Gravity's Increasing Gravitas$_1$

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The importance of gravity in land surveying (Part 1 of 2)

Written and Illustrated by V. Kelly Bellis, PLS

Gravity's importance in geodesy has long been recognized. Beginning with Galileo Galilei's (1564 - 1642) gravity experiments and theories in the late 16th century, gravity's force, and more over, its global variations, continues to play an ever increasing role for those of us measuring along Earth's surface. The benefits from physical geodesy (the study of Earth's gravity field) also extends well beyond the field of surveying to other disciplines including isostasy, seismology, meteorology, oceanography, climatology and others monitoring the health of our planet. And those are just a few examples with an eye *on* the Earth.

Today we take it for granted, if we think about it at all, that the centrifugal force along the equator from the Earth's rotation contributes to the decrease in the pull of gravity, and when combined with its greater distance from Earth's center, an object at the equator weighs about 0.5% less than it does if it were at one of the poles, though its mass remains unchanged.

The other primary generalized factor shaping the Earth's gravity field, and that being irregularity of mass, both at the surface and within the Earth, is basically understood (at least in concept) by most of us today who were awake in school when having been introduced to Sir Isaac Newton (1642 – 1727) and the laws of gravity.

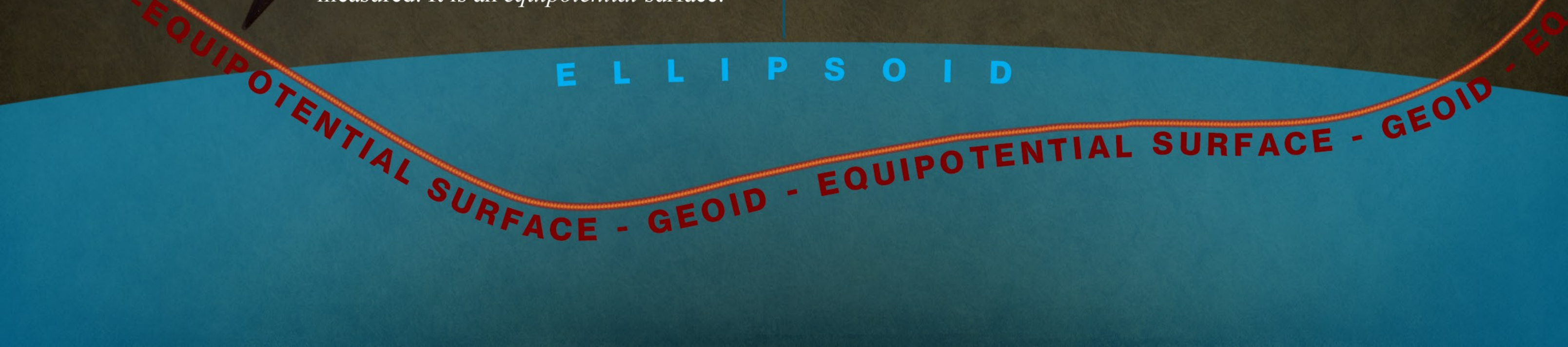
While this article isn't intended to detail the historical developments between Galileo and the current efforts underway by NGS's Gravity for the Redefinition of the American Vertical Datum (GRAV-D) surveys, there was just too much incredibly cool measuring stuff along the way to leave out and that I think most surveyors will appreciate. So part one of this article is intended to help introduce the future by explaining just a little as to how we got to the present. In part two, we'll catch a glimpse of an individual gravity survey being conducted by NGS.

> ***"So what does gravity have to do with my work in the first place!?***
>
> ***I'm just a dirt surveyor!"***

Equi-what?!!

"S*o what does gravity have to do with my work in the first place!? I'm just a dirt surveyor!*" you might ask. Whether we embrace it or not, if we're surveying with any type of GPS equipment we're geodetic surveyors and if our work product is at all concerned with heights and in what direction water is directed, then gravity becomes paramount.

An imagined ideal surface covering the entire planet, somewhere in the vicinity of mean sea level, but totally calm, smooth, void of the effects of tide, currents and breezes is the geoid. It is a surface on which no marble will roll of its own accord. It is a surface determined solely by gravity, and more particularly, where the potential energy of gravity is perfectly equal - no matter where on its surface gravity is measured. It is an *equipotential* surface.



