Teaching Modern Geodesy

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SUMMARY

Geodesy is enjoying a golden period. A myriad of new geodetic devices is sensing ever finer dynamics of the Earth system to unprecedented precision. Geodetic products now underpin services used by a growing number of users and are permeating into the mainstream. For example, the Intergovernmental Panel on Climate Change 5-yearly reports rely on the reference frames provided by international geodetic services, and even the United Nations now recognises geodesy as fundamental to much of its operations evidenced by the establishment of the Global Geospatial Information Management committee (UN-GGIM).

Nationally, Australia is modernising its datum. Continuously Operating Reference Station (CORS) networks are enabling high-precision Global Navigation Satellite System (GNSS) surveying, GNSS heighting is improving and regulations are being updated to accommodate new techniques. Laser scanning (terrestrial and airborne), Unmanned Aerial Vehicle (UAV) topographic products and national foundational datasets are available for modern surveyors to use in their daily operations. What therefore should the modern academic be teaching the new cohort of students in geodesy?

Classical geodesy and the history of datums are important to appreciate the historic legacy, but datum modernisation is crucial in the wake of GDA2020 and ATRF. Some basics such as time systems and satellite orbits should always be included in a geodesy course, especially now that satellite geodesy techniques are so entrenched. But the course is now very crowded.

This paper will ponder which topics of geodesy should be taught. What skills should a recent graduate surveying student possess upon graduation? Where should the emphasis lie and what topics should just offer exposure? Documents such as the GDA2020 Technical Manual, ICSM SP1, Surveyor General’s Directions No. 9 and 12 should be covered as well as an understanding of data formats such as RINEX v2 and v3, RTCM, NTrip, NMEA and SP3. RTK-GNSS, Network RTK (NRTK), CORS networks, multi-GNSS and Precise Point Positioning (PPP) are all very detailed topics.

How much should a student know? Is there still value in providing a practical GNSS baseline processing exercise with a rapid static, multi-session project and network adjustment?

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1. OVERVIEW

Geodesy has gone mainstream. GPS and nowadays multi-GNSS has resuscitated classical geodetic theory as satellite positioning techniques have infiltrated most large- and small-scale surveying projects. Professional surveyors must consequently understand at least some basic geodesy to appreciate how their device produces coordinates for their daily tasks.

Further to this, the International Association of Geodesy services (especially the IGS, IERS, IVS and the ILRS (IAG 2020)) provide a reference frame for global geophysical processes such as the monitoring of sea level rise due to human activities as documented in the Intergovernmental Panel on Climate Change 2019 report (IPCC 2020). The United Nations Committee of Experts on Global Geospatial Information Management (UN GGIM) is a relatively recent addition to the United Nations giving recognition to the role modern geodesy plays in global affairs; specifically, the Subcommittee on Geodesy (UN GGIM 2020). The general public's heightened understanding of human induced climate change acknowledges the application of science and the recent advances in space geodetic techniques is fundamental to our understanding of our changing climate.

Since 2007, GNSS positioning on smartphones have changed our lives and the myriad applications enabled by mapping and positioning infrastructure is now expected by consumers. Consumers have no idea that their device uses multi-GNSS or the sophistication behind their moderate accuracy applications. Professional users, and indeed geodesy students, therefore need to understand the intricacies specific to their higher accuracy applications to service this growing user awareness. All of these GNSS services rely on geodesy and geodetic principles.

In this context, developing a curriculum in a surveying/ geospatial engineering degree program has changed enormously in the last few decades and the teaching of modern geodesy has had to adapt accordingly. Graduates should feel equally comfortable with GPS as they do with GIS. They learn the use of total stations and electronic distance measurement during their studies. This is expanded into the use of laser scanners which nowadays has evolved from stationary and terrestrial to mobile, mounted on airborne, vehicle mounted or pedestrian platforms. UAVs are now used routinely by surveyors, therefore students need to understand pixels, point clouds and DEM generating software. These techniques could be categorised as a subset of remote sensing techniques which can be further expanded to DInSAR, radar and the myriad of geodetic satellite missions sensing the Earth. Of course, traditional cadastral land boundary and construction surveying is a staple of contemporary surveying programs and frequently uses some of the new techniques mentioned.

