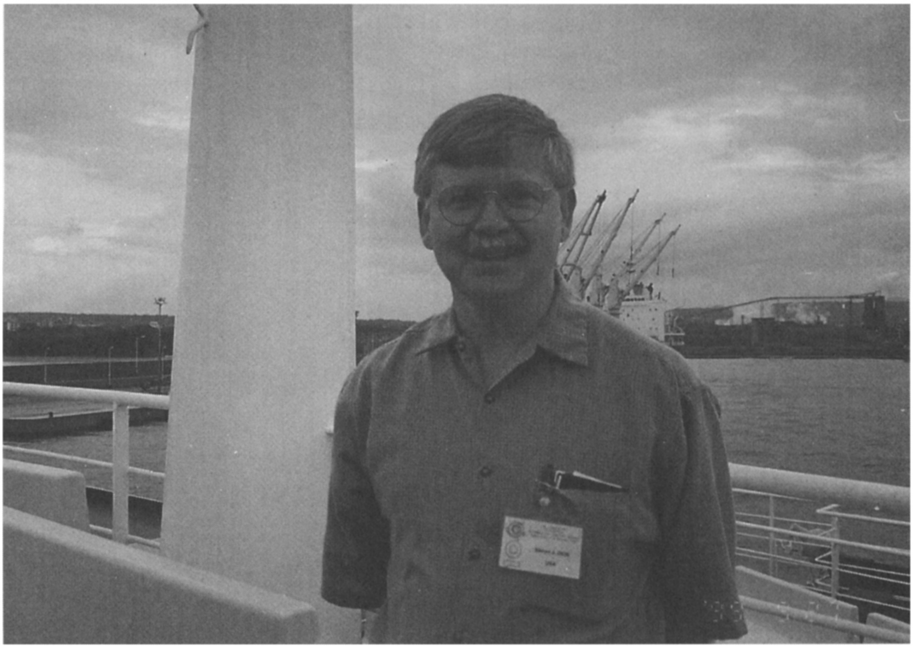
Historical Sessions



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Polar Motion: Historical and Scientific Problems
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Polar Motion: A Historical Overview on the Occasion of the Centennial of the International Latitude Service

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Abstract. The study of polar motion, termed "variation of latitude" at the time of its discovery in the late 19th century by F. Küstner and S. Chandler, is of historical interest for many reasons. From a scientific viewpoint, its discovery must be seen in the context of positional astronomy, geodesy and Earth rotation studies. From an institutional viewpoint, the founding of the International Latitude Service (ILS) in 1899 represents an early case of international cooperation in astronomy, preceding the International Astronomical Union by two decades. In addition to discussing these themes in this review, we analyze in some detail the Gaithersburg (USA) station of the ILS as a case study of the early problems and promise of polar motion studies. With milliarcsecond accuracies, polar motion studies are important today not only for astronomy and geophysics, but also for practical problems like spacecraft navigation and positioning.

1. Introduction — the Context of Polar Motion Studies

The discovery and subsequent refined measurement of polar motion over the last century must be seen in several contexts: astrometrically, in terms of the evolution of instrumental accuracies; conceptually, in terms of its place in astronomy, geodesy and geophysics, and Earth rotation studies; and internationally in terms of the evolution of international cooperation in science. Seen in these terms, the past century of polar motion research is a rich subject for historical study.

A broad view of astrometric accuracies (Fig 1) shows where matters stood at the end of the 19th century when polar motion was unambiguously discovered — half way between the star catalogues of Argelander in 1842 and Boss in 1937. Table 1 reveals three eras: the naked eye, telescopic and interferometric/space eras, corresponding roughly to the minute of arc, second of arc and milliarcsecond accuracy regimes. Polar motion studies encompass the last two eras, with accuracies ranging from a few tenths of an arcsecond at the beginning of the century to one milliarcsecond at its end; the field now has the promise of making further discoveries by exploiting the microarcsecond regime. Table 1 also shows that both visual and photographic methods were capable of reaching these accuracies of a few tenths of an arcsecond, and indeed one of the continuing debates through much of 20th century polar motion studies is the comparative value of visual versus photographic methods.

Table 1. Improvement in Precision of Astrometric Measurements

Method	Representative Observer/ Institution	Date	Precision* (Arcsec)	Instrument	Representative Discoveries
Naked Eye	Hipparchus	150BC	1200″	armillary	precession
	Ptolemy	150AD		sphere	(50″/yr)
	Ulugh Beg	1437	1200″	same	
	Tycho Brahe	1600	15″	quadrant	
Telescopic					proper motion
visual					(Halley, 1718)
	Flamsteed	1700	15″	quadrant	aberration, 20″
		1725	8″		(Bradley,1728)
	Greenwich	1800	1″	transit circle	
	Bessel	1838	.02″	heliometer	parallax, .3″
	Pulkovo	1855	.7″	transit circle	unseen stellar
					companions
	Chandler	1885		almucantar	polar motion, .2″/yr
	Küstner		.03	universal transit	
	USNO	1910	.3″	transit circle	
	USNO	1980s	.07″	transit circle	
photographic					
	Gill	1886–	2″–	astrograph	star streams
	Kapteyn	1900	4″	plate	(Kapteyn,1904)
	22 obsys	1891–	.17–	astrograph	galactic rotation
	Carte du Ciel	1950	.40″		(Oort, 1920s)
	Schlesinger	1910	.02″	long-focus	planetary
	USNO	1915	.01″	PZT	
	USNO	1980s	.004″	telescopes	companions? 1960s
	USNO	1980s	.15″	astrograph	
electronic					
	USNO	1990s	sub- .001″	61-inch reflector	
Interferometric					
radio	NASA, USNO, NRL, NGS	1980s	.001″	VLBI	
optical	USNO/NRL	1994	.005″		
Space					
	HIPPARCOS	1989– 93	.002″	satellite	

*In the present table the internal accuracy, or "precision", of a given instrument with its random errors must be distinguished from the true accuracy, which takes into account systematic errors.

