, 4, pp.3-28.

7 See Brunet, P., 'La science dans l'Antiquité et le Moyen-Age'. In *Histoire de la Science*, Encyclopédie de La Pléiade (Paris, 1957) (A plausible translation of the Arab mile leads to an estimate of 111km for the degree.)

8 Norwood, R., *The Sea-mans Practice. Containing a Fundamental Probleme in Navigation, Experimentally verified: Namely, Touching the Compasse of the Earth and Sea and the quantity of a Degree in our English Measures* (London, 1659).

9 See Schwab, K., Bruckner, N. and Packard, R.E., 'Detection of the Earth's rotation using superfluid phase coherence', *Nature*, London, Vol. 386 (1997), p.585. The measurement of the Earth's rotation in a closed laboratory, with no visible connection to the celestial sphere, is surely one of the most astonishing experiments of recent years.

Chapter 2

Prelude to an Odyssey

The problematically-named 'Scientific Revolution' of the seventeenth century advanced on several fronts, the grand issues of planetary motion and universal gravitation in the vanguard and less well-defined concerns for the nature of life and matter bringing up the rear. On this scale of universality, questions of the geometry of the Earth might seem a minor preoccupation, left to germinate in the best minds of Europe as they contended over more dramatic issues. The fact that this was not altogether so is something of a curiosity of the History of Science, but one which, as we shall see, was a key indicator of the prevailing climate of ideas.

The relatively sudden shift of attention from the question of the Earth's size to that of its precise shape came about through the conjunction of several factors, both practical and theoretical. Firstly, some chance measurements yielded the surprising fact that the force of gravity was apparently not constant over the whole surface of the Earth, as it would surely have to be if everything were spherically-symmetric; then newly developed ideas on the mechanics of rotating bodies were brought to bear on the Earth as a whole; lastly, and most telling of all, perhaps, was the provocative entry of the great Isaac Newton himself into the theory of the problem. Such interplay was inevitably complicated, and must be seen in the light of parallel developments both technical and philosophical. For one thing, as characteristic of the age, no questions of the *state* of the Earth could be altogether dissociated from the matter of *cosmogony*, the doctrine of creation – perhaps one should say The Creation – and all the metaphysical snares that this entailed.

In examining the interplay of the technical, philosophical and social factors that went into the Figure of the Earth controversy, two items stand out in primary relevance. One was the growing sense of the importance of *quantitative* science, marked by the availability of new instruments, along with a certain scrupulousness in calibrating and using these to new levels of accuracy. Another was the emergence of professional scientific bodies with the inclination, and increasingly the resources, to promote projects on a scale that rivalled the more usual military and architectural extravagance. To this latter aspect might be added a predictable degree of international rivalry.

The Institutions that will dominate the present narrative can be reduced to two: the Royal Society of London, and the Académie Royale des Sciences in Paris, in-augurated in 1660 and 1666 respectively, each with its complement of distinguished men of science, each with its inevitable make-weight of the titled and the well-connected. Although these bodies were securely in place by the time the Figure of the Earth problem emerged, they inherited a special history of more amateurish measurements and surveys, necessarily linked to the practical ends of cartography in the large, and the delimiting of estates and properties in the small. Whatever these early surveys lacked in accuracy they can be said to have made up in scope and innovation; indeed they laid the foundations of method and pioneered the procedures that would be taken for granted in later, more professional, ages. While the end-products of the early surveys were usually maps, in arriving at these the techniques employed connected intimately with the more venerable science of astronomy, where the plotting of stars in the celestial sphere had generated its own armoury of instruments and mathematical methods. The former were relatively crude, but comprised a considerable range of devices: astrolabes, quadrants, astronomical rings (*annulus astronomicus*) and cross-staffs (*baculus Jacob*), all these in use for centuries before Galileo's telescope opened up new vistas of detail and precision upon its invention in 1609.[1]

