NAVIGATION METHODS OF EUSEBIO FRANCISCO KINO, S. J.

by

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ONE of our treasured legacies from the Jesuit mission era is the beautiful and famous map "Passo por Tierra a la California," drawn in 1707 by Eusebio Francisco Kino, S. J., known to history as "The Apostle to the Pimas": maker of Christians and builder of missions. So accurate is this map that it did not become completely obsolete until 1912, when Lumholtz' map "Papaguería" was published.[1]

As might be expected, the Kino map was widely circulated and widely plagiarized during the early eighteenth century, so that many versions, many of them not credited to the original author, are now extant. Checking of this map against the best available today shows that all major features of Papaguería are shown in their correct interrelations to a rational scale ("Leguas Castellanas"), that the latitudes are all correct to less than a degree of arc, and that the longitudes are

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[1]Karl Kumholtz, *New Trails in Mexico* (New York: Scribner's, 1912).

all in reasonable proportion. And, as will be shown later, Kino had no way of making rigorous longitude determinations.

Field checking of the may amply demonstrates its practical utility. Almost any reasonably intelligent person using this map – and, in a few instances the descriptions from Kino's notes,[2] or the substantially parallel Manje notes[3] – can recover any site shown on the map, usually within a few hundred feet. This was actually done by the late Herbert E. Bolton in retracing hundreds of miles of Kino's trails; and the present writer has had equal success in the lavas and sand dunes around Pinacate, where Professor Bolton did not go.

Interestingly, although the "Passo por Tierra" is Kino's most famous map, it is not his only competent cartographic effort. Eight Kino maps, still extant, are listed by Bolton;[4] and it seems possible, from internal evidence in Kino's writings, that his total map output may have been as high as twenty. Checking of the known Kino maps, and consideration of the possible additional output not available to us today, both indicate that Kino's title "Royal Cosmographer," granted him in preparation for the Atondo expedition to Baja, California, was not an empty one.[5]

From the viewpoint of our present overspecialized culture – in which a student usually learns "more and more about less and less" until, on finally attaining the doctorate, he reputedly knows "everything about nothing" – it is somewhat surprising to find that a man extensively trained in theology, as was Father Kino, was also an expert in cartography as well as several other fields from architecture to astronomy. Such multiple competences, however, are not uncommon, and apparently never were. Leonardo da Vinci, known to us as an artist, was also a competent inventor and engineer; Sir Isaac Newton, discoverer of the Laws of Gravitation and Motion and one of the developers of

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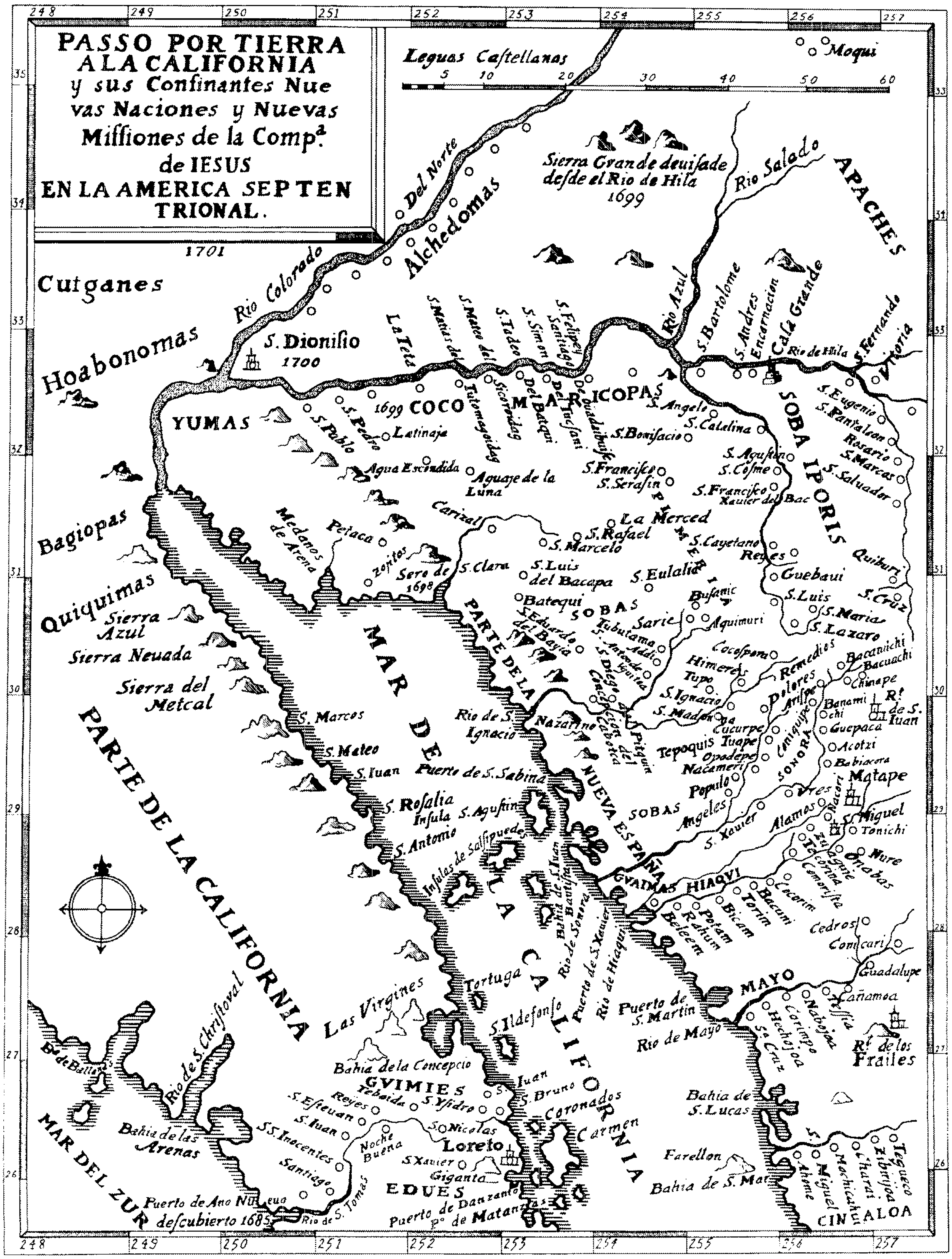
2 See H. E. Bolton, *Kino's Historical Memoir of Pimeria Alta* (Cleveland: Arthur H. Clark Company, 1919), *passim;* Bolton, *Rim of Christendom: A Biography of Eusebio Francisco Kino, Pacific Coast Pioneer* (New York: Macmillan, 1936); Ernest J. Burrus, *Kino Reports to Headquarters* (Rome: Inst. Hist. S. J., 1954).

3 See Juan M. Manje, *Unknown Arizona and Sonora, 1693–1701,* trans. and ed. Harry J. Karns (Tucson: Arizona Silhouettes, 1954).

4 *Rim of Christendom,* pp. 606–610.

5 *Ibid.,* p. 75.



DRAWN 1701 BY EUSEBIO FRANCISCO KINO, S. J.

TRACED 1948 BY R. L. IVES

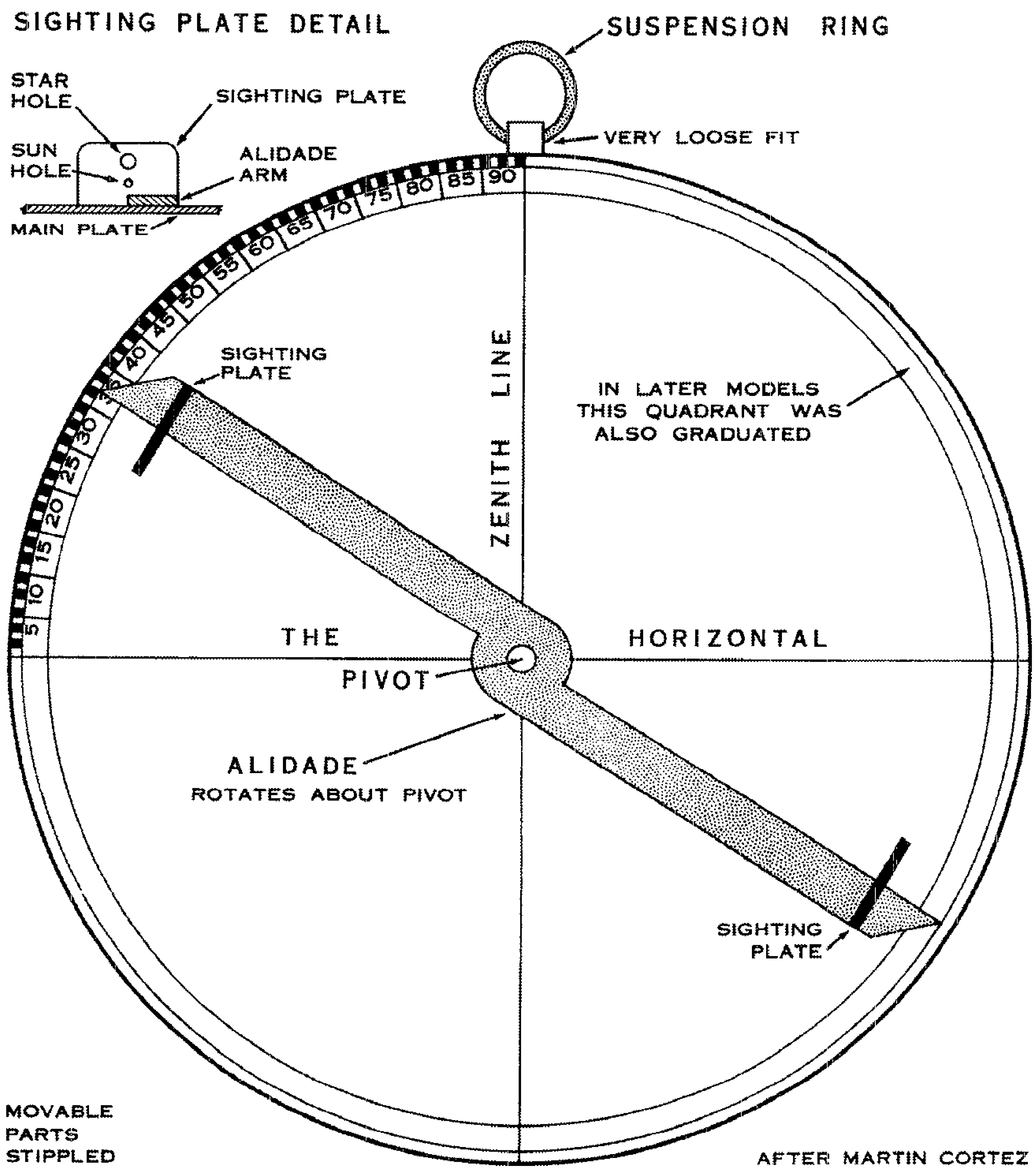


Fig. 1 Summary diagram of a mariner's astrolabe, or shipman's quadrant, based on diagrams and descriptions by Martin Cortes (ca. 1551).