USNO = U. S. Naval Observatory, NRL = Naval Research Lab, NGS = U.S. National Geodetic Survey

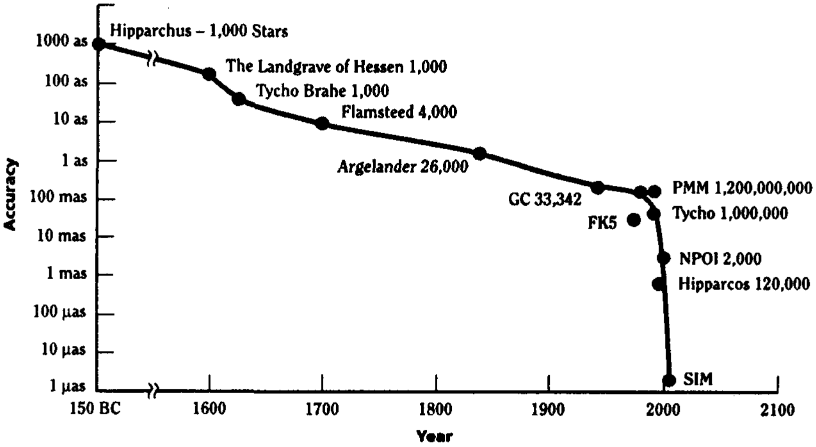

Figure 1. Astrometric accuracies over two millennia. The discovery of polar motion took place during a period of only very slight improvements in accuracy. From *Space Interferometry Mission: Taking the Measure of the Universe* (NASA, 1999).

A glance at Table 1 shows that stellar parallax, an effect of a few tenths of an arcsecond, was detected in 1838. An immediate historical question is why polar motion was not detected and announced earlier. Indeed, at this meeting Verdun and Beutler (2000) discuss possible earlier determinations beginning in the 1840s. Of course, the detection of such small effects is related to methodology. Markowitz (1976), in perhaps the best succinct history of polar motion studies, noted possible reasons for the failure of an unambiguous detection and announcement of a variation in latitude prior to the late 19th century; he emphasized especially Küstner's use of the Talcott method with a zenith telescope, a method that required only micrometer readings, no circle readings with all their attendant problems. But this does not solve the problem, since Andrew Talcott had designed and used his zenith telescope as early as 1834.

Moreover, the astronomer and optics expert Frank Ross, whom we will see later in connection with the Gaithersburg latitude station, noted that the Airy reflex zenith tube "had been accumulating observations continuously for a period of more than 30 years before the discovery of the latitude variation, which remained a mine of hidden wealth until opened up by Dr. S. C. Chandler." Chandler, he noted, analyzed these observations, traced the variation of latitude effect, and "removed the stigma of inefficiency from an instrument which had been tried, patiently and tenaciously, and apparently found wanting". Ross also noted that although the zenith telescope, using the Horrebow-Talcott method, was the most accurate way to determine variation of latitude, this variation had also been detected by meridian circles, visual and photographic almucantars, prime vertical transit instruments, as well as the Airy reflex zenith tube (Ross, 1915, p. 9). In fact, in his seminal paper on variation of latitude, Chandler (1891b) discusses how perplexed astronomers at the Naval Observatory worried about anomalies in observations made with the prime vertical instrument from 1862–1867 to determine the aberration constant (Hall, 1888). So in the spirit of this meeting, I pose to the Colloquium the first of several historical problems:

Historical Problem # 1: Why did it take so long to discover polar motion, and how did astronomers explain discrepancies prior to its announcement?

Part of the goal of this meeting is to shed light on these and other historical problems.

A second context is the scientific effects on astronomy, geophysics and Earth rotation. In a general sense polar motion affects nearly everything having to do with absolute measurement in astronomy (see section 4). A knowledge of polar motion is an essential part of today's International Terrestrial Reference Frame (ITRF), so the history of polar motion is essential to the study of the evolution of more precise reference frames. With regard to Earth rotation, polar motion of course affects the measurement of Universal Time. Although polar motion amounts to several hundredths of a second of time, it was not until the second half of the century that this quantity was incorporated into the daily dissemination of time. Polar motion could only be determined months after the fact, and for many years the Bureau International de l'Heure (BIH) applied polar motion corrections only in its annual analysis of time signals. The Royal Greenwich Observatory first applied polar motion corrections as a daily practice in 1947.

With the IAU's establishment of a Rapid Latitude Service in 1955, however, and its provision for the BIH to extrapolate Earth rotation corrections a year in advance, the timing community was poised to incorporate polar motion and seasonal variations in Earth rotation into the disseminated time in a coordinated and systematic way. At the meeting of the IAU in Dublin in 1955, William Markowitz, the incoming President of Commission 31 on Time and the Director of Time Service at the Naval Observatory, introduced 4 resolutions, including one instructing the BIH to compute for those observatories cooperating in international time service the longitude corrections due to polar motion (Oosterhoff, 1957). The result was that, beginning 1 January 1956 Universal Time (UT), as observed by the visual and photographic instruments of the time, was designated UT0, while UT1 was corrected for polar motion and UT2 was further corrected for seasonal variations in the Earth's rotation. In effect each step from UT0 to UT2 produced a more uniform time scale. Guinot (2000) provides more detail in this volume.