The birth of the precision survey can be said to have occurred at the critical moment when an astronomical protractor of some description, most likely a quadrant, was first turned from the vertical plane to the horizontal, and knowingly used to measure the angles subtended between distant objects on Earth. This easily visualized process would have remained valueless, however, without a suitable calculus for converting angles to absolute distances on the ground – and this required the new-born subject of trigonometry. Once it was possible to 'solve' triangles, that is, to obtain two sides from the length of a third plus the angles at its ends, or a third side from two others and their included angle, the way was opened for the measurement of both heights and distances over long expanses of country and between end-points far out of sight of each other. If a single triangle could be solved when constructed upon a measured *baseline*, then each of its sides could tbe used to form a new triangle, and so on until a network of known segments would be built up from measurements of angles taken at each vertex. The network might spread in all directions eventually to cover a whole province; or a *suite* of triangles might be connected to form an elongated polygon, covering the inter-mediate ground between two far-distant points, and leading to the exact distance between them. This is the process of *triangulation*, which, with precautions against accumulated errors, can lead to a map in which the relative locations of the triangulation points are precisely known, and those for other, arbitrary points can be read off from the resulting map, or if necessary found to greatest precision by further sightings. The origins of this procedure, already taken for granted by the eighteenth century, form an interesting by-way in the history of quantitative science (Figure 2). A mathematical outline is given in Appendix 1.

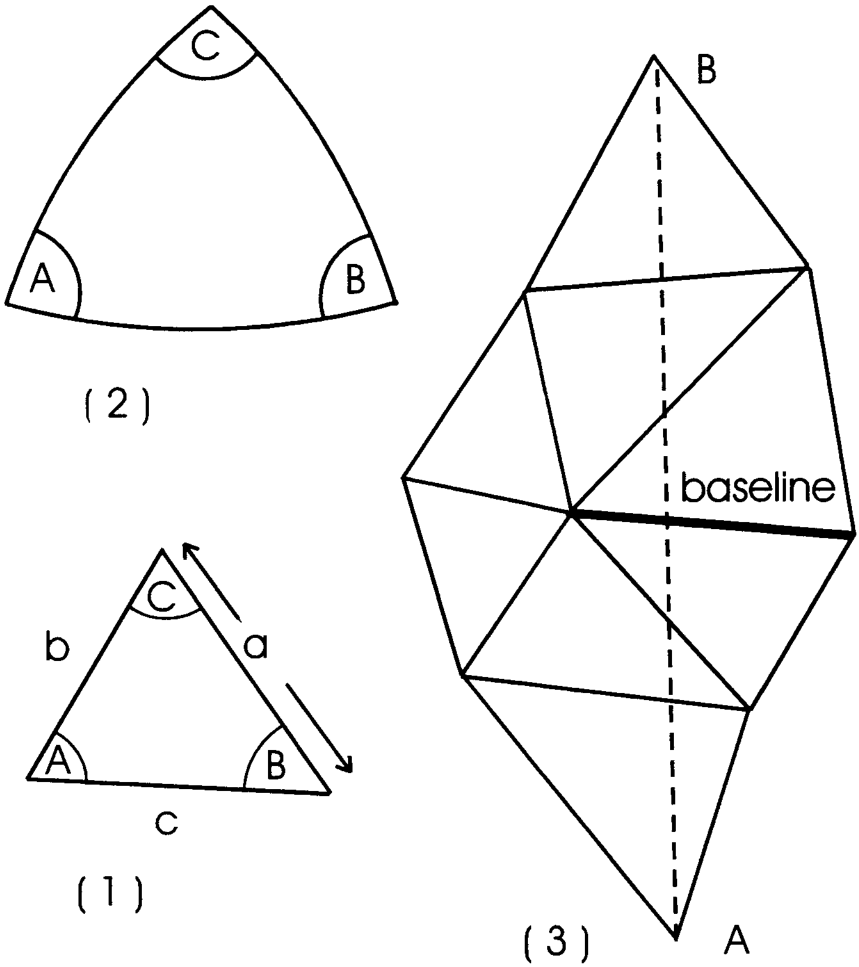

Figure 2 The method of triangulation. 1) A simple plane triangle 2) A spherical triangle 3) A suite of triangles with baseline leading to measurement of the distance AB.