The geoid is the surface on which no marble will roll of its own accord

Measuring Gravity

The gravity pendulum has historically been used in measuring the Earth's gravity field during most of the past 400 years. Its amazing development into both relative and absolute gravity measuring devices (gravimeters) with increasing sensitivity and precision is wonderfully chronicled in the scholarly article written in 1965 by Victor F. Lenzen and Robert P. Multhauf entitled "*Development of Gravity Pendulums in the 19th Century*". Thanks to the preservation work accomplished through Project Gutenberg, this excellent article is freely available [eBook #35024].

Concurrent with the geodetic research of the late 16th and early 17th centuries focused in understanding the planet's size and shape; i.e., spheroid vs. prolate spheroid (greater diameter in the polar plane) vs. oblate spheroid (greater diameter in the equatorial plane), gravity measurements even then played a significant role in geodesy's development.

Since about the mid-twentieth century spring-based measuring devices have been developed and are widely accepted as the instrument of choice for measuring gravity at a given station relative to another.

The other method employed today in measuring gravity at a given station and determining its absolute value involves the principal of a free-falling object and monitoring its descent with extraordinary precision.

Mendenhall Pendulum – An Early Workhorse

The desolate 43-acre piece of rock rising abruptly nearly 300' above the water in the middle of the Pacific Ocean that native Hawaiians call Mokumanamana was chosen by the Coast & Geodetic Survey to be included in its 1928 survey operations. The gravity station on Necker Island was just one amongst the 342 gravity stations across the United States, Puerto Rico, Alaska and Hawaii reported in its "*Annual report of the Director, United States Coast and Geodetic Survey to the Secretary of Commerce for the fiscal year ended 1928*".

The work party's observations, led by Lt. (J.G.) E. J. Brown, also included astronomic measurements in the establishment of a longitude station with precise time ticks broadcast by the Naval Observatory sounded over the radio equipment also seen in this amazing photo.

Timeline

Measuring Gravity

Gals	year	notes
	1581	swinging chandalier Galileo Galilei
	1644	seconds pendulum Marin Mersenne
	1672	Cayenne observations Jean Richer
	1673	Horologium (cycloid) Christiaan Huygens
	1687	Principia published Isaac Newton
	1735	method of coincidences J.J. Mairan
980.7	1737	inavariable pendulum Bouguer
	1792	seconds pendulum (Paris) J.C. Borda & J.D. Cassini
	1817	convertible compound pendulum, Henry Kater
	1819	invariable pendulum Henry Kater
	1826	Königsberg experiments Friedrich W. Bessel
	1830s	in vacuo experiments Baily, Wikes, Kater, et als
	1862	Repsold-Bessel Reversable portable pendulum
980.76	1872	U.S. Coast & Geodetic gravity surveys (Pierce)
	1875	structure flexure study Charles S. Pierce
	1881	invariable reversable pendulum, Charles S. Pierce
	1887	1/2 second w/ chronometer Robert von Sterneck
980.765	1890	1/2 second improvements Thomas C. Mendenhall
	1932	upgrades to apparatus E. J. Brown, C&GS
980.7654	1934	zero-unstressed-spring Luien J.B. LaCoste
980.76543	1950s	widespread use of spring-based surveys
980.765432	1970s	development of free- fall absolute meters
980.7654321	1980s	large scale gravity surveys for NAVD
	2007	NGS announces GRAV-D surveys

Fun facts to know :)