Finally, we should recall that it was geodesists, not astronomers, who began the International Latitude Service (ILS), and that today the measurement of both polar motion and the length-of-day aspect of Earth rotation provide important data for geophysics. Sir Harold Jeffreys (1952) provided an early overview, and Munk and MacDonald (1960) pioneered in synthesizing the geophysical aspects, both in terms of excitation causes and consequences. Their work has been extended by many researchers, synthesized in several excellent treatments, including Lambeck (1980), and will be the subject of more papers at this meeting. So polar motion is important in the history of geodesy and geophysics.

A third context is international cooperation, particularly as it related to the International Association of Geodesy (IAG) and its predecessors. Stimulated by the need for cooperation in the measurement of the central European arc, the inaugural conference of the Central European Arc Measurement (Mitteleuropäische Gradmessung), the forerunner of the IAG, met in Berlin in 1862, and by the end of that year 15 European states were participants (Höpfner, 1999; Levallois, 1980; Mueller, 1990). It became the "Internationale Erdmessung" in 1886, known in its French and English translations as the Association Internationale de Géodésie and the International Geodetic Association, and since 1932 officially the International Association of Geodesy. Thus when variation of latitude was verified, the international scientific community was in a good position to act, and it did with the IAG's founding of the ILS (Torge, 1993).

At the founding of the International Astronomical Union in 1919, "Standing Committee" 19 on Latitude Variation was appointed with Hisashi Kimura as President (Blaauw, 1994); following the IAU's first General Assembly in 1922 the ILS work was put in charge of a joint Commission of the IAU and the International Geodetic and Geophysical Union (Lambert, 1931, p. 272); the IAU's Commission 19 on variation of latitude maintains its identity now as the Commission on Earth Rotation. Following recommendations at IAU Symposium 13 on "The Future of the ILS", held in Helsinki in 1960, in 1962 the International Polar Motion Service (IPMS) began using both the ILS and independent latitude stations (Melchior, 1961). Both the IPMS and the Earth rotation section of the BIH have now been replaced by the International Earth Rotation Service (IERS), to which the International GPS Service (IGS) makes invaluable contributions. It is therefore appropriate that all of these organizations are sponsoring this colloquium.

2. Landmarks in Polar Motion Studies

So as not to lose sight of the big picture, I want to give an overview of the landmarks of polar motion studies (Table 2); many of these landmarks will be elaborated in the course of the meeting. As is well known, Euler (1765) was the first to discuss theoretically the possible variation of latitude due to the rotation of a rigid body about its center of gravity; he predicted the period of this variation should be about 10 months. Verdun and Beutler (2000) have shown at this meeting how Bessel suspected an effect in 1843 based on observations of C. A. F. Peters, and furthermore that Magnus Nyrén in 1873 determined statistically significant values for the amplitude of polar motion, and even a secular variation in polar motion, based on observations made by Peters, Johann Gyldén and Nyrén. In terms of a correct interpretation of the data, however, all were misled by the "Eulerian paradigm" prediction of a 10-month period. The "Königsberg-Dorpat-Pulkovo" tradition that these astronomers represent places in new perspective the work of the German astronomer Friedrich Küstner in Berlin and the American astronomer Seth Chandler.

There remain differences of opinion as to the relative role of Küstner, Chandler and the International Association of Geodesy in the discovery of variation of latitude; the papers in this volume help to clarify some of these differences, while still demonstrating that the concept of "discovery" is not always a simple

Table 2. Landmarks in Polar Motion Studies

1765	Euler's prediction of polar motion with period of 305 days due to rotation of a rigid body about its center of gravity
1842–1844	Bessel (Königsberg) and Peters (Pulkovo) observations show possible variation of latitude
1862	Inaugural Conference of Central European Arc Measurement (Mitteleuropäische Gradmessung), forerunner of International Association of Geodesy, in Berlin
1873	Nyrén determines statistically significant values for amplitude of polar motion
1884–85	Chandler's Harvard observations Küstner's Berlin observations Küstner announces variation of latitude of .2 arcseconds/year
1891/92	Chandler's discovery that polar motion results from two periodic components, a 428-day free circulation, and an annual forced motion
1891	Crucial test: simultaneous measurement at Waikiki and Berlin show curves in opposite phase
1899	International Latitude Service (ILS) founded with six stations
1901	Chandler announces discovery of a 436-day component of polar motion, whose amplitude is much smaller than the 428-day component
1917	B. Wanach finds evidence for secular polar motion of 0.003 arcseconds, based on ILS data
1919	International Astronomical Union founded, including "Standing Committee" 19 on Latitude Variation, with Kimura as first President Bureau International de l'Heure (BIH) founded
1955	BIH begins independent observations for polar motion service
1962	International Polar Motion Service (IPMS) started
1983	MERIT begins main campaign
1980s	SLR, LLR, VLBI observations for polar motion begin — order of magnitude improvement in accuracy
1988, Jan. 1	International Earth Rotation Service (IERS) replaces IPMS and Earth-rotation section of BIH
1994	International GPS Service for Geodynamics created by IUGG

one. It was while trying to determine the constant of aberration via a series of observations beginning in 1884, that Küstner noticed that his data could not be explained unless a variation of latitude was included, which he announced in 1888, in the amount of a few tenths of an arcsecond per year (Küstner, 1888, 1890). Chandler in 1885 had noted differences in the latitude of Cambridge, Massachusetts using his almucantar (Fig 2; Chandler, 1885, 1887), but remarked in 1891 that an actual variation of latitude "seemed at the time too bold an inference to place upon record" (Chandler, 1891a). By November 1891, however, Chandler not only accepted variation of latitude based on new data, he also announced a period of 427 days (Chandler, 1891b). This was 40% more than Euler's classic period, an anomaly explained by Newcomb (1891) as due to the elasticity of the Earth. Chandler followed up on his work with a whole series of papers in the *Astronomical Journal* in the late 19th century (Carter and Carter, 1995, 2000). While others had determined the amplitude of the variation of latitude, to Chandler goes the undisputed achievement of first determining the true period.