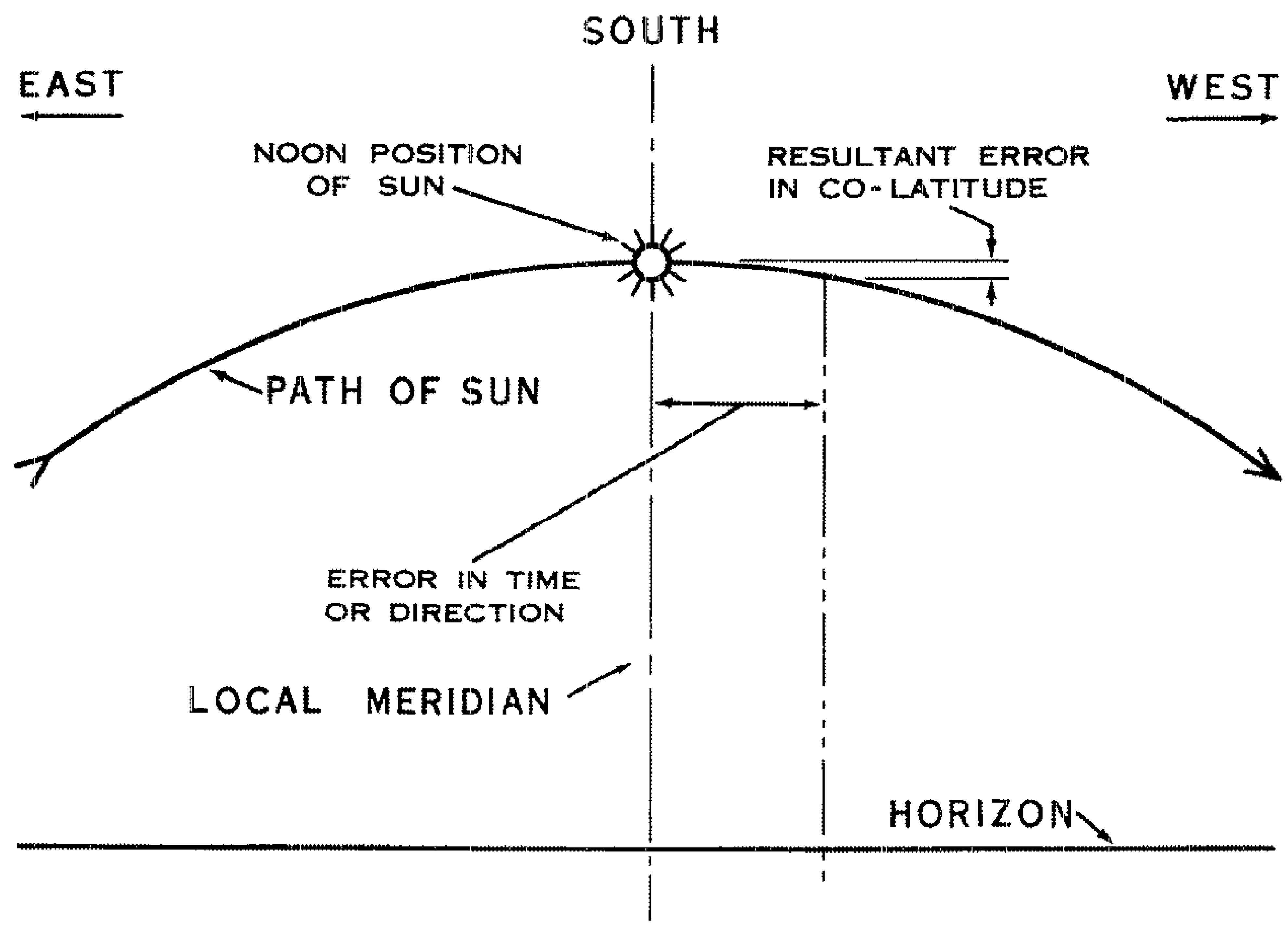


Fig. 2. Errors in meridian altitude sights.

the Calculus, was better known in his lifetime as a theological researcher; William Henry Jackson, pioneer photographer of the American West, was also a painter of respectable attainments and author of a number of meritorious historical papers.

Because of the great breadth and depth of Jesuit training, and of careful personnel selection, we should expect to find a large number of multiple-talented men in that famous order, and such has been the case for more than four centuries. An outstanding early example was Athanasius Kircher, whose published works include a pioneer attempt to decipher the Egyptian heiroglyphics, a very good early work on geology[6] and a description (perhaps the first) of the now-familiar projection lantern. Today we find that Jesuits are substantial contributors to most fields of learning, a current example being Father Daniel J. Linehan who, during a recent tour of duty in Antarctica with primary duties as a geophysicist, was also expert in getting radio signals through the Aurora Australis and reputedly was able to fix "anything from a troubled conscience to a malfunctioning radar."

Modern science is indebted to the Sonoran Jesuits for many gems of scientific observation, among which are Juan Nentvig's [supposedly] description of the geodes of Oputo,[7] Cristobal de Cañas' [supposedly] summary of Indian ceremonial dances,[8] and Pfefferkorn's lucid description of the habits and attributes of the *zorillo*.[9] Kino's own "quest of the blue shells,"[10] which was collateral to his field explorations, was actually a competent ecological investigation, and probably the first American use of "tracers." From direct evidence, largely collected by Bolton, we learn that he also had specific training and associations qualifying him for advanced cartographic work.

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6 *Mundus Subterraneus* (Amsterdam, 1665).

7 "*Rudo Ensayo*," trans. and ed. Eusebio Guiteras, *Records of the American Catholic Historical Society of Philadelphia*, v. 5 (1894), pp. 214–215. Cf. R. L. Ives, "The Geodes of Oputo," *Rocks and Minerals*, v. 23 (1948), pp. 387–391; Ignaz Pfefferkorn, *Description of Sonora*, trans. and ed. Theodore E. Treutlein (U. of New Mexico Press, 1949), p. 82.

8 "The Sonoran Census of 1730," trans. and ed. Ronald L. Ives, *Records of the American Catholic Historical Society of Philadelphia*, v. 59 (1948), pp. 319–339.

9 *Description of Sonora*, pp. 115–116. Cf. the substantially parallel account in *Rudo Ensayo*.

10 Considered in Bolton, *Kino's Historical Memoir of Pimeria Alta*, v. 1, pp. 46, 55, 195, 230, 231, 234, 237, 241, 259, 272, 310, 317, 322, 342, 352; v. 2, pp. 87, 170, 174, 185, *passim*. (Similar coverage is given in *Rim of Christendom*.)

The ample records summarized by Bolton show that Kino studied at the famous Jesuit colleges of Trent, Hala, Freiburg, Ingolstadt, Munchen, and Oettigen.[11] These were the Yales, Harvards and Caltechs of seventeenth-century Europe. While at Ingolstadt he studied under Fathers Adam Aigenler and Henry Scherer, both outstanding geographers of their time and authors of important works. While still a student Kino was invited to become a professor of mathematics under the patronage of the Duke of Bavaria. Kino's mathematical studies were undertaken because of the great prestige of mathematics in China, where he hoped to go as a missionary. Because of this same missionary desire, Kino did not accept the proffered professorship in Bavaria. From other sources we know that Kino was familiar with at least parts of Giovanni Battista Riccioli's *Tables;*[12] and at least one member of the Kino party which visited Sierra de Santa Clara in 1701 was sufficiently familiar with the writings of Athanasius Kircher to reason correctly from them. This led to the first North American identification of the extinct volcano Pinacate before the usually-credited discoverers of extinct volcanoes (Desmarest and Guettard) were born.[13]

Academically, then, Father Kino was certainly well prepared for a career as a cartographer. Practically, and prior to his coming to the New World, Kino demonstrated that his knowledge was not just rote memorization of lectures and textbooks. On his voyage from Genoa to Cádiz, he assisted the captain of his ship in the taking of latitudes. Later, while in Spain awaiting passage to America, Kino and his companions constructed a number of compasses and sundials. During his stay in Cádiz Kino observed the famous comet of 1680, giving specific figures on its trajectory and rate of travel. These, plotted on a star map, agree closely with other records of the same comet, indicating clearly

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[11] See Bolton, *Rim of Christendom,* pp. 32–38.

[12] *Georgraphia et Hydrographia Reformata* (Bologne, 1661; Venice, 1672); *Astronomia Reformata* (Bologne, 1669). Father Riccioli, an astronomer of great competence, reportedly was assigned the task of writing an omnidemolitive study of Copernicus' *De Revolutionibus Orbium Coelestium,* then regarded as false and heretical. This study (resulting in the publication, ultimately, of the *Astronomia Reformata*), led Riccioli to the persuasion that the Copernican system (heliocentric) was far superior to the ancient and then accepted Ptolemaic system (geocentric). Largely as a result of Riccioli's studies, the Copernican system became universally accepted.

[13] See Ives, "The Discovery of Pinacate Volcano," *Scientific Monthly,* v. 54 (1942), pp. 230–238.

that Kino's knowledge of astronomical observation was sound and practical. His later description of the comet, published in Mexico in 1681,[14] is a curious mixture of sound science and contemporary beliefs in signs and portents. It is thus clear that, on arrival in Mexico, Father Kino not only had adequate training in the art and science of cosmography, but also had demonstrated his ability to apply that training to the solution of actual problems.

From internal evidence in his own writings and from the diaries and reports of his field companions, we can state with certainty that Father Kino's navigation instruments consisted of a compass — which was probably equipped with a gnomon, so that it could also be used as a sundial — and a telescope and an astrolabe. His navigation handbook was Adam Aigenler's *Tabula Geographic-Horologa Universalis,*[15] which included selected portions of Riccioli's *Tables.*[16] This work, specifically mentioned in Kino's diary,[17] antedated both Bowditch and Weems.[18] Careful checking of Aigenler's Latin text shows that the accuracy of his method was superior to the best instruments available in his time, and consequently that many of the deficiencies of seventeenth-century cartography and navigation were due to instrumental inadequacies rather than to lack of technique.

We have no full description of Kino's compass, but we do know that he made one or more instruments which were combinations of compass and portable sundial; and from this we can assume with some confidence that his field instrument was such a combination. As the design of the mariner's compass was fairly well standardized before 1550 and has not changed greatly since that date, the compass used by Kino probably differed little from those available today — and the method of use in 1700 was almost identical to the most modern methods.

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14 *Exposicion Astronomica de el Cometa Que el Año 1680. . . .*

15 (Ingolstadii [Ostermayri], 1668).

16 Tables of latitude and longitude from Book 9 of Riccioli's *Geographiae Reformatae* are appended to Aigenler's *Tabula Geographico-Horologa Universalis.* Incidentally, Aigenler credits his source fully — an uncommon practice at that time.