What material should therefore constitute a modern geodesy course? Where in the program should geodesy taught? Should more than one course be devoted to geodesy? Should surveying students understand some basic electrical engineering material to understand multi-GNSS? Where will graduates be employed and therefore what should they be exposed to during the 4-year surveying program? Some students will graduate as cadastral surveyors (30-40% at UNSW), some will go into construction/ infrastructure, others will branch into geospatial disciplines (councils, environmental agencies, insurance companies, startups, consultancies) and others may contribute to science/ research.

This dilemma is an ongoing topic at UNSW as the 3rd year geodesy course GMAT3700 – Geodetic Positioning and Applications (Roberts, 2019a) evolves every year and tries to provide a useful and relevant geodetic education for surveying students. How are surveying graduates best prepared for the ever-changing world of modern geodesy?

2. CURRICULUM

The Bachelor of Engineering (Surveying) degree is a 4-year honors program. It is taught as 3 x 10-week terms per year whereby students choose 8 courses in any combination of 3-3-2 courses per term. Certain courses such as Maths, Physics, Computing are common across all engineering programs. The surveying part of the curriculum is scaffolded to introduce students to basic surveying tasks in year 1, as well as a broad overview of geodesy, photogrammetry, GIS, remote sensing and boundary surveying which are pre-requisite knowledge for more advanced courses in year 2 and beyond (Roberts, 2019c). Foundations of geodesy and references frames is inserted early in the program (Year 2, Term 1) along with survey computations. By the end of year 2, students have conducted numerous field practical exercises using total stations and levels, understand that the atmosphere bends their line of sight, that the Earth is curved and have grappled with least squares for adjustment of survey measurements using FIXIT4 software (Harvey, 2020). GIS and more advanced survey applications for construction, mining and hydrographic surveying are introduced early in year 3 as well as an intensive field survey camp. After this point, modern geodesy is introduced to the students. Students have so far been exposed to the basic theory of GPS positioning and have conducted various field exercises using handheld and RTK GPS/GNSS within a CORS network (Roberts, 2019c). Students know how to press the buttons and get a coordinate but are unaware of the theory and complexity of the processes.

Given this background, the main geodesy course (GMAT3700) is taught in year 3, term 2 (Roberts, 2019a). The final term of year 3 investigates more deeply remote sensing and photogrammetry as well as the law behind boundary surveying. Year 4 comprises a thesis, some discipline specific electives and a management course.

3. INGREDIENTS OF A MODERN GEODESY COURSE

Lectures (2 hrs)	Lectures (2 hrs)	Workshop (2 hrs)
Intro to the course/ admin (1) Revision of datums (2) GDA Tech manual revision + professional associations (3)	Modern geodetic technologies, the IAG & GGOS; Space geodetic applications (4,5) Essay (due 1 Aug)	Wkshp 1: Mapping exercise. GDA assignment (due 18 June)
No Class – Public holiday	Principles of satellite orbital motion (6) Revision of GPS (7)	Introduction to GPS signals & measurements (8)
Analysis of Least squares GPS measurement modelling (9) GPS Carrier Phase based positioning, DD (10)	GPS Errors (11)	Wkshp 2: Planning software and online services, precise orbits
Introduction to GPS baseline processing (12) Planning & executing surveys (13)	Planning & executing surveys (13) RINEX (& other) formats (14)	Wkshp 3: Download RINEX data and investigate. Wkshp 4: Using Infinity for baseline computations
From baselines to networks (15) ***Class exercise Prac planning***	***Practical:*** *GNSS static baseline survey*	***Practical:*** *GNSS static baseline survey*
GNSS Heighting (16)	***Practical:*** *GNSS static baseline survey -* ***spare***	Processing of GNSS baseline survey
Multi-constellation GNSS (17) SBAS (18)	Datum modernisation, GDA2020 and ATRF (19)	Processing of GNSS baseline survey
Principles of GNSS RTK (20) & N-RTK positioning (21)	CORS networks (22,23)	*(Prac due 26/7)*
Precise Point Positioning (PPP) (24,25)	Datum transformations (26)	Wkshp 5: AUSPOS Exercise *(Essay due 1/8)*
Standards & practices for control Surveys (27) S/G Directions # 9 & 12 (28)	**Class presentations**	**Class presentations**

Figure 1. Geodetic Positioning and Applications, course timetable showing the order topics are presented.

