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THE MONTHLY MAGAZINE ON POSITIONING, NAVIGATION AND BEYOND

SUSTAINABLE URBAN DESIGN and PLANNING

Assessment of GNSS-based systems for railways safety


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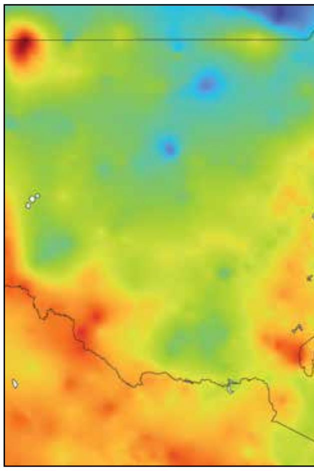

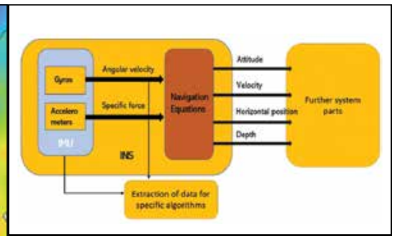

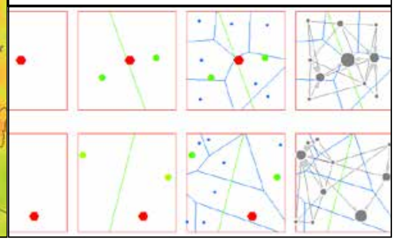

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This issue of Coordinates is of 40 pages, including cover.

Vaccinalism

As the Covid-19 virus keep surging again and again,

The world rushes to get vaccinated.

And some saw and see opportunities in many ways,

There are many, who contributed to the crisis,

There are few who rival for credits and occupying market share.

Hence, my vaccine is better than yours!

Though the debate is understandable

On the qualities and efficacies of vaccine,

It is the recognition of the vaccines by all that needs attention.

When the world is getting divided in ‘vaccinated’ and ‘non-vaccinated’

A further segregation of vaccines on the basis of ‘country of origin’

Will lead to a vexed situation.

It is challenging..but this must be resolved.

Bal Krishna, Editor
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Assessment of GNSS-based systems for railways safety

Under consideration of current approval processes in railway environment based on standards like EN 501026 RAMS-process (reliability, availability, maintainability, and safety) and available GNSS standards like EN 16803-1 and ETSI TS 103 246-3, the described approach presents a possible high-level process for assessment of GNSS based systems

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European Railway Traffic Management System (ERTMS) is the European standard for the Automatic Train Protection (ATP) and command and control systems. ERTMS is a safety system enforcing compliance from trains with speed restrictions and signalling status.

In last years, GNSS was acknowledged as an important sensor system for implementation of ERTMS in field of virtual balises., This document presents an approach for qualification of GNSS-based reference equipment for assessing GNSS equipment to be later used in trains for safety critical applications e. g. identification of moving blocks. Main focus of the document is the underlying assessment process according to the regulations required in an accredited laboratory for GNSS like NavCert as the only laboratory accredited in Europe in the scope of GNSS.

1. Introduction

In the context of Intelligent Transport Systems (ITS), railway domain depends on usage of GNSS for both safety-critical and non-safety-critical applications. As an example, project CLUG (Certifiable Localisation Unit with GNSS; http://clugproject.eu/fr) can be cited which develops a new approach for train localization. Aims of the CLUG project are:

- to provide position, velocity, and acceleration of train
- to replace or enhance board equipment (e.g., odometry, balise reader)
- to foster new concepts as Moving block, European Rail Traffic Management System (ERTMS) L3
- to prototypical certify prototype based on project internal standard

However due to missing mapping of GNSS to functional safety requirements of rail so far, balises are still main reference for absolute positioning. There is an emerging concept of virtual balises, which are virtual points, recorded in an embedded geographic database. These points could be e.g., coordinates of real physical balises. Basic idea is to derive deviation of train positioning solution obtained by GNSS to this database of points. n same telegram as a physical balise can be sent from "virtual" one. This enables a cost-effective modernization and a significant increase in efficiency of monitoring systems. For usage of such systems, qualification is necessary. In following, qualification for such systems will be presented on a high level.