17 See Bolton, *Kino's Historical Memoir of Pimería Alta,* p. 330.

18 Nathaniel Bowditch, *Practical Navigator* (Salem, 1801); P. V .H. Weems, *Air Navigation* (New York: McGraw-Hill, 1938). Bowditch's manual is still current, after innumerable reprintings and a few revisions. Current editions, titled *The American Practical Navigator,* are available from the Government Printing Office, Washington 25, D.C.

Although it was known before Kino's time that the magnetic compass did not everywhere indicate true north, we have no direct evidence that he made corrections for local magnetic variation, which is now about 12 degrees East in most of Papaguería. As Kino's maps and observations do not contain the errors which would occur if compensation were not made for such variation, we can assume either that this variation was substantially zero in 1700 – which is improbable – or that he corrected for it, at least approximately. This correction is rather easily made for a small area, such as Papaguería, by the standard and well known method of comparing magnetic north, as indicated by a magnetic compass, with true north, as determined by a sight on Polaris.[19] The observed difference is then applied to all magnetic bearings taken thereafter, giving a reasonably valid true north anywhere in the area for a few years after the observation is made. Because magnetic variation is not fixed – due in part to migration of the magnetic poles – local corrections become obsolete in a relatively short time.

Kino set down no detailed description of his telescope, but, as this instrument first became generally known to Europeans about 1609, it was still, in Kino's time, an "advanced" scientific instrument. Although Galileo in 1610 made telescopes having magnifications up to 33, it seems probable that Kino's telescope, which was portable, had a magnification not greatly exceeding 10, an objective not over 2 inches in diameter, and a resolution not better than perhaps 3 seconds of arc. Numerous refracting telescopes, made for use at sea after about 1650, had these characteristics. A better telescope, having a greater magnification, larger objective, and better resolution, was surely available by 1685; but just as surely Kino did not have one. Such a telescope would have been portable only with difficulty, usable only if mounted on a tripod, and usable then only for a few minutes to a few hours a day because of atmospheric turbulence which interferes even with naked-eye observations in the Sonoran Desert.

All of the latitudes specifically recorded in Kino's works were measured by use of an astrolabe, an instrument completely unfamiliar to most twentieth-century readers. In its basic form, the astrolabe is an open-sight pendulum clinometer. As commonly made, the instru-

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[19]Noted by Kircher, *Magnes Siue, De Arte Magnetica* (Colonia Agrippina, 1643). Cf. Frederic H. Lahee, *Field Geology* (New York: McGraw-Hill, 1941), pp. 422–423, 493–495.

ment performed additional functions, serving as a star-finder, a nocturnal clock, or even as a crude form of circular slide rule.

The origin of the astrolabe is lost in the mists of antiquity. Some historians cite excellent evidence to show that it originated in India, some time before the Christian era. Others cite equally good evidence to show that the instrument was developed by Babylonian astrologers, possibly as long ago as 2,000 B.C. Certainly the calibrations on the instruments surviving today show Bablylonian influence, as the circle is divided into 360 degrees, a Babylonian, and not a Hindu, division. The instrument was early adapted by Arab astrologers, who brought it to Spain, perhaps as early as 800 A.D. Knowledge of the astrolabe was officially brought to the Christian world by Gerbert (The Necromancer) of Aquitaine, who studied under the Moorish scholars in Córdova from 967-970, learning not only the use of the astrolabe, but also the decimal system, Arabic numerals, and the "black arts" of algebra and trigonometry.[20] On returning to the Christian world Gerbert taught extensively for twelve years, then advanced rapidly, becoming Abbot of Bobbio (983), Archbishop of Rheims (991), Archbishop of Ravenna (998), and Pope Sylvester II (999-1003). His astrolabe, still extant, has been described in detail by Robert T. Gunther.[21]

By the latter part of the sixteenth century, the astrolabe was shorn of its astrological attrributes, and became a utilitarian scientific instrument. Some of the finest astrolabes ever built are the work of Humphrey Cole (*ca.* 1575), who reputedly made all of Sir Francis Drake's navigation instruments. Many of these instruments, as well as a variety of others of Spanish and Portuguese manufacture, are preserved, many of them in working condition, in a group of British museums.[22] With them, in many cases, are the detailed instruments for their use, and descriptions of just how they were made. A typical mariner's astrolabe, also known as a shipman's quadrant, is illustrated in the summary dia-

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[20] See Horace K. Mann, *The Lives of the Popes in the Early Middle Ages* (London, 1910), v. 5, pp. 91–120.

[21] *Astrolabes of the World* (Oxford U. Press, 1932), v. 1, pp. 230–231; illustrated in Plate LII(2). This instrument, dated A.D. 990, is in the Galileo Tribuna, at Florence, Italy.

[22] Especially the National Maritime Museum, Greenwich; the Science Museum, South Kensington, London; the British Museum, London; the Museum of the History of Science, Oxford; the University of St. Andrews, Fife, Scotland; and Albert Institute, Dundee, Scotland.

gram comprising Fig. 1. This is based on a diagram by Martin Cortez, which, with accompanying descriptions, gives all necessary data for the construction and use of the astrolabe. Geoffrey Chaucer, better known for his *Canterbury Tales*, also wrote a description of the Astrolabe and its use.[23]

Essentially, the mariner's astrolabe consists of a main plate, with a suspension ring loosely mounted at the top. When hung by the ring, the zenith line was vertical, and the horizontal line, at right angles, horizontal. Pivoted at the intersection of the zenith and the horizontal was an alidade, which contained a sighting plate at each end. One or more quadrants of the main plate were divided into degrees, usually numbered with zero at the horizontal, and ninety at the zenith (as in Fig. 1). The sighting plates contained two holes, one, the star hole, "as bigge as may conteyne a great pinne," and the other, the sun hole, "so subtile and small as a fyne sowyng needle." These were aligned so that a line of sight through them was parallel to the line between the two pointers of the alidade.

Because the suspension ring, even when fitted very loosely, had some friction, early mariners recommended suspending the astrolabe "by a thread or lyne." (This difficulty was, of course, less with astrolabes having chain suspension.) In order to measure the angular elevation of any celestial object except the sun above the horizon, the astrolabe was suspended (by string or chain) so that it hung vertically, much like a plumb bob; the alidade was rotated about its pivot until the star could be seen through the "greate holes;" and the angle of elevation was then read at the pointer of the alidade adjacent to the graduated quadrant. (The angle indicated in Fig. 1 is 32°.)

To obtain higher accuracy, a few astronomers, and a very few mariners, rotated the alidade 180 degrees, and repeated the observation. The two values so obtained were then averaged, in an effort (sometimes successful) to secure a more accurate value. Similarly, when two quadrants of the astrolabe were graduated, a few careful workers repeated their measurements, using first one quadrant, and

[23] *A Treatise on the Astrolabe* (1391). This was many times reprinted, after its first printing in London by Wm. Thynne in 1532. An excellent modern version is contained in Volume Five of R. T. Gunther's *Early Science in Oxford* (Oxford U. Press, 1929).

then the other, in the belief that the average value would be more accurate than any single value. Although these refined methods are mathematically sound, they were not very much used, as they involved the complicated processes of addition and division, which were difficult for mariners who had trouble counting above ten without taking off their sea-boots.

Measurement of the angular elevation of the sun, or, as it was more commonly stated, its altitude, was performed in a different manner, as the sun cannot be directly viewed many times without permanent ocular damage. A method of doing this, dated 1545, follows:

> To take the altitude of the Sunne, hange up the Astrolabe by the rynge: and set the Aluidada against the Sunne. And rayse it or put it downe in the quarter that is graduate, untyll the beames of the Sunne enter in by the lyttle hole of the tablet or raysed plate, and precysely by the other lyttle hole of the other tablet. Then looke uppon the lyne of consydence. And howe manye degrees it sheweth in the quarter that is graduate (beginnynge fro the horizontall lyne) so many degrees of height hath the Sunne....[24]

Although these instructions are approximately 400 years old, they are still valid today, and would apply quite well to the use of a modern pendulum clinometer or bubble sextant. In a modern handbook, we would modernize the spelling a bit, substituting our modern "madde consystencie" for the archaic forms.

The latitude of any point on the earth's surface is defined as the angular distance of that point from the equator. By modern convention, the latitude of the equator is zero, that of the poles is 90 degrees, the arithmetical sign of latitudes north of the equator is positive (+), and that of points south of the equator is negative (—). Although Kino used these conventions, they were not universally accepted until the beginning of the nineteenth century, so that some old maps list latitudes as measured from "el polo del Norte," or "el polo Boreal." We now call such designations co-latitudes, and the change from co-latitude to latitude is made by substracting the co-latitude from 90 degrees.

Perhaps the earliest method of determining latitude was by measuring the angular elevation of the pole star, which gave an approximate latitude directly. This method was crudely satisfactory in high

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[24] From Martin Curtes, *The Arte of Nauigation* — "Translated out of Spanyshe into Englyshe by Richard Eden, 1561."

and middle latitudes, marginally useful in low north latitudes, and useless south of the equator, where Polaris could not be seen.

If we assume, as did the earliest navigators, that the pole star, Polaris, is always directly overhead at the north pole, and that it is infinitely distant, then it should be, and approximately is, on the horizon at the equator. At intermediate points on the earth's surface, the angular elevation of Polaris should be the latitude. As long as measurements were relatively crude, so that the elevation of Polaris was expressed in "fingers above the horizon," this method works well. Fifteenth-century navigators using it usually made landfall within a hundred leagues or so, north or south, of this desired destination.

Early astronomers, perhaps during the time of the Ptolemies, found that Polaris was not exactly over the pole, but revolved about the celestial pole (the infinite extension of the earth's axis), so that the elevation of Polaris was not always a true indicator of latitude. In 1000 A.D. Polaris was about 7 degrees from the celestial pole, this distance reducing to 3½ degrees by about 1500, 2 degrees in 1700, and about 55 minutes today. This change is due in large part to the precession of the equinoxes, which run a full cycle in about 26,000 years.

Early mariners were aware that something was amiss with their computations, but found that latitudes taken by the pole star method were consistent if the observations were made when the "Guardes" (such as the star *Kochab,* in *Ursa Minor*) were always in the same position. By the mid fifteenth century, this knowledge was organized into the "Rule of the North Star," so that substantially correct latitudes could be measured by Polaris observations at any time that Polaris was visible, and a number of ingenious mechanical devices were available to correct for the difference between the elevation of Polaris and that of the celestial pole.[25] With improved instruments and information, this method is still useful today,[26] particularly in "survival navigation."

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[25] See D. W. Waters, *The Art of Navigation in England in Elizabethan and Early Stuart Times* (Yale U. Press, 1958). Consult Waters' internal index under "Regiment of the North Star."