3.1 Classical geodesy and satellite orbits

Classical geodesy proposes the three pillars of Geodesy: Geometry, Earth Rotation, Gravitational field (Vanicek and Krakiwsky, 1986). These all remain fundamental to modern geodesy but now all consider the 4th dimension, ie changes over time. Sadly, astronomy and celestial positioning cannot by accommodated in a modern geodesy curriculum, however the concepts of celestial vs terrestrial reference frames are crucial for an understanding of satellite positioning. Principles of satellite orbital motion and therefore Keplers' and Newtons' laws must be reviewed from previous physics courses. Indeed, in a multi-GNSS world, a sound understanding of the various constellations and the various timing systems that underpin spaced based positioning is more important than ever.

3.2 History of datums

The heritage of classical, local, non-geocentric datums fitted to the shape of the Earth to minimize geoid-ellipsoid separation must still be presented in the context of datum modernization. There is still much legacy data referred to older datums that new graduates will have to understand in their professional working lives as well as a word of caution about the use of WGS84. In Australia, federal and state government agencies provide good resources to assist surveyors to operate between datums and map projections but encourage a transition to the latest reference frames (Geocentric Datum of Australia GDA2020; Australian Terrestrial Reference Frame ATRF). An understanding of this heritage enables spatial professionals to know which transformation tools to apply (eg conformal with distortion models or not) (Geoscience Australia, 2020a). In this course, a hands-on mapping exercise using paper maps (!) and a whiteboard is presented as a fun and engaging way to reinforce some mapping basics that 3rd year students should know.

3.3 Positioning modes

The evolution of low-cost, satellite-based positioning uses GPS as a starting point. Methods such as code- based single pointing positioning (SPP) are revised, taking the opportunity to present the least squares development of the functional and stochastic models as a form of revision. This is useful for later processing where students realise that what they learnt in surveying network adjustment classes in year 2 applies equally importantly to GPS surveying. Code-based differential GPS (DGPS) is revised quickly and presented as an early form of augmentation. The concept of double differencing with carrier phase measurements (CDGPS) and real time kinematic positioning (RTK) are presented theoretically for the first time. Concepts such as Continuously Operating Reference Station (CORS) networks are introduced to facilitate expansion into Network RTK techniques and Virtual Reference Stations (VRS).

3.4 Multi-GNSS

Students are very aware that not only GPS but also GLONASS, Galileo, QZSS, Beidou and IRNSS constitute the new paradigm of multi-GNSS. It is challenging to know when to introduce these similar but different navigation systems in a modern geodesy course. It is also difficult to know how much technical detail is required for a class of students who may graduate into roles from construction surveyors to geodetic researchers.

Differences in timing systems and geodetic datums by the various systems as well as the concept of compatibility and interoperability are presented to give students an appreciation of the complexity of combining these various systems.

A major difference between multi-GNSS systems is the signal structure which impacts the precision of raw measurements and their robustness and performance in difficult environments. Electrical Engineering concepts are first introduced in year 2 with signal modulation using Electronic Distance Measurement (EDM). Signal modulation is very important for GNSS positioning when considering binary phase shift key (BPSK) modulation of codes and navigation data onto L1 carrier waves used for GPS. Newer GNSS constellations use different modulation strategies such as quadrature phase shift key modulation (QPSK), and binary offset carrier modulation (BOC) and alt-BOC for Galileo which enable more robust positioning. A working knowledge of these concepts is important for the modern surveyor/geodesist as well as an understanding of bandwidth, wavelength, amplitude, power density functions (PDF), in-phase/quadrature signals, right hand circularly polarized (RHCP) and antenna phase centre offset/ variation (PCV/PCO) (Roberts, 2019b). When faced with purchasing new equipment, professional surveyors should understand the jargon used on technical specifications (Roberts, 2012).