The practice of triangulation is usually credited to Willebord Snel van Royen (Snellius) (1580-1626), who seems to have been the first to have carried it out on a useful scale. But the idea is now thought to belong to an earlier Dutchman, Gemma Frisius (1508-1555). Gemma Frisius was a medical man by training, but spent most of his life studying astronomy, designing instruments, becoming in the process an accomplished mathematician. Gemma was also a skilled cartographer and a friend of the Mercator (Gerard Kramer, 1512-1594), whose fame has proved more enduring. His books on mathematics and astronomy were translated into several languages (though not English) and reprinted many times, but it is one in particular, the *Arithmeticae Practicae methodus facilis liber Petri Apiani*, that contains the seeds of the triangulation procedure.[2] Gemma Frisius was also the originator of the idea that longitude could be obtained by time measurements. In a passage which, incidentally, may claim to mark the origin of the 'watch' he states:

> There are beginning to be used miniature clocks which are called *montres* [watches]. Their lightness permits them to be transported, and they run for almost twenty-four hours, and for longer with a little help.[3]

Whereupon he describes how longitude may be obtained by comparison of the watch set by the Sun at one point with local time determined likewise at the other. This was, of course, the now celebrated solution to the problem of finding longitude at sea, but only proved useful after the development of the chronometer over two centuries later. Better methods became available for measuring longitude on land, however, and will feature incidentally in the coming narrative.

Though Snellius is regarded as the father of triangulation in a land survey, there is evidence to suggest that the practice was at least shared with the more illustrious Tycho Brahe (1546-1601). Tycho, in Copenhagen, is known to have been familiar in turn with the writings of Gemma Frisius, and he himself carried out a triangulation project in the 1570s which in effect covered the whole of Denmark. There were twenty-eight triangulation points from Hälsingborg in the north to Copenhagen in the south, eastwards to Høјbjerg and westwards to Lund and Malmø, the whole centred at his observatory at Uraniborg. Most of the sighting points were church-spires, but many of the triangles were ill-proportioned and the accuracy poor. Unfortunately, too, the data were incomplete and the map which should have resulted was never made. Significantly, Tycho met Snellius in Prague in 1600, when, it may be conjectured, the idea of triangulation was discussed, and, in likelihood, its provenance in Gemma Frisius handed on. There is some insubstantial evidence that Gemma did himself carry out a triangulation in Lorraine, leading to a map, now lost, but this appears to be highly speculative.[4, 5]

With distances on the ground now able to be determined relatively accurately, the stage was set for modern updates of the original Eratosthenes method for measuring the degree. This was first attempted in Gemma Frisius' lifetime by the Frenchman Jean Fernel, though quite independently and without the benefit of triangulation. Fernel, like Gemma a medical man, and in fact sometime Physician to Henri II, attempted an estimate of the degree in 1528. His method was disarmingly straightforward; he simply proceeded approximately due north from Paris until a one-degree change was observed in the elevation of the Pole Star. Relying on a somewhat questionable distance measurement – counting revolutions of a carriage-wheel – he arrived at a figure for the degree given as '68,906 pieds géometriques, equal to 56,746 toises 4 pieds de Paris'. This corresponded to an Earth diameter of 20,420 toises, or 39,800km.

It was almost a century after Fernel that Snell, in 1617, performed his more meticulous survey, covering the length of Holland from Alcmar in the north to Berg-op-Zoom in the south. With the advantage of the flat terrain, and the abundance of church-towers, he was able to create a network covering a large part of the country. His distance from Alcmar to Berg-op-Zoom, a line close to the meridian, yielded a value for the degree of '28,540 perches du Rhin equal to 55,100 toises de Paris' (some 107.3km). Happily, most of the church-spires used by Snell still exist, so that his angles can be checked with modern instrumentation. (Though for the highest accuracy there must be an unknown displacement correction – onward sightings, for obvious reasons not taken from the very point of the spire.) Snell's account, entitled *Eratosthenes Batavus, de Terrae ambitus vera quantitate*, (Figure 3) represents the first well-documented account of a true triangulation survey.[6] Some doubt attaches to the way he measured his baseline, but it seems indisputable that his was the first useful triangulation, if not the first experimental one.