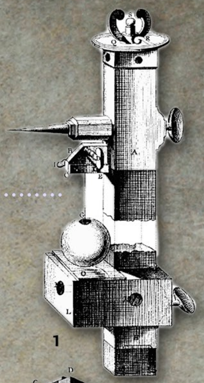
F = mg

g = gravity's acceleration and is measured in Gals

1 Gal = 1 cm/sec^2

g's value varies and is both location and time dependent

g's value ranges from about 983 Gals near the poles to about 976 Gals along the equator at high elevations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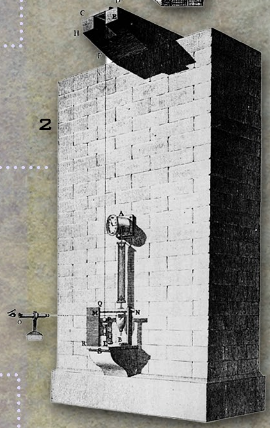
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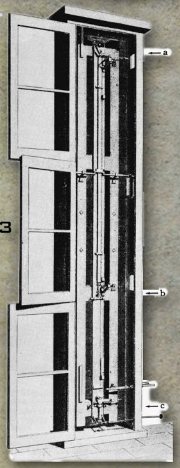
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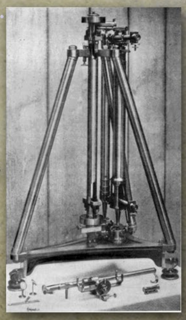
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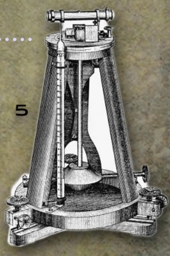
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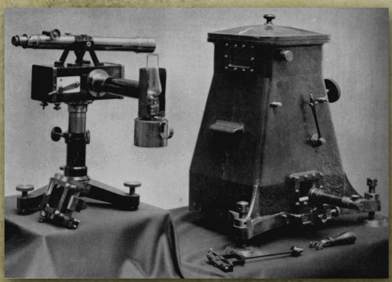
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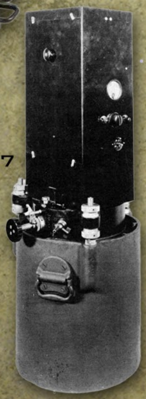
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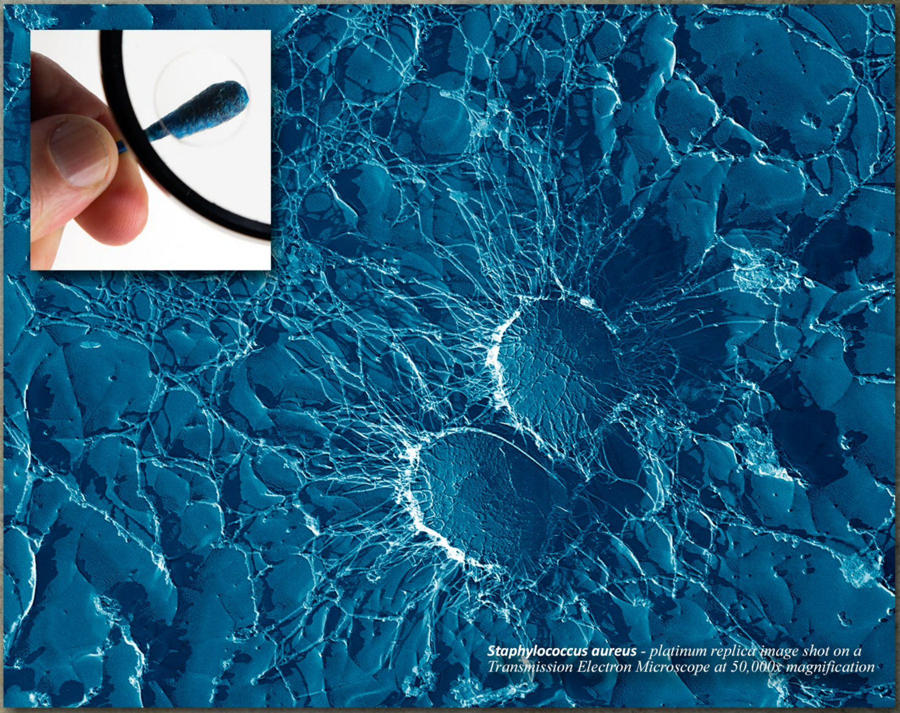
The phenomenal development in the ability to measure gravity has been much like going from looking through a hand glass to electron microscopy.

There is a tremendous wealth of information regarding terrestrial-based gravity measurements and its shaping of our past vertical datums which has been omitted from this piece; not to mention ever touching on the amazing gravity measurements being conducted from space. The ever increasing importance of gravity measurements will continue into the immediate future in defining the National Spatial Reference System and in the long term, defining a Global Height System.