3.5 GNSS Survey practice

Surveyors still constitute the largest group of high precision (sub-cm level) GNSS positioning users. Consequently, GNSS errors are presented in some detail supported by hands-on exercises using GNSS planning software which reinforces and understanding of the impact of the various GNSS constellations currently available for positioning.

Further information about preparing and executing field surveys, an introduction to baseline processing and network adjustment for GNSS surveys (Van Sickle, 2015) is presented in conjunction with hands-on activities processing sample data with a commercial GNSS baseline processing software. The differences and significance of the major data formats such as RINEX v2 and v3, RTCM, NTrip, NMEA and SP3 are given at this time.

These activities are given as a precursor to a large practical exercise whereby the whole class works together on a static GNSS baseline network task to coordinate some unknown marks on campus. The lecturer chooses several survey marks with known and unknown coordinates, with varying qualities of skyview.

The class self-organise into groups of three whereby up to 8 field parties can observe simultaneously in a series of four unique sessions (Figures 2 & 3). GDA2020 coordinates (the national datum used in Australia) are derived from the CORSnet-NSW network using both a nearby station (5km) and a distant station (25 km) (CORSnet-NSW, 2020). Students plan their own logistics taking into consideration the skyview, baseline length to the CORS reference station, number of repeat observations to unknown stations and other logistical factors.

	VLWD		FTDN		VLWD		FTDN	
Session	Grp5	Start Time	Grp6	Start Time	Grp7	Start Time	Grp8	Start Time
1st	B433	01:00:00	B403	01:00:00	B432	01:00:00	B404	01:00:00
2nd	B403	01:45:00	B404	01:45:00	B805	01:45:00	I232	01:45:00
3rd	B805	02:30:00	I232	02:30:00	B433	02:30:00	B403	02:30:00
4th	B432	03:15:00	B805	03:15:00	B404	03:15:00	B433	03:15:00

Figure 2. Student example observation schedule showing CORS stations used (VLWD & FTDN), planned start/stop times, group number and point to observe.

Figure 3. Student example diagram of GNSS baselines observed per session.

They prepare a plan, practice use of the gear then, at the specified time, carry out the field survey. All observed data is made available to all students and the student groups process the data and perform a network adjustment independently – the first time many students have used a commercial software to perform least squares. The final report is prepared for assessment from this project and provides the lecturer with an opportunity to compare student results and feed those findings back to the students. This field exercise provides a rich education for students and is challenging for both students and lecturers.

3.6 GNSS Heighting

Students have already undertaken numerous practical exercises with digital levelling, leap-frog EDM height traversing, trigonometric levelling and RTK GNSS levelling in year 2. They understand the difference between the geoid and ellipsoid and have had a theoretical introduction to the basics of physical geodesy. This geodesy course expands their knowledge describing how a geoid is computed from terrestrial, airborne and some recent satellite gravity missions such as CHAMP, GOCE and GRACE and introduces the concept of a spherical harmonic geoid model. Students learn that the AusGeoid products in Australia are actually working surfaces which have distorted the gravimetric geoid to fit with a legacy realisation of height that is used widely across Australia. This knowledge is important when considering the new reference surfaces used within Australia. The ELVIS elevation foundation spatial data is introduced to students as an example of open data (ELVIS, 2020).

3.7 Datum modernisation

Over the last decade, Australia has been undergoing datum modernisation from the Geocentric Datum of Australia 1994 which was designed to be compatible with GPS positioning through to the more modern GDA2020. This topic presents the opportunity to discuss in depth both geometric geodesy and the development of the ITRF. Implicit in this discussion is the contribution of VLBI, SLR, DORIS and GNSS to the global datum. Cautionary remarks are given about the misuse of the WGS84 datum which is widely used by non-geodesists. This is linked with the use of EPSG codes by GIS professionals. The IGS service (IGS 2020) is presented in some detail and an understanding of the various products generated by this service is emphasised as well as the real time IGS service.