[26] See Ives, "Atemporal Polaris Correction," *Economic Geology,* v. 53 (1948), pp. 419–426; Ives, "Latitude Determination Without a Sextant," *School Science and Mathematics,* v. 48 (1948), pp. 441–445.

The other effective early method of determining latitude was by measuring the meridian altitude of the sun. This method depends for its operation on several fundamental relations in the solar system. The intersection of a plane through the earth's axis and any surface point is a north-south line, called the local meridian. When the sun is observed to be on the local meridian, it is local noon, and the sun is at its maximum elevation for that day.

Twice each year, at the equinoxes, which occur about March 22 and September 22, the noon sun is directly overhead at the equator and the elevation of the noon sun is the co-latitude of the point from which it is measured. At all other times, because the plane of the equator is inclined about 23½ degrees to the plane of the earth's orbit (the ecliptic), the noon sun is not directly overhead at the equator, and the observed meridian altitude is not the true co-latitude of the point of observation.

Because all major motions in the solar system are regular and systematic, the angular difference between the solar meridian altitude at any point and the co-latitude of that same point, known as the sun's *declination,* can be computed in advance for any day. These corrections were first systematized by the Jewish astronomer, Zacuto of Salamanca, about 1475. After simplification for navigational use by a commission under King John II of Portugal, these tabulated corrections, in various forms, and under various titles, became a permanent part of every navigator's armamentarium. Known in Elizabethan times as "The Regiment of the Sun," and included in Aigenler's *Tables,*[27] they today form an important part of the Nautical Almanacs published annually by all major maritime nations.

Measurement of the latitude by the meridian altitude method, on any clear day of known date, using an astrolabe (or equivalent instrument), and having available a table of solar declinations, is a relatively simple process. The angular altitude of the noon sun is measured with the astrolabe. To it is applied the declination correction for the date. The result is the co-latitude. Subtraction of this from 90° gives the latitude. If local noon is certainly known, or if true south is determined in advance of the observation, only a single "shot of the sun" is

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[27] *Tabula Geographic-Horologa Universalis,* p. 19.

required. If noon is not certainly known, or if the direction of true (not magnetic) south is uncertain, successive observations are taken, beginning shortly before noon, and continued until the solar elevation stops increasing. The time of maximum solar elevation is local noon, and the direction of maximum solar elevation is true south, in the northern hemisphere.

Most fortunately, this method of latitude determination is not only simple, but also insensitive to minor errors of time, direction, or date. At and near local noon, the angular elevation of the sun changes very slowly, as in Fig. 2, so that a small error in the timing or direction of the sun sight produces an even smaller error in the co-latitude measurement.

Because the solar declination takes 182½ days to make its cyclic change of 47 degrees, average daily change in declination is only about 15½ minutes of arc. This means that "missing the date" by one day will produce an error of about 15 nautical miles in the north-south position. This will be somewhat more at the equinoxes, when the declination changes rapidly, and less at the solstices, when declination change is slow, but the error from this cause will never be as much as a day's walk, and hence usually the true position will be within "sight distance" of the supposed position, erroneously determined.

An astronomer or navigator will point out, correctly, that the usual tables of solar declination are correct only for a single meridian – that for which they were computed – so that an error in longitude determination will result in an erroneous declination correction, and hence in a wrong latitude computation. This is a pertinent objection, as we know that Kino's longitude determinations leave much to be desired.

Numerical evaluation of this error shows that if the longitude is "off" by fifteen degrees (about 900 miles at the equator), the declination error will be about 1/24 of the interdiurnal change, or approximately 34 seconds of arc. This averages out to about 3,400 feet – little more than the traditional "arquebus shot"!

In his memoirs, Father Kino clearly describes how he measured latitudes:

> At midday [March 3, 1702] we took the altitude of the sun with the astrolabe, and found it to be fifty-two degrees, which, adding to it the six and a half of south declination of that day, made fifty-eight degrees and a half.

> The complement to ninety degrees is thirty-one degrees and a half, and this was the . . . geographical latitude in which we found ourselves.[28]

This is a succinct description of the determination of latitude by the meridian altitude method. The declination for the day was obtained from Aigenler's handbook, which Kino brought with him "to the Indes and even to these now conversions." The important "Tabella Declinationum Solis ab Æquatore" is contained in this manual.[29]

From Kino's own writings, confirmed in large part by Manje's diaries,[30] we know that the latitudes shown on his maps were instrumentally determined, by the sound and practicable meridian altitude method. We also know that Kino's instrument was an astrolabe, and that he found his declination corrections in Aigenler's Tables, which are substantially correct.

A detailed study of the latitude errors in Kino's maps, reported elsewhere,[31] shows that Kino's astrolabe, which probably was not over 12 inches in diameter, had an index error of perhaps 11 minutes of arc around the 60-degree point. This small an index error indicates that it was a good instrument, well cared for. The mean deviation of all latitude observations attributed to Kino, which can be checked against modern geodetic observations, is 9.09 minutes of arc (read this "about 9 minutes," as the 0.09 given by the computations is probably without significance), which amounts to an error of only about 1/60th of an inch on a 12-inch astrolabe! Few skilled observers, either in 1700 or today, could consistently do as well!

The longitude of any point on earth is the angular distance, measured at the equator, between the meridian through that point and the index meridian. Today, by international agreement, we use the meridian of Greenwich, England, as the index (or prime) meridian, and describe longitude in angular degrees east or west of Greenwich. In Kino's time, there was less agreement among nations, but many Spanish maps used the meridian through the "Islands of Dogs" (Canary Islands) as the index, Tanarive (Tenerife) being on the usually-

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28 Bolton, *Kino's Historical Memoir of Pimería Alta*, p. 341.

29 Aigenler, *Tabula Geographico-Horologa Universalis*, p. 19.

30 See Manje, *Unknown Arizona and Sonora.*

31 Ives, "California no es Ysla . . .," *Records of the American Catholic Historical Society of Philadelphia*, v. 64 (1953), pp. 189–198.

chosen prime meridian. Use of an arbitrarily-chosen and mutually agreed-upon prime meridian is necessary because there is no convenient celestial indicator of the meridian of Greenwich (or any other meridian). This same "Heavenly fault" greatly complicates determination of longitude, particularly at sea, so that there was a lapse of almost 2,000 years between a clear understanding of the problem, and its consistent practical solution.

At some unknown time before the beginning of the Christian Era, Greek astrologers and navigators became aware that each difference in longitude was related to a difference in time, and were vaguely aware that if the time difference between two places could be learned, the longitude difference could also be determined. Although the Greek ideas seem quite rational (even though our information is largely based on copies of copies of copies of the original writings, some of them many times translated), the ancients probably could not make effective use of their knowledge, because they lacked effective time measuring devices. In 1522, Gemma Frisius of Louvain, a teacher of Gerald Mercator, clearly stated the longitude problem as follows:

> When the sun is directly overhead at any point on the earth's surface, it is [local] noon at that point, and at all points on the meridian running through it. At any position east of it, toward the sun's rising, it is already past noon; west of it, it is not yet noon. If the difference in time could be found, could not this be used to find the position of these places with reference to one where it was, say, already noon? As the earth in 24 hours rotates through 360°, in one hour it rotates through 15°, in one minute through 15′. Clearly position east and west could be found if time could be accurately measured.[32]

Frisius' pertinent words "If time could be accurately measured" explain why, even though sound methods of longitude determination were surely known to European navigators at least as early as 1522, consistent determinations of longitudes at sea were not possible until after 1761.

The portable timepieces of Frisius' time were accurate to about a quarter of an hour a day, when the temperature was reasonably constant, when the instrument was not jiggled around too much, and when the rest of the mechanism was working approximately right.

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[32] Explained fully in William Cunningham, *The Cosmographical Glasse* . . . (London, 1559).

Such an error would lead to a distance error of more than 200 nautical miles, at the equator, if the time indications were used in navigational computations. The other time determiner of Frisius' time was an hour glass, which, if carefully used, was about as accurate as the "Nurmberg Egg", provided "Ye dampenesse of ye sea" did not enter to slow the sand. Although some of the ship's hour-glasses were sealed with "waxe," to exclude moisture, the trouble continued in cold weather. Apparently condensation was not understood in the sixteenth century Because there were neither suitable portable timekeeping devices (the Harrison chronometers wer not proof-tested until 1761) nor radio time signals (1905 on), seventeenth-century navigators used, or tried to use, various astronomical occurrences, such as eclipses and occulations, to determine local index meridians; and used various methods of departures for day-to-day longitude determinations. Although many of these methods, such as Herne's *Method of Lunars* (*ca.* 1678), were brilliantly conceived, their application was too difficult for the average navigator, so that attainable accuracy tended to be low, and the methods were rapidly supplanted by others, made feasible by John Harrison's development of the modern marine chronometer.[33]

The only archaic method of longitude determination meriting consideration here is that involving simultaneous observations of lunar eclipses. Such observations were attempted by Columbus, on his voyages of 1484 and 1504, with somewhat less than satisfactory results, due in large part to inaccurate tables. Lunar eclipse observations were

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[33] John Harrison (1693–1776), a carpenter by trade, almost single-handedly developed the automatic temperature compensation for chronometers, making them sufficiently dependable for use in navigation. As early as 1726 he demonstrated the "gridiron pendulum" for clocks, a device which made their rate independent of temperature. Later, with the promised backing of the British "Commission for the Discovery of Longitude at Sea," he developed and perfected similar temperature compensators for marine chronometers. Finally, in 1761–1762, he produced a marine chronometer consistently accurate to better than 0.8 seconds per day, as demonstrated on a voyage from England to Jamaica (147 days). Similar accuracy was demonstrated on the return voyage; and on a later test, the accuracy was almost doubled. Although these tests proved that the chronometer, as improved by Harrison, more than met the requisite specifications, the Royal Commission did not pay him in full until eleven years later – in 1773. The modern marine chronometer differs little in fundamental design from Harrison's, and is one of the most dependable scientific instruments known.

specifically mentioned in the *Rudo Ensayo*,[34] also with unhappy results, this time due to an Indian revolt. The fundamental method of "Telling Longitude from Eclipses" is clearly outlined in a treatise (*ca.* 1271) of Robertus Anglicus.[35] There is no assurance that the method was original with him; and much vague evidence suggests that the general principles were known considerably more than 1,000 years previously.

Throughout its area of visibility (approximately an entire terrestrial hemisphere), a lunar eclipse occurs at the same instant of cosmic time, however we may define or measure it. The local time of the eclipse, however, will be different at different points (not on the same meridian), because local time is a function of longitude. In consequence, if the local time[36] of the eclipse is noted at two points, the difference between the noted times is a measure of the difference in longitudes. This may be evaluated by multiplying the time difference in hours (and fractions) by 15, giving the difference in degrees (and fractions), because the earth rotates 15 degrees on its axis during each hour of time.