In 1899 the ILS was set up, with observations beginning in September, just 100 years ago. The 12th General Conference of the Internationale Erdmessung (already referred to by some as the International Geodetic Association) had been held in Stuttgart in 1898 and decided to finance the organization of four stations, all located at latitude 39 degrees, 8 minutes: Carloforte (Italy), Gaithersburg (Maryland, USA), Mizusawa (Japan) and Ukiah (California, USA). Cincinnati was on the same parallel and offered to cooperate, as did the Russians with a station at Tschardjui. Some of these stations changed over the years. Gaithersburg was closed in 1914 for reasons of economy, but reopened in 1932 for 50 more years of observations. Cincinnati dropped out permanently in 1915. The Russian station was replaced in 1930 with a station some 3 degrees to the west at Kitab, near Samarkand (Ehgamberdiev, 2000; Lambert *et al.*, 1931, p. 255). Carloforte did not observe from 1943–1946 due to the War. Although Mizusawa and Ukiah observed continuously, the number of ILS stations varied from 3 during the period 1927–35, to 6 from 1901–06 (Table 3).

The primary source for the history of polar motion is found in the published volumes of the ILS data. These volumes delineate several eras in terms of ILS data: the German era under Albrecht *et al.* (1900–1922); the Japanese era under Kimura (1922–1935), the Italian era under Carnera and Ceccini (1935–1962); and a second Japanese era from 1962 to 1987 as the Central Bureau of the International Polar Motion Service (IPMS) (Table 4). A landmark was reached in 1955, when the Bureau International de l'Heure (BIH) in Paris began an independent set of polar motion observations. By 1962 this was joined by the International Polar Motion Service (IPMS), with some 50 stations. The "Main Campaign" of MERIT (Monitor Earth Rotation and Intercompare the Techniques of observation and analysis) began in 1983, and MERIT continued until January 1, 1988, when the International Earth Rotation Service (IERS) replaced IPMS and the Earth-rotation section of the BIH. The Central Bureau of the IERS is at Paris Observatory, and the sub-bureau in the United States (U. S. Naval Observatory, National Oceanic and Atmospheric Administration, and the National Aeronautics and Space Administration) comprise the National Earth Orientation Service.

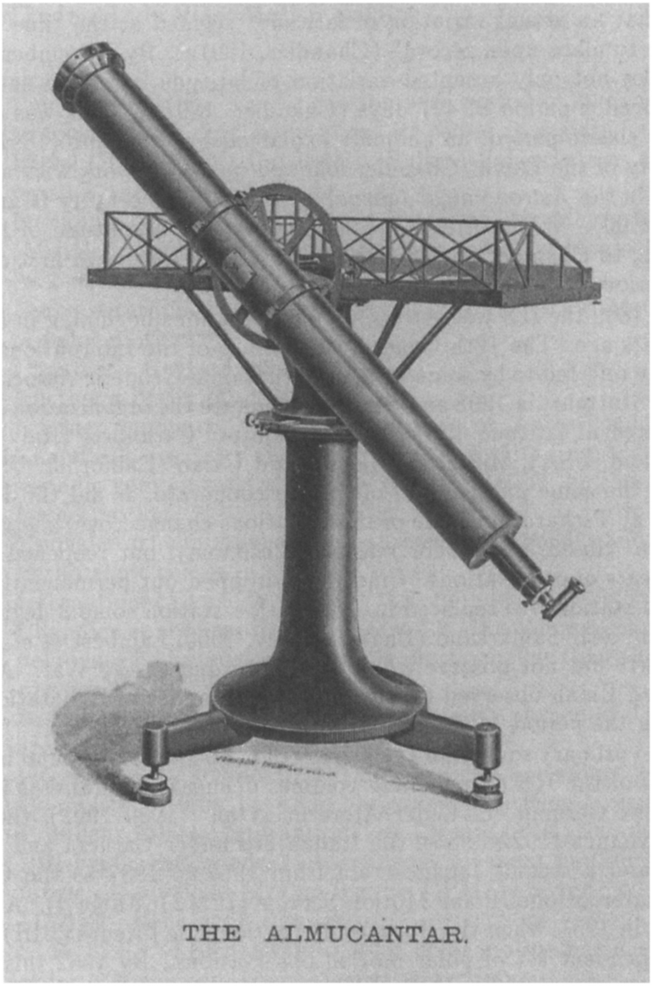

Figure 2. The almucantar, the instrument Chandler used to measure differences in the latitude of Cambridge, Massachusetts in 1885. From Chandler (1887).

Table 3. International latitude service stations.