Staphylococcus aureus *- platinum replica image shot on a Transmission Electron Microscope at 50,000x magnification*

A Little About the Timeline Figures

1. Six-ounce copper ball hung by a thread of tampico fiber (derived from the agave plant, also known as pite or pita) over and nearly touching a mirror used in the pendulum's vertical alignment. The length of pendulum is about 37" with its exact length controlled by the topmost micrometer in experiments done by the French geodesist C.M. de la Condmine – source credit: Portion of plate 1, Mémoires publiés par la Société française de Physique, vol. 4

2. 22-ounce platinum ball 1.5" diameter suspended by an iron wire 12' in length in front of a seconds clock used in experiments determining the exact length of the "seconds pendulum". Observations of the coincidences were made through the telescope (shown closer than originally drawn). The derived length of the pendulum with its half-period of one second was in close contention with another derived length in defining the meter in the late 18th century using the meridional definition - source credit: Plate 2, Mémoires publiés par la Société française de Physique, vol. 4

3. Two different points of suspension allowed the ball hung from a thin strand of wire to be used in different experiments by Friedrich Wilhelm Bessel in determining the length of the seconds pendulum. The apparatus was isolated from air disturbances in a cabinet that stood about 10' tall and the method of coincedences employed using a projected image of the clock pendulum onto the gravity pendulum using a lens - source credit: Plate 6, Mémoires publiés par la Société française de Physique, vol. 4

4. The Royal Prussian Geodetic Institute in 1868 had A. Respold & Sons build this portable reversible (pendulum geometrically symmetrical) based on Bessel's design developed in 1862 which uses two micrometer microscopes which enhanced measurements. The Repsold-Bessel reversible pendulum became the instrument of choice throughout Europe and was adopted for field work under Benjamin Pierce, Superintendent of the U.S. Coast Survey sometime prior to 1872 and shown pictured here circa 1875.

5. The portable ½ second pendulum developed by Maj. von Sterneck and perfected in 1887 stood about two feet high, contained a non-reversible pendulum ¼ meter in length with a ½ second swing which took place in a vacuum. The other major technological advancements included observation of the coincidences with chronometer signals and the relayed electrical spark seen through the telescope.

6. Thomas Corwin Mendenhall, Superintendent of the U.S. Coast and Geodetic Survey ordered construction in 1890 of this ¼-meter, ½ second non-reversible, invariable pendulum based on von Sterneck's design with modifications that included a flash apparatus beneath the telescope whose shutter was controlled by the chronograph. The light source was from a kerosene lamp or an electrical spark. The Mendenhall pendulums were used extensively throughout the United States in gravity surveys for the next 40 years.

Note: Figures 1 through 6 were obtained from the earlier cited [eBook #35024]

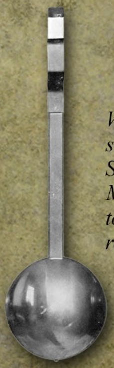
7. Significant improvements to the Mendenhall pendulum are credited to Lt. E. J. Brown of Coast & Geodetic Survey included increased stability during observations, maintaining the pendulum chamber's vacuum for entire field seasons, improved transportation handling and better time scaling. The Brown pendulum became the country's next workhorse for gravity surveys conducted across the nation until being retired from service around 1960 – photo credit NOAA Photo Library

8. Micro-g LaCoste's FG5 was first introduced in 1992 for measuring an absolute value for gravity using the free-fall principal where the trajectory of the falling object is precisely monitored using an interferometer and a Helium-Neon laser all tied into the precise timing controlled by an onboard atomic clock. This device also features sophisticated real-time gravity corrections for tides, ocean loading, polar motion and atmospheric attraction. After 24 hours of observation at a quiet site is reported being able to measure gravity to a precision of 0.000002 Gal or 2 microGal !

9. Eight years after the FG5 was first introduced, Micro-g LaCoste's A10 "portable" gravimeter was created. Weighing in with a total combined weight of over 230 lbs, this unit has become NGS's instrument of choice and is currently being used for ground-based absolute gravity measurements tied to the GRAV-D airborne surveys. Like its laboratory big sister, this instrument employs similar principals and technologies offering in-the-field 10 microGal precision with 10 minutes of observation.