An eclipse of the moon occurs whenever the moon passes through the earth's shadow in space. In natural consequence, lunar eclipses are visible only from the night side of the earth, and these eclipses occur only at the time of full moon. They do not occur at every full moon because the plane of the moon's orbit is inclined to the plane of the earth's orbit (Ecliptic) by about 5 degrees, 9 minutes. The full moon, in many instances, is outside of the earth's shadow.

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[34] Trans. and ed. Eusebio Guiteras, *Records of the American Catholic Historical Society of Philadelphia*, v. 5 (1894), pp. 117–118. The context here seems to be somewhat confused. Available records show no lunar eclipse in 1751 which could be observed in both Sonora and Tenerife. However, an astronomically useful total eclipse of the Moon (Oppolzer #4574), having a mid-totality at Tenerife (Long. 16° 20′W.) at about 0038 local time, December 13, 1750, and mid-totality in Sonora (110°W.) at about 18:23 local time, December 12, 1750, seems to meet all requirements, and may be the one referred to. Finding of the missing records referred to would permit a most interesting recomputation of the data, and a clarification of the *Rudo Ensayo* text at this point.

[35] *Commentary* [on *The Sphere of Sacrobosco*], Lectio XV: "Item sciendum quod per eclipsim potest homo certissime scire longitudinem civitatis. . . ." Cf. Lynn Thorndike, *The Sphere of Sacrobosco and its Commentators* (U. of Chicago Press, 1949), pp. 244–245. (I am indebted to Mr. Roberrt J. Drake, of Vancouver, B.C., for calling attention to this most interesting work.)

[36] That is to say, local *sun* time – not local zone time.

Because the earth's shadow is complex, and the path of the moon through and near it varies systematically, there are several types of eclipses. Earth's shadow in space is bipartite, consisting of an outer half-shadow (penumbra) and an inner (nearly) complete shadow (umbra). Shadow relations are shown in Fig. 3A.

When the moon passes partly or wholly through the penumbra, a partial or total enumbral eclipse occurs. These are somewhat difficult to detect in the field, and are seldom used for navigational purposes. When the moon passes partially or wholly through the main shadow of the earth, a partial or total umbral eclipse occurs. These are what is commonly known as partial or total eclipses of the moon.

Duration of an (umbral) eclipse may vary from a few seconds in the case of a partial eclipse to more than two hours for a total eclipse. In consequence, determination of the same instant in an eclipse may be somewhat difficult, and observers have found that use of several identifiable positions of the moon with respect to the earth's shadow facilitates observations. These positions are called "contacts" and are numbered as in Fig. 3B, position number one being called "First contact," etc. Times of contacts are rather easily determined, requiring only a single observation. Time of midtotality is more difficult to ascertain, requiring two observations and a computation. It may not be feasible to make the two requisite observations (times of contacts 1 and 4, or 2 and 3) in bad weather.

Because the orbit of the moon about earth, and the orbit of the earth about the sun, are both stable, we can predict, by rigorous mathematical methods, when eclipses will occur, and when they will be visible. One such table of predictions, Ritter von Oppolzer's *Canon der Finsternisse,*[37] gives the date, time, duration, and geographical position of every (umbral) lunar eclipse from 1206 B.C. to 2163 A.D. – 5,200 eclipses in all.[38] Sun-earth-moon relations during an eclipse are shown in Fig. 4A; systemic relations not leading to an eclipse are shown in Fig. 4B and 4C.

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37 (Vienna: *Akademie der Wissenschaften,* 1887), pp. 325–376. (I am indebted to the U.S. Naval Observatory, Washington, D.C., and to the Lick Observatory, Mt. Hamilton, California, for eclipse references and information.)

38 See Alexander Pogo, "Additions and Corrections to Oppolzer's Canon der Mondfinsternisse," *Astronomical Journal,* No. 1083 (February 1938).

From this information, which was perhaps 1,500 years in gestation, navigators were able, on occasion, to determine longitudes with some accuracy. After 1700, when improved "tables of lunars" became available, including not only eclipses, but also occulations of stars and planets by the moon, use of "lunars" was a standard navigational procedure. Wide adoption of the marine chronometer made simpler methods possible by about 1850; and these methods, augmented by radio time signals, with received accuracy better than 0.1 second of time, are now adequate for most terrestrial navigation problems.

Because Father Kino undeniably had sufficient astronomical and mathematical knowledge and skill to make use of lunar eclipses as a method of determining longitudes; and because he might have brought or else constructed adequate timekeeping equipment to apply the method, a search was made of the astronomical tables and the historical records, to determine just what eclipses were available to Kino, and what use, if any, he made of them.

During the time that Father Kino was actively working in Sonora (1685–1711) there were forty-three lunar eclipses, according to the aforementioned "Canon der Finsternisse" a table which is known to be not quite perfect, but extremely good.[39] Of these umbral eclipses, twenty-six were partial, and seventeen total.

Now, for an eclipse to be navigationally useful, it must be visible not only at the point of interest (Dolores), but also at an index point (here taken as Tenerife). This requires that the geographical position of the eclipse (the point where it is directly overhead at totality) be between 20 degrees west of Greenwich and 106 degrees wst of Greenwich. All other eclipses, no matter how spectacular, are of no value in this case.

Meeting these conditions, during the period under consideration, are nine umbral eclipses, five total and four partial. Pertinent data on these are contained in Table *infra*, which is derived from that in the "Canon der Finsternisse," with Dolores date and Dolores Local Time added for convenience.

The first eclipse, No. 4475, occurred at Dolores on September 28, 1689, and was a total eclipse, with totality beginning just after

[39] No errors of importance during the period of our interest (1685–1711) have been reported.

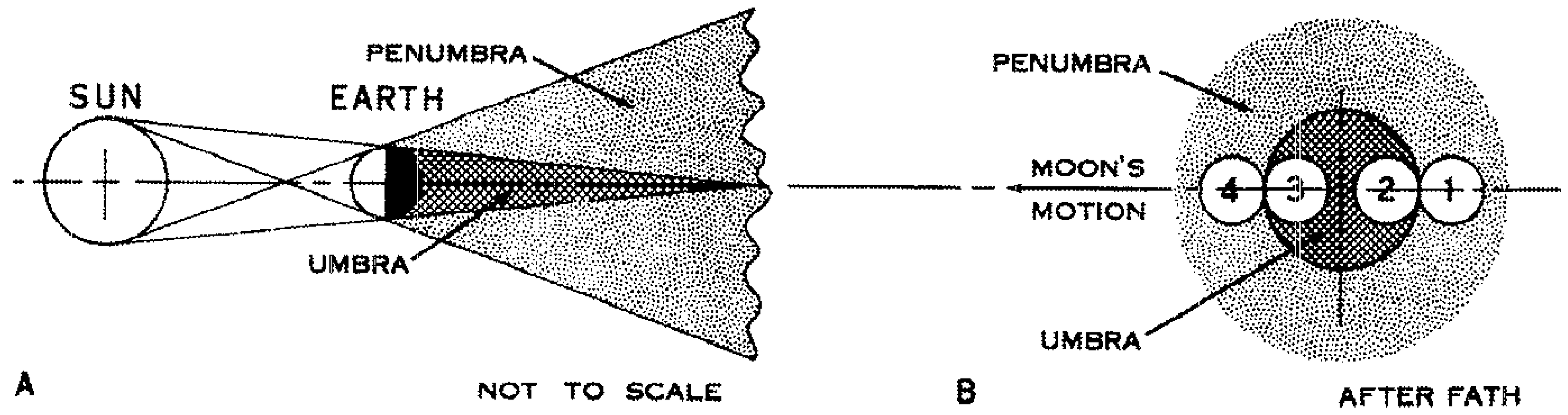

Fig. 3. A. Shadow formation in space. B. Parts of eclipse.

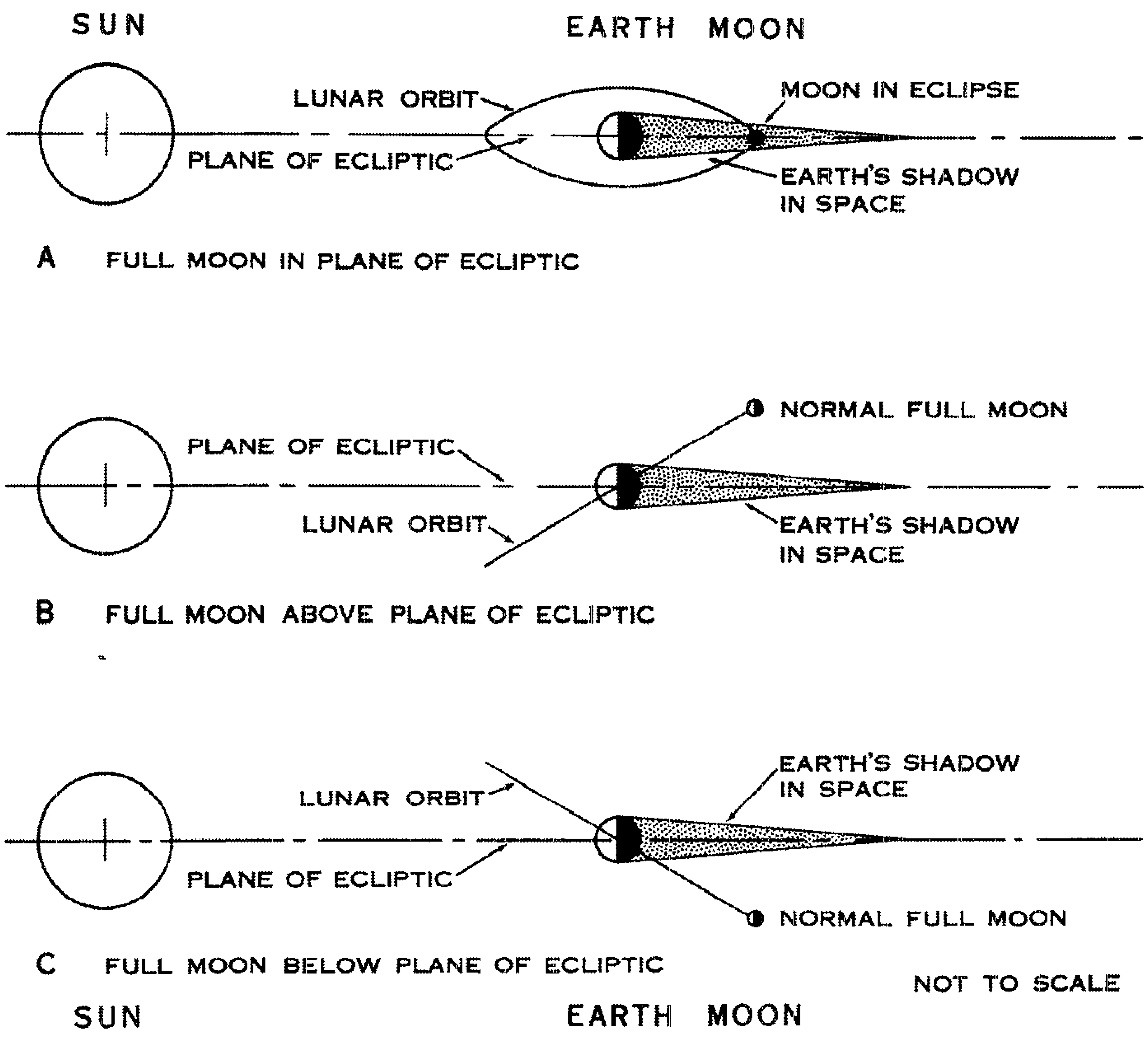

Fig. 4. Eclipse relations.