Name	Nominal longitude	Nominal latitude (39°8′)	Period of observations	instrument
Mizusawa	141°07′51″	3″.602	1899–1984	VZT
Carloforte	8°18′44″	8″.941	1899–1942 1946–1984	VZT
Tschardjui	63°29′	10″.662	1899–1909.5 1909.5–1920	VZT
Ukiah	−123°12′35″	12″.096	1899–1984	VZT
Gaithersburg	−77°11′57″	13″.202	1899–1914 1932–1984	VZT
Cincinnati	−84°25′	19″.364	1899–1915	VZT
Kitab	66°52′51″	1″.850	1922–1984	VZT

Adapted from Henriksen (1977)

This simple recitation shows the tremendous international cooperation required for polar motion studies, and masks many interesting stories and much science politics. The end result was more and more accurate measurements of polar motion, and an increase in the timeliness of dissemination and the accuracy of predictions.

One of the main goals of polar motion studies has been a determination of its periodicities. Table 5 is an overview of the periodic polar motions now known. A striking feature of the table is the remarkable increase in accuracies attained in the 1980s and 1990s by the new techniques of Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), and Lunar Laser Ranging (LLR). The question of excitation of the periodic motions remains open in many cases. McCarthy will have more to say about this in his scientific overview.

What is not shown in the table is the problem of secular polar motion, first suspected by Chandler already in 1892, reported by B. Wanach in 1917 in the amount of 0.003 arcseconds/year toward 55 degrees West longitude based on ILS data, studied by Lambert, Kimura and others in the 1920s, and still a research problem today. Markowitz (1960a) provided both a history and an analysis of the data at the beginning of the Space Age, concluding that the mean pole had moved about .2 arcseconds from 1900–1959, and that it was likely a real motion. Lambeck (1980, p. 91) put the secular drift at the same magnitude as Wanach, but in a direction 65–75 degrees West longitude, with an uncertainly of 20% in rate and 10 degrees in direction, and questioned whether the motion was apparent or real. McCarthy and Luzum (1996) find a secular motion of 0.333 arcseconds per century in the direction of 75 degrees West longitude.

3. The Gaithersburg Station as a Case Study

I want now to turn in more detail to the institutional response, particularly as seen in the Gaithersburg case of the ILS. The Gaithersburg (Maryland) station

Table 4. Publication of Polar Motion Results

Vol	Author	Title	Publication	Data for
	GERMAN			
1	Albrecht	Resultate des Internationalen Breitendienstes	1903	1899–1902
2	Albrecht Wanach	same	1906	1902–1904
3	Albrecht Wanach	same	1909	1899–1905
4	Albrecht Wanach	same	1911	1906–1908
5	Albrecht Wanach	same	1916	1908–1912
6	Wanach Mahnkopf	Ergebnisse des Internationalen Breitendienstes	1932	1912–1922
	JAPANESE			
7	Kimura	Results of the International Latitude Service	1935	1922–1931
8	Kimura	same	1940	1922–1935
	ITALIAN			
9	Carnera	Resultati del Servizio Internationale della Latitudini	1957	1935–1941
10	Nicolini Fichera	same	1970	1941–1948
11	Ceccini	Results of the International Latitude Service	1973	1949–1962
	JAPANESE			
12	Yumi Yokoyama	same	1978	1962–1967
	Central Bureau Of the IPMS Mizusawa	Annual Report of the IPMS	Annual	1962–1979
	Central Bureau Of the IPMS Mizusawa	Monthly Notices of the IPMS	Monthly	1977–1987
	FRANCE and U. S.			
	IERS Central Bureau, Paris Observatory Sub-Bureau, NEOS	Bulletins A, B, C, D; www, ftp, e-mail	1988–present	

Table 5. Polar Motions

Frequency	Amplitude (arcseconds)	Detected	Discovery Technique	Cause
Decadal (Markowitz)	few hundreths	1960	VZT	?
427 days (Chandler)	few tenths	1890s	VZT* Transit	Free Oscillation
365.25 days (annual)	few tenths	1890s	VZT	Meteorological
Monthly	few thousandths	1980s	Space Geodetic VZT, PZT	Meteorological/ Oceans
< 10 days	one thousandth	1990	Space Geodetic	Atmospheric
1 day/0.5 days	few thousandths	1990s	Space Geodetic	Tidal forcing of Oceans
Hourly	few millionths	?	?	?

* VZT: Visual Zenith Tube. Discovery based on data using a variety of instruments

of the ILS, about 20 miles north of Washington, D.C., became one of the first 6 latitude observatories of the International Latitude Service by an agreement with the U. S. Coast and Geodetic Survey dated January 23, 1899. (The Naval Observatory, a logical place to locate such a station, has a latitude of 38 degrees 55.3 minutes, and so was slightly out of the latitude band of 39 degrees 8 minutes for the ILS stations.) Edwin Smith and Frank Schlesinger, in charge of the stations at Gaithersburg and Ukiah respectively, described the site, buildings and instrument in the U. S. Geodetic Surveys report for 1900 (Smith and Schlesinger, 1901). A map of the location and layout of Gaithersburg (Fig. 3) and the other ILS stations is also found in the first volume of ILS observations (Albrecht, 1903).

The instrument employed for observation of variation of latitude at Gaithersburg and the other ILS stations was the Wanschaff [Visual] Zenith Telescope (Fig 4). This instrument, however, was known to have small errors due to personal equation, and at the instigation of Frank Ross, at the IGA meeting in Cambridge, England in September 1909, the Superintendent of the Survey submitted plans for the construction and operation of a photographic reflex zenith tube that would remove this personal equation. The idea was to compare the visual and photographic observations with each other and with the other stations, to discover any short-period or diurnal terms in the latitude variation, and as a byproduct, to determine a value for the constant of aberration. The IGA (headquartered in Potsdam, Germany) voted 10,000 marks for the construction of the instrument, and an additional 2000 marks annually for plate measurement and reduction. Figures 5 and 6 show the VZT and PZT buildings at Gaithersburg, and a general view of the grounds.