10. NGS's primary thrust of the GRAV-D surveys presently underway across the United States utilizes Micro-g LaCoste's Turnkey Airborne Gravity System (TAGS) Air III Gravity Meter which combines the principals of a highly sensitive spring-based gravimeter, integrated differential GNSS positioning and advanced onboard data processing allowing the raw field data to be immediately examined in identifying data quality. This data then is post-processed in conjunction with ground based data from the A10 and other static control for each survey to yield reported accuracies of 1000 microGals or better (or 1.0 milliGals if you prefer :)

Many thanks to all who helped with their kind assistance and helpful information including Vicki Childers (NGS), Dru Smith (NGS), Dan Winester (NGS), Franz Barthelmes (ICGEM), Wolfgang Köhler (ICGEM) and Franz Ossing (GFZ).



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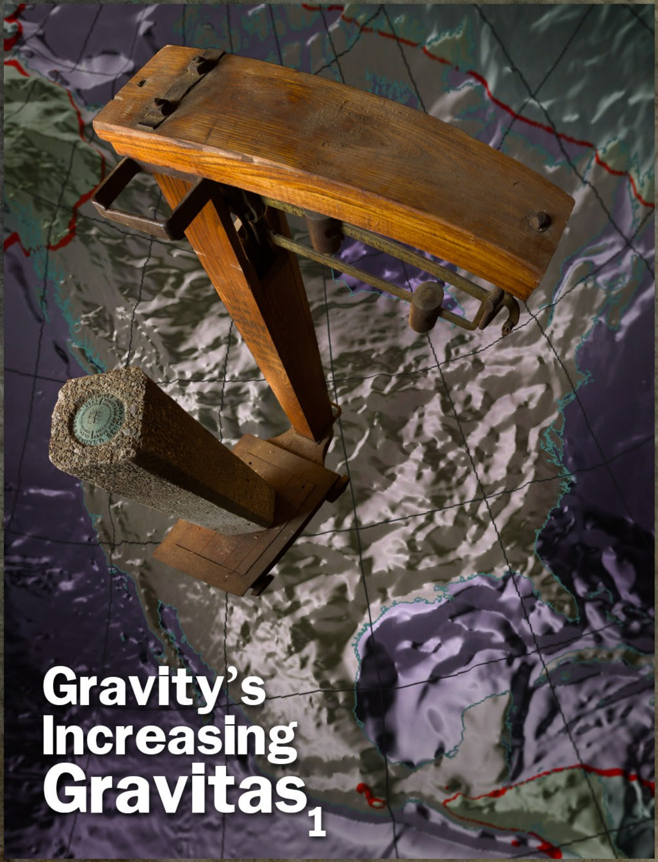
Notes



Cover Illustration – Part One

The background rendering of the geoid is based upon data from GFZ German Research Centre for Geosciences's online calculation service, and in particular, is from the combined model EIGEN6C. This model combines satellite data of varying types (from LAGEOS, CHAMP, GRACE and GOCE) and surface data. The jaw dropping resolution is partly due to 1) improved and new methods of measuring SLR Satellite (LAGEOS, ERS), GPS (CHAMP), K-Band Ranging (GRACE) satellite gradiometry (GOCE), increases of accuracy in the measurement of surface data (airborne gravimetry and satellite altimetry) and 2) the long-term data series.

Juxtaposed above the geoid rendering, is poor old forgotten `PE0115`, or more affectionately known as N 76, one of the many benchmarks set by C&GS nearly 80 years ago (in the heady days of NGVD29) and whose datasheet indicates "`STABILITY: C = MAY HOLD, BUT OF TYPE COMMONLY SUBJECT TO SURFACE MOTION`". This iconic monument highlights one of the most important reasons for surveyors to help in the timely adoption of NGS's advancing geometric diatum and modernized height system. Incidentally, N 76 was found lying horizontal by the roadside, having fallen victim of regrading and ditching efforts along State Route 200.

All spatial content and its associated mapping (including the illustrations of the geoid!) was done using the software program Global Mapper. Many thanks go out to Mike Childs of Blue Marble Geographics for his unparalleled support.

Additional graphic embellishments were done using Adobe's Photoshop, CS6.

PDF copies of this article (both parts one and two) are available at: http://panocea.us/gravitys-increasing-gravitas/

Be sure to check out the Geoid Gallery for additional illustrations and content at: http://panocea.us/geoid-gallery/