A suitable positioning algorithm for railway monitoring usually cannot rely on GNSS solely. Instead, additional measurement systems need to aid in situations where GNSS solution is not available or trustable for example

2. Assessment process for measurement equipment in laboratories

This section provides an overview of assessment process within laboratories. Process is based on laboratory standards like ISO 17025 and is split here into two sections:

- Development of test scheme with a qualification of measurement equipment
- Testing with measurement campaigns according to specifications of test schemes

2.1 Development of assessment scheme

In preparatory work, first scope of assessment is defined. In context of this paper scope is assessment of GNSS based positioning systems. Based on scope and analysis of available standards and/or regulations is conducted which need to be acknowledged in later process. These referring standards and regulations define metrics for assessment. Usually, a general metric overview is given by standards and regulations. Sometimes an adjustment of metric is needed to cover specific topic of assessment. In only a few cases metrics definition from standards and regulations can be taken over one by one. If no standards and/or regulations exists, a laboratory internal "standard" shall be defined and used.

Next step is definition and description of measurement background and observables. Thereby measurement background describes initial process of how observables are measured and how observables are connected to metrics. Standards and regulations shall be considered here because these set certain requirements and limits for these two topics. It shall be noted for laboratory tests only calibrated and validated equipment is allowed to be used. If no calibration is possible laboratory needs to define an own process instead. This serves metrological traceability of test case and test scheme.

Based on previous work an error analysis shall be conducted, whereby first an overview of all possible impacting factors based on measurement background shall be created. Based on quantification of listed factors an expected error range for measurements can be given. This shall be compared with initial metrics requirements. If a deviation is detected measurement process shall be refined and succeeding process repeated. Hereby also new requirements for measurement can be defined like for example environmental conditions.

Based on these outcomes and to refine complete process a statistical analysis shall be conducted. This process can cover topics like for example a sample analysis to determine if in defined measurement process results can be calculated with sufficient probability and quality.

After these steps, verification of complete process and method needs to be conducted to ensure its feasibility, reliability, and quality. This can be done via different methods like audits, simulations, etc. If no anomalies or deviations were detected during this process final definition of assessment process through its test cases, criteria, which are summed up in test scheme, is therefore completed. Or wise, depending on detected deviations, previous process on different levels needs to be refined and completed again. As last step, an independent review of process shall take place to ensure its integrity. With this, assessment scheme can be released and after training is used.

2.2 Implementation of assessment process

In general, for implementation process, stated requirements from test scheme shall be followed. Additionally, following points shall be acknowledged:

- Identification of test equipment, test samples and documentation of test process and test results
    - For assessment process and its implementation, it is essential, all used equipment and provided samples can be later identified to provide reliability, reproducibility, verifiability, and traceability. This applies also to measurement data, provided documentation, test process, interim results, and test results. Due to this all of these points need to be clearly and completely documented in a traceable way.
- Validation prior to usage of test equipment
    - All test equipment used for assessment shall fulfil requirements stated in test scheme. These requirements and their functionality shall be validated via specified process before performing tests.
- Handling of test sample and equipment
    - Equipment used for testing including samples shall be handled and stored generally in a way to preserve its state (e.g., no damaging). Only exception of this requirement is if a test demand (e.g., acceleration).

3. Challenges of railway environment

Railway tracks can be considered a highly challenging environment for GNSS positioning due to many circumstances. Just like for autonomous driving, problems arise especially in highly obstructed (e.g., urban) areas where satellite visibility tends to be poor and major error sources like multipath effects are encountered regularly. In comparison to automotive domain, at least a rough constraint for position solution can be assumed, which is defined by movement of train on predefined tracks. Never less, a suitable positioning algorithm for railway monitoring usually cannot rely on GNSS solely. Instead, additional measurement systems (one of these is introduced in detail in next section) need to aid in situations where GNSS solution is not available or trustable for example.

In following, we introduce an overview of some of most common error types influencing a GNSS positioning solution. Afterward, some critical environments encountered in railway domain and special challenges in detail are described. Railway tracks can be considered a highly challenging environment for GNSS positioning due to many circumstances. Just like for autonomous driving, problems arise especially in highly obstructed (e.g., urban) areas where satellite visibility tends to be poor and major error sources like multipath effects are encountered on a regular basis.

3.1 GNSS Errors

3.1.1 Multipath

Multipath effect occurs when a GNSS signal is reflected off an object, such as wall of a building, to GNSS antenna. If this reflected signal can be tracked by receiver, this results in a ranging error of distance between receiver and satellite. Normally one distinguishes two different types of multipath:

- Line of sight
- Non-line of sight

For line of sight multipath, real signal and reflected are available. Thus, this error is easier to be acknowledged and mitigated based on a simple comparison. For non-line of sight multipath, real signal is not available for receiver and thus error affects ranging of satellite can be positive or negative. therefore, this type is significantly harder (or even impossible) to mitigate in GNSS processing. usual range error value is submeter for narrow field multipath to about 150 m for wide-field multipath. Additionally, it needs to be mentioned that multipath can be divided into two-part. these are code (up to 150 meters) and carrier phase multipath (up to centimetre range) which traces back to observation type.