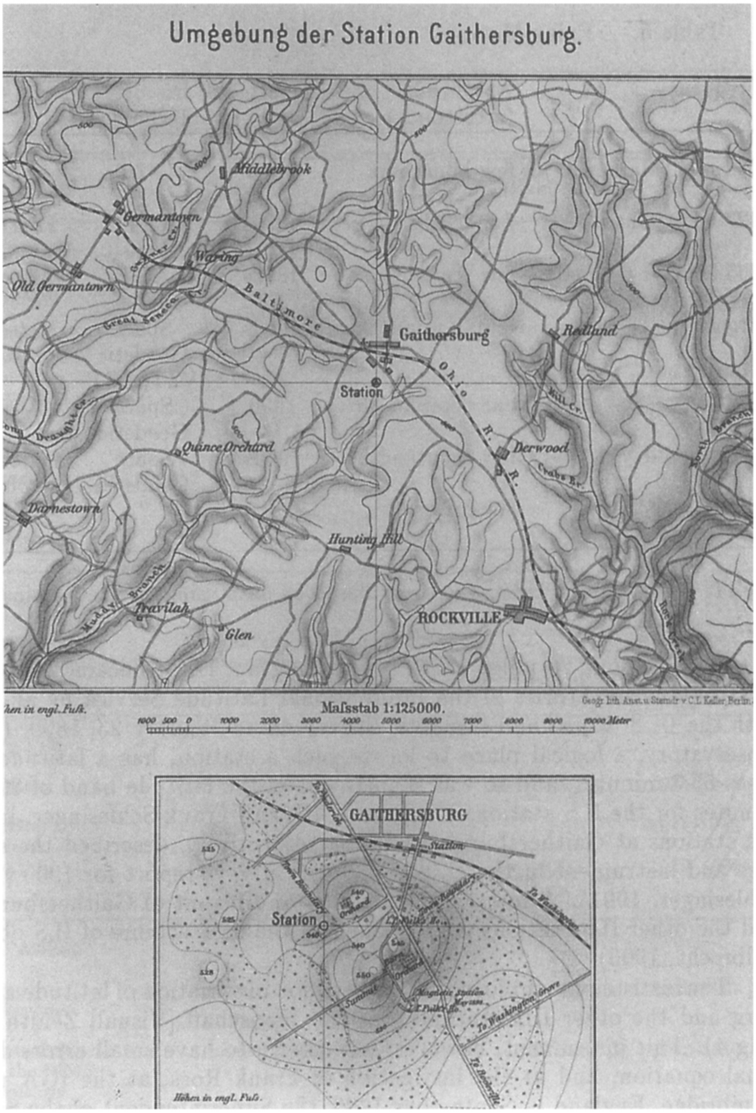

Figure 3. Map of the International Latitude Station in Gaithersburg, Maryland. From Albrecht (1903).

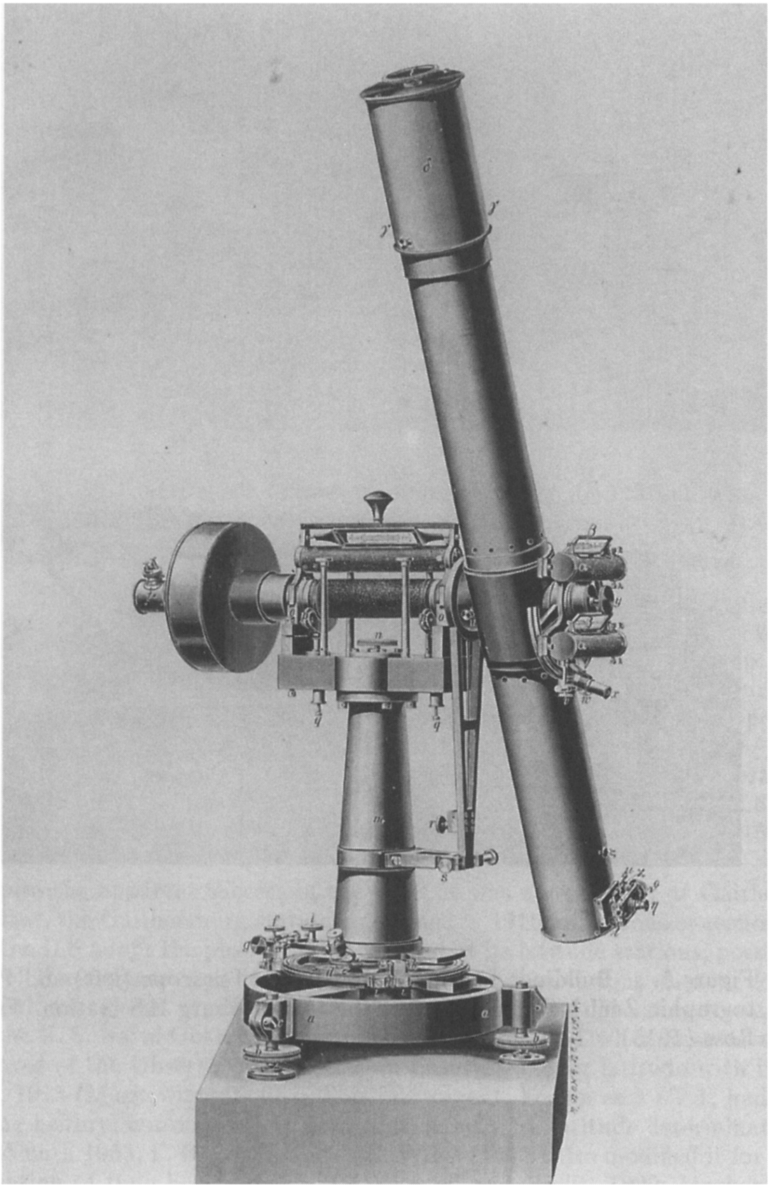

Figure 4. The Wanschaff [Visual] Zenith employed for observation of variation of latitude at stations of the International Latitude Service. From Albrecht (1902).