3.8 Precise Point Positioning (PPP)

These IGS data products provide a neat segue into the theory behind Precise Point Positioning and by now students can make comparisons between carrier phase-based GPS techniques and PPP. Issues such as system biases and longer convergence times with PPP give the student an appreciation that satellite based positioning is diverse and is still an evolving technology; a good message for budding researchers and a cautionary tale for would-be professional surveyors.

3.9 Satellite Based Augmentation Services (SBAS)

Another important part of a modern geodesy curriculum must acknowledge the widespread use of satellite-based augmentation services (SBAS) from public sector organisations such as WAAS, EGNOS, GAGAN, SDCM and from commercial services including Veripos, Atlas, Centrepoint RTX, Starfire. Roberts (2019b) provides a glossary of the range of services available. These are presented in lectures but there is not enough time to compare and contrast the quality of the various services. The student can only gain and awareness that such services exist and cater to a range of different users.

3.10 Kinematic Geodesy

A modern geodesy curriculum also seeks to inform the student of the many free online services available to the GNSS positioning community. The AUSPOS baseline processing service has been active for almost two decades and is used widely and reliably by Australian surveyors (Geoscience Australia, 2020b). It is a free online service using IGS stations globally and IGS/national CORS sites in Australia. As a way of explaining time dependent datums, a class exercise is prepared whereby students extract 24 hr RINEX files from stable CORS sites from the present time and 10 years previous. The lecturer allocates these stations based on data availability and geographic separation across the Australian continent. All students then use AUSPOS to compute station coordinates for these two time epochs, examine the quality of the results and when satisfied, copy the Earth fixed coordinate result to a shared Google document. All students then use Goudarzi's Euler pole calculator which provides velocity vectors between the time epochs and computes the location of the Euler pole for the Australian plate based on these vectors (Goudarzi, 2020, Grant, 2015). This exercise provides deep learning about the differences between Plate fixed and Earth fixed reference frames mirroring the datum modernisation advances in Australia between GDA2020 and ATRF.

3.11 Standards and Specifications

As GNSS surveying has advanced, the various regulations and guidelines surrounding these advances have been regularly updated to keep pace. Most of the graduates from the BE (Surveying) degree at UNSW will go on to become professional surveyors in some form. They should be aware of the important documents which will govern their future work practices. Documents such as the latest version of the GDA2020 Technical Manual prepared by the Intergovernmental Committee on Surveying and Mapping (ICSM) provide a wealth of relevant technical information and serve as revision for the entire course. The ICSM also produce a guideline called Standards and Practices for Control Surveys commonly known as SP1 which is widely used for tender documents and referred to in jurisdictional regulations. Concepts such as coordinate uncertainty and an appreciation of the quality of a coordinate result are highlighted in both these documents.

In NSW, the Surveyor General's Directions No. 9 (GNSS for Cadastral Surveys) and No. 12 (Control Surveys and SCIMS) are used to reinforce a number of concepts that students have learnt during this geodesy course. In Australia the legal traceability of measurement has presented challenges to authorities. Students understand that EDM calibration assures the legal measurement of a metre, but for position a whole new paradigm has been developed. Students learn that 121 National CORS stations constitute a Recognised Value Standard

(RVS) under the National Measurement Act (1960) and that all subsequent state based datums connect to this legal framework.

3.12 Jargon

Throughout the course students are overwhelmed with an enormous number of acronyms, abbreviations and initialisations used routinely in the GNSS community. The lecturer has produced a glossary of the essential terms to know and also has produced a number of online quizzes that the students can use for revision.