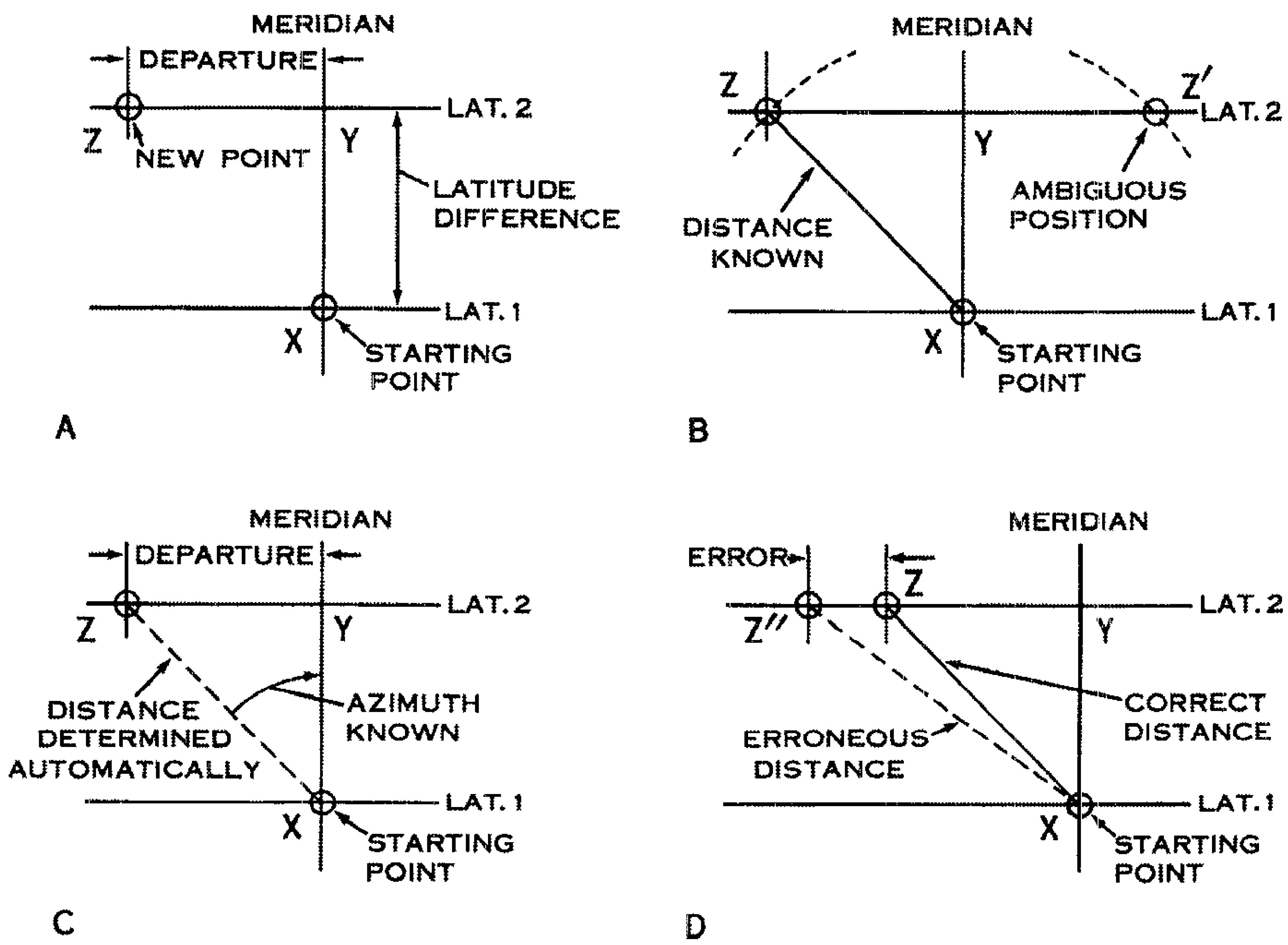

Fig. 5. Applications of the method of latitudes and departures.

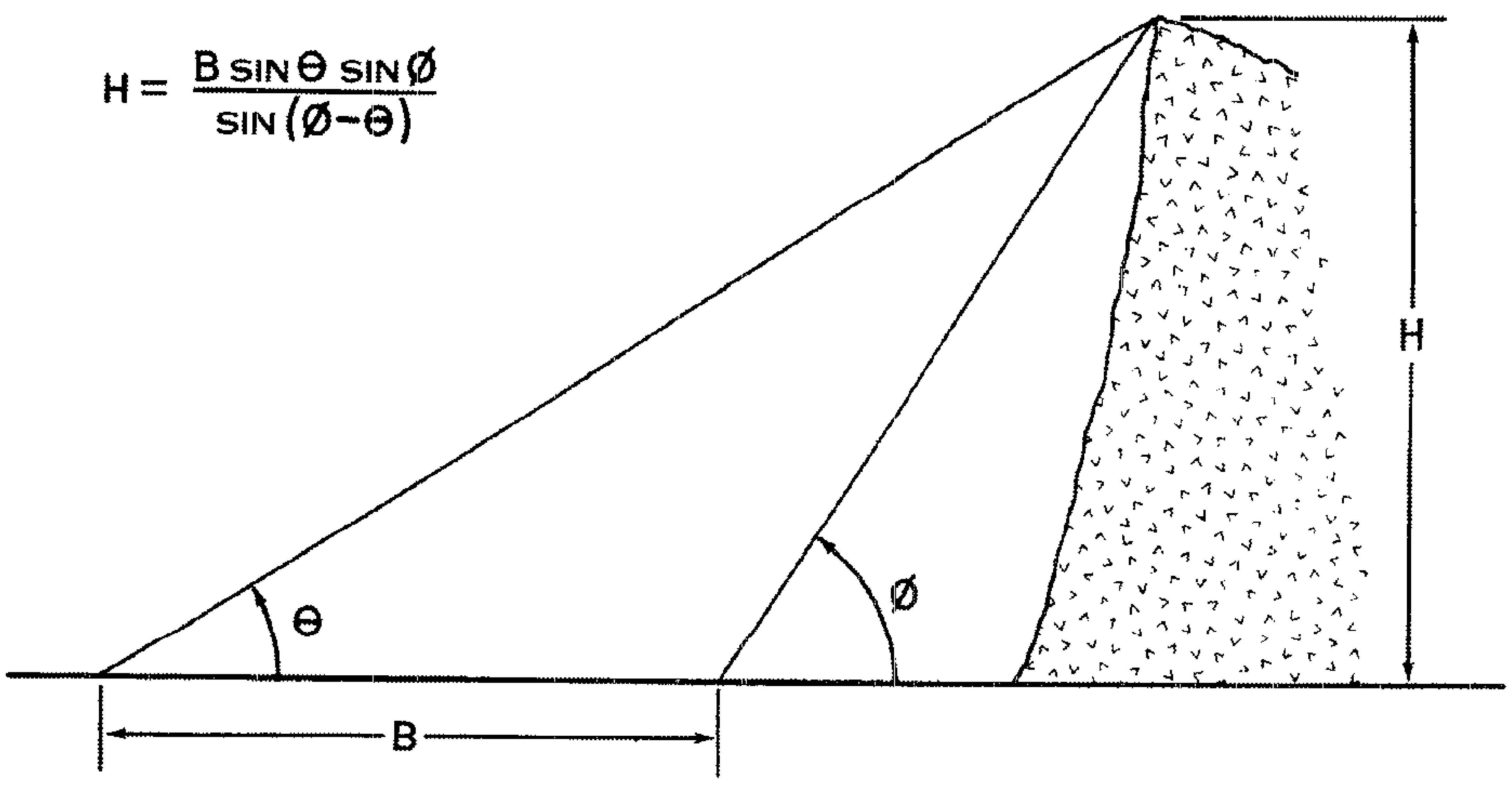

Fig. 6. Determination of the height of an object when the base is inaccessible.

No.*	Greenwich Date	GMT†	Half Duration Minutes Partial	Total	Long.	Dolores Date	DLT§
4475	Sept. 25, 1689	0221	112	51	38°W.	Sept. 28	1858
4479	Aug. 28, 1692	0310	46	—	46°W.	Aug. 27	1947
4480	Jan. 22, 1693	0400	111	50	57°W.	Jan. 21	2037
4487	Nov. 9, 1696	0429	112	52	71°W.	Nov. 8	2106
4488	May 6, 1697	0544	74	—	87°W.	May 5	2221
4498	Dec. 23, 1703	0629	112	51	98°W.	Dec. 22	2306
4501	Apr. 28, 1706	0133	74	—	24°W.	Apr. 27	1810
4503	Apr. 17, 1707	0142	112	52	26°W.	Apr. 16	1809
4505	Apr. 5, 1708	0539	76	—	84°W.	Apr. 4	2216

* No. is that listed in "Canon der Finsternisse"
† GMT is Greenwich Mean Time
§ DLT is Dolores Local Time

sunset, and ending 102 minutes later, approximately. Kino at this time was at or near Dolores, and no mention of the eclipse is found in available documents.

The second eclipse, No. 4479, occurred at Dolores on August 28, 1692, and was partial, beginning at about seven in the evening, and ending about 1½ hours later. At this time, Kino was journeying northward, through the country of the Sobaipuris, and had no facilities for longitude observations on the trail.[40]

The third eclipse, No. 4480, occurred at Dolores on Jan. 21, 1693, at about half past eight, Dolores time, in the evening. This was a total eclipse, and ideally suited for longitude observations. At this time, Kino was busy preparing his new church at Dolores for dedication, and makes no mention of the eclipse. Was it, perhaps, cloudy on the evening of January 21, 1693?

The fourth eclipse, No. 4487, occurred at Dolores in mid-evening of November 8, 1696, and was a total eclipse, ideally suited for the desired longitude observations. At this time, Kino was at Dolores, preparing for his horseback trip to Mexico City, which began on November 16. There seems to be no documentary record of this eclipse in Sonora.

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[40] We have no evidence suggesting that Kino possessed a portable timepiece.

The fifth eclipse, No. 4488, occurred at Dolores on May 5, 1697, between 2117 and 2335, local time. This was a partial eclipse, of dubious navigational utility. At this time, Kino was probably at Dolores, resting between trips.