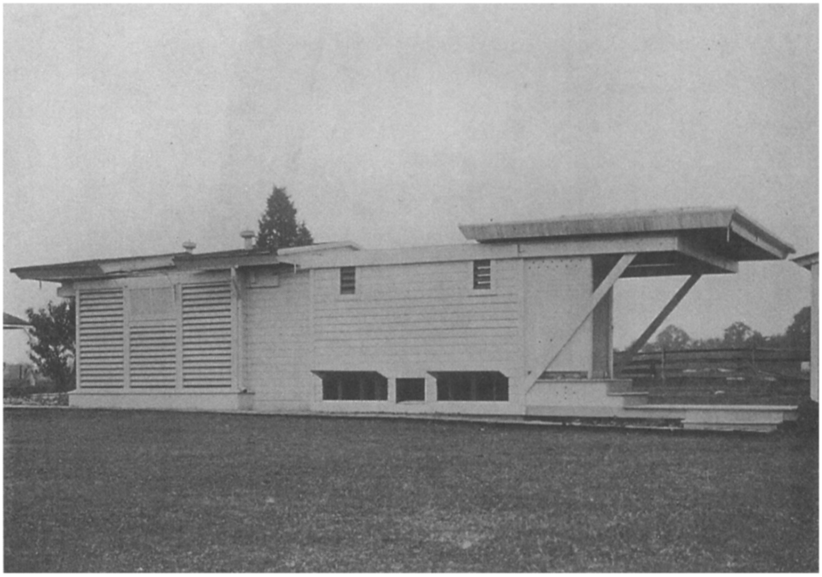

Figure 5. Buildings for the Vizual Zenith Telescope (left) and Photographic Zenith Tube (right) at the Gaithersburg ILS station. From Ross (1915).

Figure 6. General view of grounds of Gaithersburg ILS station. The site was named a national historic landmark in 1990. From Ross (1915).

The PZT (Fig 7) was built by William Gaertner and Co. in Chicago, and from June, 1911 to October 1914 some 6,944 stars (down to magnitude 8.5) were photographed on 450 nights, an average of some 15 per night (Ross, 1915, p. 7). After a detailed analysis of these observations Ross concluded that "the accuracy of the individual latitudes obtained with the photographic instrument appears to be considerably greater than that obtained with the visual instrument. For the study of the minute quantities here dealt with this is a matter of considerable importance. That there is also greater freedom from systematic errors has been proved for some of the classes [of stars], and is probably true for all" (1915, p. 127).

Despite the apparent success of the PZT, it was not adopted at Gaithersburg, in fact, the Gaithersburg station was closed in 1915 for reasons of economy. Nor did the ILS adopt the photographic method at its latitude stations, possible because of the expense, and the desire to keep the observations on a uniform system with a single set of instruments. The PZT, however, did not go to waste. In 1915 the U. S. Naval Observatory purchased the Ross PZT when Ross became an employee of the Observatory, and began observations for latitude with it in October, 1915 (Markowitz, 1960b). This instrument, known as PZT 1, had an interesting history; not only was it used continuously for latitude determination from 1915 until 1955, F. B. Littell and J. E. Willis (Fig 8) also modified it for the determination of time beginning in 1934 (Littell and Willis, 1929; Markowitz, 1960b). This was the first time a PZT was used for time determination, a task typically reserved for the transit instrument.

Surprisingly, the use of the PZT for time and latitude determination spread only gradually; in 1955 small transit circles were still the instrument of choice for time determination, and visual zenith telescopes still the instrument of choice for