3.13 Science

Satellite geodesy missions nowadays measure at unprecedented precision, sensing geophysical phenomena in our Earth system never before imaginable. These fascinating new developments provide an opportunity for the curious geodesy student to investigate the science involved in geodesy. In order to achieve this, an overview lecture is given in week 1 and the student is given a range of topics to research. Students choose a topic and then prepare an essay (limited to 10 pages) explaining the science behind the topic and are scheduled at the end of the term to present their findings to their classmates. They are encouraged at all times to present their findings to help advance the learning of the entire class, and not to direct the presentation to the lecturer exclusively. Whilst an essay at first appears onerous for an engineering student (unlikely to be a fan of essay writing), it provides excellent training for concise writing, referencing and presentation in a limited time frame (5-minute presentations). All students must be present for all presentations and they provide assessment for each other. Previous years have reinforced the value of this exercise for the individual student and to the rest of the class. Indeed, for those students who graduate and ultimately become Registered Surveyors in NSW, they will be required to gather 15 Continuing Professional Development (CPD) points in order to maintain their registration. This exercise is an excellent sandpit for their future endeavours.

4. SUMMARY and CONCLUDING REMARKS

Teaching geodesy in isolation would be very difficult. This course relies very much on pre-requisite knowledge in order to build quickly on known concepts. There are many more geodetic sensing technologies than ever before and some convergence of these technologies. This becomes an overarching obligation for geodesy educators to expose students to the range of technologies, relevant online services in preparation for a diverse range of possible vocations.

The course GMAT3700 Geodetic Positioning and Applications includes 28 lectures presented over 33 hrs. There are five supervised hands-on tutorial activities which are completed in their allocated timeslots in a computer lab and one small take home assignment exercising geometrical geodesy. All attract a small assessment. There are three assessable online quizzes offered progressively during the course to test knowledge. The early lectures are scheduled to lead up to the large field practical exercise in the middle of the term and subsequent supervised lab sessions are offered to assist with computations thereafter. Throughout the term students work on their own essay topic and prepare a short presentation at the completion of the term. A final written exam tests the student knowledge and always includes an applied, scenario-based question to test a broader understanding. The course is packed with material and the challenge is to not overburden students with too much information. Reference is made to the subsequent remote sensing and photogrammetry course following, emphasizing that remote sensing and geodesy share several concepts.

Classical geodesy was a highly mathematical course with much time spent on high accuracy traverse computations on the ellipsoid with all associated corrections, or programming map projections formulas using Fortran or similar. Nowadays many applications, spreadsheets and software perform these complex computations with a user-friendly interface. The student uses these tools to understand the concept rather than writing their own programs. This is generally a faster approach to learning, enabling the ever-growing range of new technologies to be experienced in a limited time. It is therefore important to structure relevant hands-on activities to exercise these concepts which have not been rigorously learnt through the pain of programming.

Ideally, surveying graduates should use their knowledge of modern geodesy to understand:

- Measurement uncertainty, transformations between reference frames, coordinate systems and map projections.
- The difference between vectors, point clouds and pixels.
- The difference between precision and accuracy and the statistics that describe the quality of measurements.
- Appreciate how to combine data from different sources and instruments and how this impacts georeferencing.
- The process of planning, executing, processing, network adjusting and presenting a static survey to coordinate new survey marks in 3D using hands-on activities.
- The regulations and guidelines governing survey practice.
- The concepts behind the many newer technologies and satellite missions SBAS, PPP, NRTK, geoid models, reference frames (time constraints limit a more in-depth study)
- The science behind one particular topic of choice as the subject of essay/presentation assignment and listen to presentations from their colleagues.

In a world where the general public are being exposed to and subsequently demanding higher precision positioning on their consumer devices, surveying and geospatial graduates need to be equipped with the requisite education to be regarded as the measurement experts. This course tries to satisfy that goal.

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BIOGRAPHICAL NOTES

Craig Roberts bridges the gap between teaching and research, industry and academia of modern high technology precision GNSS positioning and its practical application. Expanding from a humble degree in Surveying, pioneering experiences in international field work using GPS for tectonic studies and a PhD in GPS volcano monitoring have ignited his passion for teaching and sharing expertise in this growing field. Current research interests include the implications of datum modernisation and leveraging multi-GNSS CORS infrastructure for practical application to surveying and geospatial engineering as well as applications of UAVs for high precision mapping.

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