Meanwhile, England was not to be unrepresented in the growing curiosity as to the size of the Earth. The eccentric Richard Norwood, whom we met earlier, measured the altitude of the Sun at noon on the same date in London and York in 1633 and 1635, obtaining values of 62° 1' and 59° 33' respectively. He then determined the meridian distance between the two in somewhat cavalier fashion, an account of which is also to be found in his *Seaman's Practice*, of 1659 :

> ...Yet having made Observation at *York*, as aforesaid, I measured (for the most part) the Way from thence to *London*, and where I measured not, I paced; (Wherein through Custom I usually come very neer the Truth) observing all the way as I came with a Circumferentor,[7] all the principal Angles of position, or windings of the Way, (With convenient allowance for other lesser Windings, Ascents and Descents) ...; so that I may affirm the Experiment to be neer the Truth.[8]

Thus, even though an expert in trigonometry, he dispensed with triangulation, preferring to use the surveyor's chain, recently invented by Edmund Gunter. The result was a value for the degree of 367,196 English feet, equal to 57,300 toises.[9] As the original account shows, Norwood's measurement was less rough and ready than it sounds. The Roman road from London to York is notably straight and level; moreover it seems he did use his trigonometry to prepare tables of corrections whenever there were local deviations in the road.

It was thirty years before another serious competitor took the field. In 1661 the Italian Jesuit Giovanni Battista Riccioli (1598-1671) measured an arc in Italy between Ferrara and Bologna, finding the degree '64363 pas de Bologne, equal to 62900 toises de Paris' – a significant discrepancy with the Norwood figure. Riccioli was a respected astronomer, having recently produced the *Almagestum novum* (1651), in which, among much else, he introduced the system of naming craters and mountains of the Moon after famous astronomers. His review of all

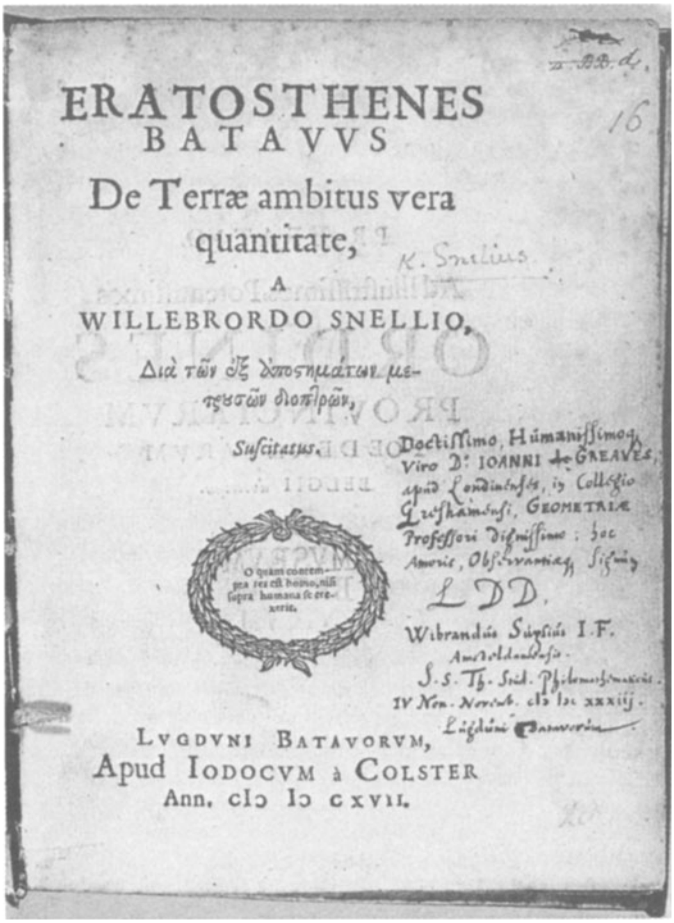

Figure 3 Title page of *Eratosthenes Batavus* by Willebord Snell, 1617, with handwritten dedication to John Greaves of Gresham College, 1633. British Library.

types of survey method in the monumental work *Geographiae et Hydrographiae reformatae* (1661)[10] was a landmark in its time, somewhat ungraciously overlooked in both French and English circles.[11]

Interest throughout Europe seems to have intensified in the 1660s along with a more realistic appreciation of the accuracy that might be achieved. Naturally it was astronomers who were most familiar with the process of taking angular measurements, and they were invariably critical of the seemingly amateurish attempts of surveyors to emulate them. They could well feel superior, enjoying as