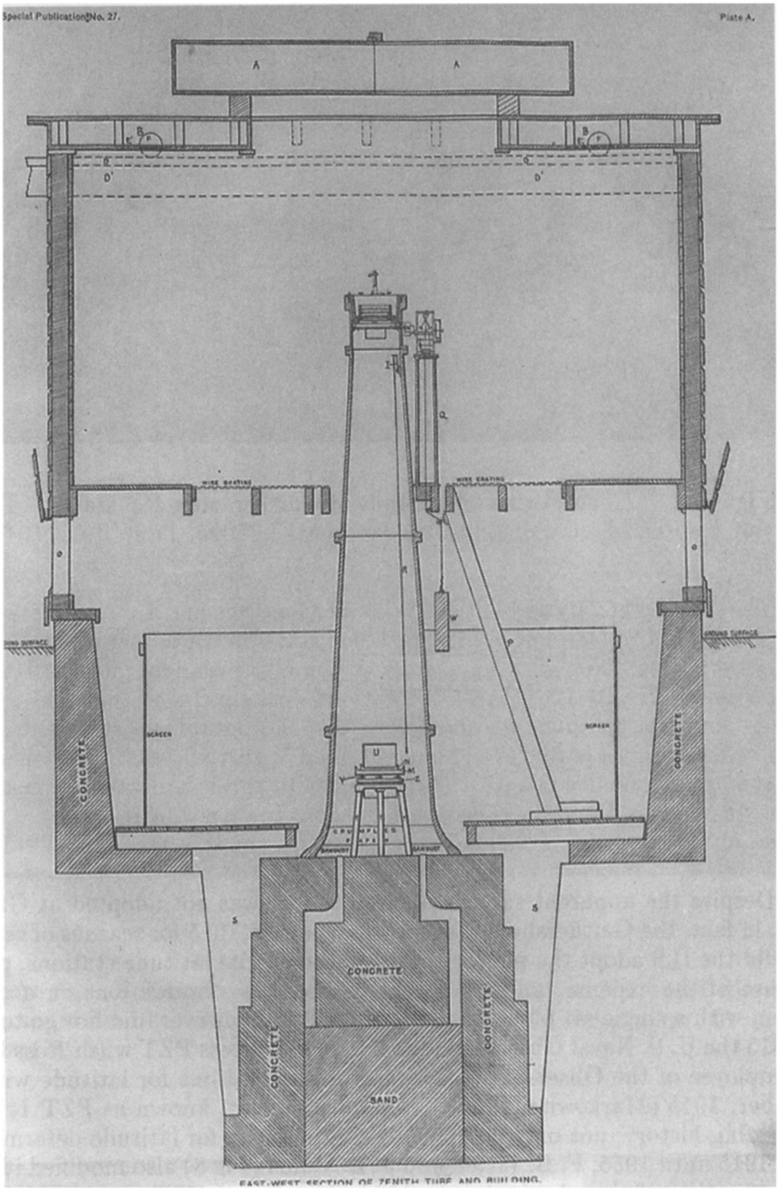

Figure 7. Schematic of Photographic Zenith Tube at Gaithersburg. From Ross (1915).

Figure 8. J. E. Willis with the PZT originally used at Gaithersburg, and shown here about 1932 at the U. S. Naval Observatory in Washington, with modifications for determining time in addition to latitude. USNO Archives.

latitude observations. By 1960 nine or ten PZTs were in use around the world (Spencer Jones, 1955, 1958). Another instrument for latitude determination was the Danjon astrolabe (Danjon, 1958, 1960). An idea of the distribution of instruments is given by the fact that during the International Geophysical Year (1957–58), 22 visual zenith telescopes, 10 PZTs and 16 Danjon Astrolabes were in operation at over 30 latitude stations (Munk and MacDonald, 1960, p. 61). This gives rise to

Historical Problem # 2: What were the factors over the last century influencing the choice of instrumentation for time and latitude determination?

One would think that accuracy would be the chief factor, but especially given instruments of approximately equal accuracy, funding, nationalism, and personal preference undoubtedly were important factors. It is interesting, however, that when the accuracy could be increased by an order of magnitude or more in the 1980s, the transition to the new techniques was rapid and almost universal. The PZT at USNO was superseded by VLBI for time determination in 1984 (Archinal, 1993).

As reported in the official volumes of the ILS, the Gaithersburg station was reopened in April, 1932, still under the auspices of the U. S. Coast and Geodetic Survey. Visual latitude observations continued at Gaithersburg until 1982, and in 1990 the Gaithersburg Latitude Observatory was named a National Historic Landmark (Butowsky, 1989). The story of some of the other ILS stations will be told by others at this meeting. Collectively they represent the longest-running series of focused observations in the history of astronomy.

4. Summary: The Importance of Polar Motion

To non-scientists the rigorous study of polar motion over a circular area with a diameter of only about 10 meters may seem much ado about little. Such was the advancement of astronomy, however, that already at the end of the 19th century its importance was undisputed. As Chandler (1893) pointed out, all determinations of celestial coordinates and of astronomical constants had been made on the assumption of an invariable zenith. Not only would variation of latitude need to be taken into account in the future, but also, he noted "nearly everything that concerns absolute astronomical measurement must have been to greater or less extent vitiated — equator-point, equinoctial point, obliquity of the ecliptic, aberration coefficient, absolute measurements of parallax, absolute systems of right ascensions and declinations, and even, possibly by sensible amounts, the refraction, nutation and precession constants."

We have already mentioned how polar motion was eventually incorporated into Earth rotation studies, and into daily time dissemination. Of course, polar motion results also had to be incorporated into meridian circle catalogues, and Rafferty (1982) and others have shown how not only polar motion, but different sources of polar motion data, could have a significant effect on individual observations as well as the overall catalogues of star positions. Today, the IERS is responsible for the maintenance of the International Terrestrial and Celestial Reference Frames, and today, in the era of milliarcsecond accuracies, polar motion is important not only to astronomy and geophysics, but also for practical problems like spacecraft navigation, unforeseen a century ago.

Finally, polar motion is important to geophysics in a variety of ways that will be elaborated at this meeting. The simultaneous needs of astronomers, the Earth rotation community, and geophysicists gives rise to a final historical problem I wish to pose:

Historical Problem # 3: What have been the factors driving the increase in polar motion accuracy? More specifically, what has been the interface between polar motion data providers, and polar motion data users?

As we celebrate the centennial of the International Latitude Service and the first internationally coordinated observations of polar motion, I cannot help but think how amazed Euler, Küstner, Chandler, and the other pioneers in the field would be at the modern work on polar motion, and how it has become integrated into the broader programs of astronomy and geophysics. No matter how much progress has been made a century from now, surely the 1980s and 1990s will stand as a turning point in polar motion studies. I hope this IAU Colloquium and its Proceedings will serve to document the progress in polar motion, and stand as a pivot point between the past and the future.

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