The sixth eclipse, No. 4498, occurred at Dolores on December 22, 1703, about one hour before local midnight. This was a total eclipse, with totality lasting about one hour and forty-two minutes. At this time, Kino was in the vicinity of Dolores, preparing for the coming of the long-hoped-for additional missionary, Father Geronimo Minutuli, who was assigned to Tubutama. Again, contemporary documents contain no mention of an eclipse.

The seventh and eighth eclipses, No. 4501, of April 27, 1706, and No. 4502, of April 16, 1707, occurred at Dolores just about sunset, and were over before full darkness set in. As, in each instance, the moon rose in eclipse from behind the Sierra de Santa Rosalia, it is doubtful that either eclipse was observed at Dolores; and improbable that such an observation, if made, would have been navigationally useful.

The ninth and last eclipse, No. 4505, occurred at Dolores at about quarter after ten, local time, on April 4, 1708. This was a partial eclipse, of short duration. At this time, Kino was apparently at Dolores, apparently working on the final chapters of his *Favores Celestiales,* "in addition to his regular duties."

From the foregoing, it appears that Kino made no navigational use of lunar eclipses, and apparently also made no mention of them in his currently available writings. In fact, the only mention of eclipses in Sonoran documents of that time seems to have been made by Manje.[41] We also find no clear evidence that Kino ever had a table of eclipses; and there is no contemporary reference to any of the timekeeping devices (clocks, watches) which are essential for effective use of eclipse observations. It is almost certain that some of the eclipses listed in Table I were not visible because of cloudiness; but it is unlikely that all of them were so concealed.

Because of the near impossibility of measuring longitudes with any certainty, navigators in the seventeenth and eighteenth centuries

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[41] See Manje, *Unknown Arizona and Sonora,* p. 244: "When . . . there is an eclipse of the sun and moon they all yell. . . ."

developed a method known as *departures*. Coupled with measurement of latitude, this method permitted exact location of a point, and land surveyors, to this day, make location designations by the method of *latitudes and departures*, applied either graphically, as did Kino, or mathematically, as became the accepted method when good trig tables were generally available and understood.

Given a starting point whose location is known by latitude and longitude (or otherwise) and a new point whose relative location is to be determined, the new point can be located rigorously by the method of latitudes and departures. The simplest method is to proceed along the meridian of the starting point until the latitude of the new point is reached. The travel in this direction is the latitude difference of the new point relative to the starting point. Next one proceeds along the parallel (of latitude) of the new point until it is reached. Distance travelled from the meridian of the starting point to the meridian of the new point is the departure of the new point (relative to the starting point). This elementary approach to the problem, outlined in Fig. 5A, is much like the "constant latitude sailing" common in Kino's day and earlier. Distances were usually measured in leagues, kennings, or sea miles, and later converted to degrees, minutes and (sometimes) seconds, by tabular or graphical methods. William Bourne, as early as 1574,[42] depicted an entirely workable device for ascertaining "how many miles there are in a degree of longitude in any given latitude."

From Kino's own diaries we know that he did not make doglegs all over Iitoi's domain, but that he travelled directly from point to point. We also know beyond any doubt that he was in the habit of determining latitudes by astronomical measurements to an accuracy which was remarkably good at the contemporary state of the navigator's art. In consequence, he had available two possible *modi operandi,* in applying the method of latitudes and departures.

Location of a new point, by latitude and departure, with the latitudes known, and the distance also known, is done graphically by straightforward means. The two parallels of latitude are drawn on the

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[42] *A Regiment for the Sea*... (London, 1574, 1577, 1580, 1592). There also exist several pirated and plagiarized partial versions.

paper to any desired scale, and are intersected at right angles by the meridian of the starting point. Then, with the starting point (X in Fig. 5B) as a center, and the distance (to scale) as a radius, an arc is drawn, intersecting the parallel (of latitude) through the new point at Z and Z′. This determines two equal departures, Z–Y and Z′–Y, one of which is ambiguous. The undesired ambiguity is eliminated if the approximate bearing of the course X–Y is known, and the construction (after eliminating the ambiguity) automatically determines the azimuth of the course (X–Z). This is a geometrically valid determination because "two right triangles are congruent if the hypotenuse and a side of one are equal respectively to the hypotenuse and a side of the other."[43]

The new point can also be located accurately, the respective latitudes being known, if the azimuth of the course (X–Z in Fig. 5C) is known. With the same initial construction as previously, the course is laid off from the starting point, with the requisite azimuth. Intersection of the course line with the latitude of the new point locates the new point (Z), and automatically determines the distance (X–Z). This is a geometrically valid determination because "two triangles are congruent if two angles and the included side of one are equal respectively to two angles and the included side of the other."[44] As should be obvious, the intersection of a meridian and a parallel (of latitude) is always a right angle ZYX, any part of Fig. 5).

In the hilly Sonoran environment, where "straight sights" from starting point to destination are frequently impossible, the first method (Fig. 5B), employing (in addition to latitude measurements) distance and approximate direction, is likely to be the most useful. The azimuth method (Fig. 5C), useful only where "straight sights" are possible, is less applicable here. It requires, for effective use, a sighting compass calibrated in degrees (which Kino apparently did not have) and correction for local magnetic variation, by Polaris sight or other method. The azimuth method is also vulnerable to local magnetic attractions, which are numerous in the volcanic areas west of Sonoyta,

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43 George Wentworth and D. E. Smith, *Plane Geometry* (New York: Ginn & Company, 1938), p. 43.

44 *Ibid.*, p. 30.

and in some placer regions, such as Puerto del Humo, where black magnetite sands are naturally concentrated.

Because both methods employ plane geometry and the earth's surface is curved, a small curvature error will be present in all such measurements. As the curvature error is considerably smaller than the other unavoidable errors in Kino's maps, it is of only academic interest here.

From Kino's own writings, and from those of his companions on the trail, we know not only that he measured latitudes, but also the exact method that he used. These same sources tell us that Kino also made all necessary measurements for mapping by the "distance" method. His diary entries of these facts are commonly as follows: "On October 3 . . . we set out for the west . . . after a journey of six leagues . . . we arrived at . . . Guoydag. . . . After going seven leagues more, we reached San Mateo del Batki."[45] The essential data here are "thirteen leagues" and "west".

Had the azimuth method been used, Kino would have had to report the same travel substantially as follows: "From El Tutto, we took a course south 82 degrees west to San Mateo del Batki." Kino made no such detailed directional observations, nor did Manje, his field companion on many expeditions. Both men commonly cited directions only to the nearest octant, and neither used the infrasedeciental compass divisions essential for effective use of the azimuth method.

The mean error of Kino's distance citations is about five per cent. Manje's cited distances, in general, exceed Kino's, but not by a fixed percentage. Comparison of cited travel distances suggests that Manje's figures approximate the distance actually travelled, whereas Kino's figures approximate the airline distance between points. So far as we can now determine, both men estimated the distance travelled. It is certain that, on many journeys, they did not have a corporal assigned to count paces, four thousand of which made one league.

Because the latitudes in Kino's maps were instrumentally measured, with relatively high precision, while the departures were determined from estimated distances, which had a relatively lower pre-

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[45] Bolton, *Kino's Historical Memoir of Pimería Alta,* pp. 246–247.

cision, lateral distortion of Kino's maps is to be expected. How this comes about is diagrammed in Fig. 5D, which shows the production of an error of departure by geometrical determination involving an error of distance estimation. It should be noted that the percentage error of departure is greatest when the course between points is nearly meridional, and least when the course is lateral.

Inspection of Kino's maps will show immediately that the longitudes are quite erroneous. Correction of the stated longitudes from the meridian of Tenerife to the present index meridian of Greenwich improves the numerical values somewhat, but leaves them still quite definitely wrong. This is due entirely to Kino's inability to measure longitudes. Not having a suitable local index of longitude, and also lacking instruments and tables sufficient for eclipse observations, he was forced to operate from a "guessed meridian" (perhaps that through Mission Dolores). Taking this difficulty into account, we find that Kino's maps are laudably self-consistent, and probably as good as the state of the cartographer's art in 1700, skilfully applied, would permit. It is noteworthy that Sonoran longitudes were still undefined in 1751, that a few key points were accurately located by the boundary and railroad surveys just after the American Civil War, and that many points in western Sonora were not accurately located until the field notes of Lumholtz and Celaya were drawn up by A. Briesemeister in 1912.[46]

Modern maps customarily locate points on the earth's surface by latitude, longitude, and altitude, usually in a form similar to the familiar U.S.G.S. "Quad" maps. Reference to the map accompanying this article will show that Kino proceeded similarly, but that the altitude indications are qualitative only. We do not know, from Kino's maps, whether the various sierras are 100 feet high, or 10,000, and we can judge the slopes of the flatlands only from the directions of flow of the rivers.

This "deficiency" in Kino's maps is more apparent than real, and it detracts not at all from their primary usefulness – showing where places are. Several million maps, constructed on about the same plan as Kino's, are published annually in the United States – we call them

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[46] I am indebted to Mr. Alberto Celaya, of Sonoyta, Sonora, and to Mr. William Briesemeister, of the American Geographical Society of New York for helpful discussions of the making of the Lumholtz maps.

road maps. For most purposes, specifically including trail and highway travel, the detailed contours of the "Geological Survey" map are of very little use, and are better omitted for the sake of clarity.

Methods of determining altitude in Kino's time were few, and quite difficult to use. The laborious rod-and-level method, used in the time of the Pharaohs, was the best for gentle slopes. Equipment for this method consists of a levelling device and one or more calibrated rods. In ancient times, the level consisted of an open sight alidade floated in a dish of water, mercury, or honey. As the liquid surface was always level, so (it was hoped) was the alidade. In operation, the rod was placed on the index point, the level set up at a convenient location, and the calibration of the rod, seen through the alidade, was noted. The rod was then moved to a second point, the process repeated, and the difference in elevation computed by subtracting the second reading from the first. This could be repeated, using the second point as the index for another setup, and so on, util the "line of levels" was completed.

According to a hoary piece of engineering folklore, this method was used by a group of Romans, who were hired by Cleopatra to dig a canal from the Nile to the Red Sea. The figures, on completion of the survey, showed that the Red Sea was nine cubits higher than the Nile. Obviously, digging the canal would flood the Mediterranean basin, imperilling Imperial Rome. Quietly, the Romans consigned the project to Tartarus, and took their tripods, dishes, alidades and rods to more friendly climes.

Today, although we use telescopic levels and accurately calibrated rods, correct for atmospheric retraction, and although we guard against shimmering of the air by working at odd hours, the fundamental method is the same as in the time of the Caesars. No record has been found, however, to show that this rod-and-level method was used in Sonora during Jesuit times, and no reference to the requisite equipment has been found in any mission document studied. The most useful method of height determination, in Kino's time, was vertical angulation, a method still widely and effectively used. In its simplest form, vertical angulation was understood, and probably used, before the time of Alexander the Great.

To determine the height of a tower or cliff, when the base is accessible, the angle of elevation of the summit from a convenient place is measured; then the distance is measured from the point of observation to the base. Height is then determinable by means of a scale drawing, or can be computed from the formula "Height = base distance X tangent of angle of elevation." Field workers, anxious to save time, early found that if the angle of elevation was 45 degrees, the height equalled the distance; and if it was 26⅓ degrees (approximately), the height was half the base distance.

At least 1,000 years ago, some unknown genius, possibly in Persia, designed an astrolabe with which angles of elevation could be measured, and the height of an object, the base distance being known, determined rapidly, without the use of tables or computations. This improvement consisted of rectangularly cross-hatching one quadrant of the astrolabe, so that the alidade, at any setting, made a family of proportional right triangles in that quadrant. The number of units of length in the base line was then counted off along the horizontal line of the astrolabe, and the height of the object, in the same units, was then given directly above it. Surviving astrolabes, suitably calibrated for this use, include that of Ahmad and Mahmud, sons of Ibrahim, makers of astrolabes, natives of Isfahan, dated A. H. 374 (984 A.D.).[47] Construction of astrolabes of this type continued into the nineteenth century, one of the best surviving later examples being an instrument "made by order of Mahmud Mirza Kajary Said – son of the greatest Shah in the Paradise-like city of Naharwand" by "this slave Mohammed Akhbar" in A.H. 1234 (A.D. 1818).[49] Study of the workmanship on this device indicates beyond question that "this slave Mohammed Akhbar" was a first-rate instrument maker.

When the height of an inaccessible object is to be determined, the measurements and computations are somewhat more difficult, but means for determining such altitudes accurately have been known for considerably more than 400 years. To make this measurement, one determines the angle of elevation of the summit from a convenient distant point; then moves a known distance toward the object; and again de-

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[47] See Gunther, *Astrolabes of the World*, v. 1, pp. 114–116, and pls. XXII and XXIII.

[48] See *ibid.*, v. 1, pp. 151–153; pl. XXXVII; and figs. 73, 74, and 75.

[49] See *ibid.*, v. 1, pp. 169–170; pl. XLIV; and fig. 83.

termines the angle of elevation of the summit. Geometry for making this measurement is shown in Fig. 6, along with the formula for computing the height. Here B is the measured base distance; θ is the first angle measured; and ϕ is the second angle. H is the height of the object, to be determined.[50]

We can be certain that these methods were known in Kino's time, for they are clearly depicted in Johan Stöffler's widely reprinted and pirated book *Elucidatio fabricae ususque astrolabii*,[51] first published in 1512.

Mathematical tables more than adequate for these and similar trigonometric computations were widely circulated through the publications of Regiomontanus, otherwise known as Johannes Muller of Konigsburg, after 1490. Where accuracy to only two figures was required, as in most field work, the requisite sine functions could be read directly from the sine quadrants of many astrolabes, making a book of tables unnecessary.

As might be expected, practical field workers soon found that much computation could be eliminated if two "convenient" angles were used in this height determination. If θ is 30 degrees and ϕ is 45 degrees, the height is 1.3659 times the measured base; and if θ is 30 degrees and ϕ is 53⅓ degrees, the height (very nearly) equals the measured base.

We find no specific references to the use of these methods in Kino's surviving manuscripts, or in Manje's diaries, but, as they were the only methods available to him, we can be sure that Kino used them on occasion, probably during the layout of his mission sites, if for no other purpose.

It has been pointed out on several occasions that Kino could perhaps have measured altitudes barometrically, as the mercurial barometer was invented by Evangelista Toricelli in 1643; and a relation between barometric pressure and altitude was experimentally demonstrated by Blaise Pascal, René Descartes, and Florin Périer about 1648. The results, however, were not published until 1663.

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50 Derivation given in C. I. Palmer and C. W. Leigh, *Plane and Spherical Trigonometry* (New York: McGraw-Hill, 1934), p. 150 (#5).

51 (Oppenheym, 1512). Nineteen other editions and translations are known through 1536.

Unfortunately, altitude cannot be determined barometrically unless the local daily barometric cycle is known (requiring a series of long-term observations at a base station) and the air temperature (preferably at both base and advance stations) is also known. These essential measurements could not be made with the requisite accuracy until Gabriel Fahrenheit developed a mercurial thermometer with a rational calibration, in 1714. The first dependable formula relating altitude, atmospheric pressure, and air temperature was developed by Jacques Babinet about 1838. Approximately a century later, the late W. J. Humphreys, using vastly more complete data, was able to improve this formula "after the third significant figure."

Because the mercurial barometer was a most difficult instrument to use effectively in the field, simpler and more portable means for measuring atmospheric pressure ewere searched for, and the ancestor of our modern aneroid barometer was demonstrated by Jacques Conté in 1799. Quantity manufacture of aneroid barometers did not begin until about 1849; and it was not until about 1885 that the instrument was accepted for field use in western North America.

One of the most extensive uses of the mercurial barometer for determining altitudes was that by John Wesley Powell during his explorations of the Colorado canyons in 1869. A parallel method, in which altitude was determined by measuring the boiling point of water, was used with somewhat ambiguous results during the Hayden Surveys of the Territories during the 1870s. This ingenious method of determining altitudes was developed after Fahrenheit's development of a rational thermometer scale (1714), and was supplanted by aneroid observations shortly after 1880. From the foregoing it appears that Kino could not have made any effective determinations of altitude by the barometric method, as the method was not adequately developed in Kino's time; and, no record has been found of the existence of a barometer of any type in Sonora during the early eighteenth century.

The preceding summary history of the development of navigational and cartographic instruments and methods from the time of their introduction to the Christian world until after the close of Kino's career, gives us a good indication of the methods available to him during his explorations of Papaguería and parts of Baja California. Investigation of Kino's educational background shows beyond any reasonable doubt that he was capable of using effectively all mapping techniques available in his time. Diary evidence shows that he practiced navigation while en route to the New World; and his comet observations evidence creditable astronomical competence.

Scrutiny of contemporary literature, largely Kino's own diaries and reports, gives us specific information concerning the field use of some of these methods, and details the instruments and tables which Kino employed. Clues to the probable use of some other methods are furnished by the types and accuracies of cited geographic facts. Non-employment of several other navigational and cartographic methods is indicated by lack of reference to the data and instrumentation necessary for their use.

From this information we can prepare, with some confidence, an "assayer's report" on the cartographic work of Father Kino. Although the basic data are not, in every instance, as complete as we would like, they appear sufficient to permit a fair appraisal of the work, and they are adequate for the certain elimination of serious anachronisms in the "Herodotus' typewriter" category.

Kino's latitudes were instrumentally measured by the meridian altitude method, by means of an astrolabe for the angular determinations, and of Aigenler's Tables for the declination corrections. No corrections were made for atmospheric refraction, which was neither clearly understood nor accurately evaluated in 1700. Choice of this method was most fortunate, for errors of time, direction and refraction are relatively minor when it is used carefully. The attained accuracy of Kino's latitude measurements is about as great as careful use of the method and instruments permit. A skilled worker, using the same instruments and methods today, would have about the same average error of observation.

Kino's longitudes are all derived figures, and they are all wrong. Kino had no firm index meridian, no method of determining longitudes in the field, and no convenient means of checking his east-west distances, other than estimation. Longitudes in Kino's maps are based on departures, which were determined trigonometrically, using measured latitudes and estimated distances as basic data. Because Kino's distance estimates were good, and his latitude measurements excellent, lateral distortion in his maps is small, and the use of a "floating index" or "guessed meridian" detracts from their practical usefulness not at all. Although longitude determination by lunar eclipse observation was understood in Kino's time, he could not make use of the method, because he had no suitable timekeeping equipment. Although several suitable eclipses occurred in Sonora during the time of Kino's explorations, no mention has been found of them in available Kino documents.

Kino's altitude designations are qualitative only, and adequate for the purposes of his maps. Although he could have determined the altitudes of the various sierras by vertical angulation, using his astrolabe, he seems not to have done this. Actually, cartographers, prior to about 1750, paid little attention to elevation per se, and the now-familiar contour maps, although invented by the Dutch engineer Cruquius, about 1728, did not become generally available until about 1878, when the original process (contour mapping) was combined with color printing.

So much for the objective portion of the assay. The subjective portion, which is the assayer's opinion, unavoidably is influenced by the assayer's background and experience. The present assayer is a geophysicist by training, and an explorer by avocation. The considered verdict is that Kino's maps are somewhat better than we could reasonably expect, in view of the state of the cartographic art in 1700, the instruments available then, and the time available for the work. One of Kino's maps, the "Passo por Tierra" is probably the most competent one-man exploration ever conducted.

During the course of this study of Kino's maps, and the methods by which they were made, it became apparent that his maps, in some instances, contained more specific information than could be found in surviving diaries and letters. Additionally, some of the parallel documents, such as the Manje diaries, contain references to observations which are not included in available Kino documents.

From these evidential discrepancies, it appears that the Kino documents now available are only a part of the total notes, letters, and diaries written by Kino. Among the documents which should be sought are:

1. One or more tables of locations, listing the names of places visited, their measured latitudes, and their distance from some other place.
2. One or more descriptions of eclipses. Taking into account probable cloudiness on several pertinent occasions, it seems almost certain that Kino witnessed at least two solar and two lunar eclipses during his active field life in Sonora.
3. One or more descriptions of meteor showers.

Additionally, the fate of Kino's copy of Aigenler's *Tabula Geographic-Horologa Universalis* has not been determined. It is barely possible that this valuable scientific work has survived to this day. If found, it would be worn from a quarter of a century in saddlebags, dog-eared from much use, and stained with the sweat, dust, and mud incident to many thousands of miles of desert travel. Perhaps marginal notes in this work constitute the field notes which we believe must have existed, but which we do not yet possess.

Lastly, a diligent search for Kino's astrolabe should be made. This instrument, made of metal, should be substantially immortal, so that chances of its survival are good. If found, even though not specifically marked, it could be identified by analysis of the metal, and study of the inherent errors in the calibration.

Lest this search be likened to the quest of the Holy Grail, let it be remembered that Drake's "Plate of Brass," nailed to a post on the shore of "New Albion" in June, 1579, was – after suffering various vicissitudes – found in 1936 and, after detailed and critical study with the edged tools of modern science, declared to be "the genuine Drake Plate."[52] Likewise, Champlain's astrolabe, lost on June 7, 1603, was found in August, 1867.[53]

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[52] See Bolton, *Drake's Plate of Brass: Evidence of His Visit to California in 1579* (San Francisco: California Historical Society, 1937); Colin G. Fink, *Drake's Plate of Brass Authenticated* (San Francisco; California Historical Society, 1938).

[53] See A. J. Russell, *Champlain's Astrolabe* (Montreal, 1879).