3.1.2. Interference

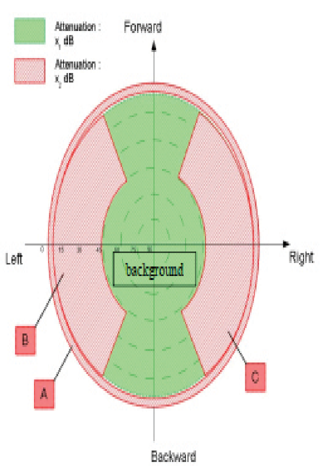
Topic of interferences can be split into two sections:

- **Jamming or intentional interference:** Intentional interference is, in many cases, a significant source of GNSS signal degradation. Intentional interference, known as intentional jamming, is caused by broadcast of malicious radio frequency (RF) signals to prevent GNSS receivers, in area, from tracking GNSS signals. Typical and direct consequences of jamming are signal frequency shifts and a drop in signal power and, therefore, worse signal-to-noise(S/N) ratio. This effect, in turn, has potential to cause severe errors in position, velocity, and time determination, and even led receiver to lose lock of GNSS signals causing a denial of service. Attacking a GNSS receiver through jamming does not require sophisticated knowledge or complex equipment. All that is needed is a signal generator with a higher power output within same frequency range of GNSS to overlay real GNSS signal.
- **Unintentional interference:** Unintentional transmission of signals, in GNSS bands, have same impact as intentional interference on GNSS receivers and thus can degrade or prevent reception of GNSS signals. These interference signals are In-band or in Out-Band of or transmitting systems. There are several sources of potential interference to GNSS from both in-band and out-of-band emitters, including mobile and fixed VHF communications, harmonics of television stations, certain radars, mobile satellite communications, and military systems. This happens usually due to defective devices or operating errors.

3.2 Critical Environments

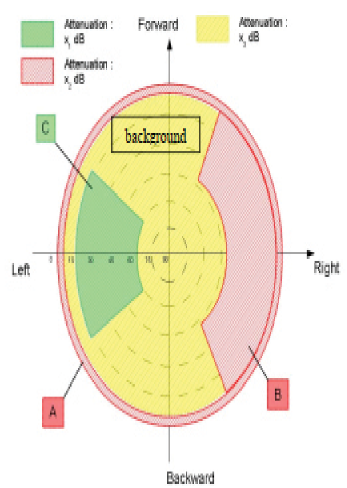
Besides different these cases encountered in railway domain (e.g., station stop, driving with different speeds), also a huge number of different environments apply. Most critical ones can be summed up by following:

Figure 1: Urban canyon plot



Zone	Elevation range (deg)	Azimuth range (deg)	Attenuation (dB)
A	0 to 5	0 to 360	$x_2 = 100$
B	5 to 60	210 to 330	$x_2 = 100$
C	5 to 60	30 to 150	$x_2 = 100$
Back-ground	Angles out of Zones A, B, C		$x_1 = 0$

Figure 2: Asymmetric visibility plot



Zone	Elevation range (deg)	Azimuth range (deg)	Attenuation (dB)
A	0 to 5	0 to 360	$x_2 = 100$
B	5 to 60	30 to 150	$x_2 = 100$
C	10 to 60	230 to 310	$x_1 = 0$
Back-ground	Angles out of Zones A, B, C		$X_3 = 15$

Source@(ETSI TS 103 246 -3 V1.3.1 (2020-10)

Key role of navigation within railway environment is to provide absolute positioning. Therefore, most Key Performance Indicators (KPI's) should be identified to measure performance of components and processes. For train Localization, performance of GNSS system delivering position is critical along with additional sensors

- Settled regions

For this environment, different topics need to be considered. Typically, in settled regions, probability for interferences due to man-made RF-signal sources, as well as for multipath due to signal reflection on buildings is generally higher. Denser region is settled, greater probability. Worst cohesion this environment can be found in traditional highly populated urban area (e.g., Frankfurt, New York). Additionally, satellite view in this environment is obstructed on a low till extreme level due to man-made buildings which can also be based on structure and design generated multipath effects for example. In ETSI TS 103 246 -3 V1.3.1 (2020-10) some examples of sky attenuation conditions are described which can be used to simulate this environment. Focus should lie on described urban canyon (Figure 1) and asymmetric visibility plot (Figure 2).

Effects for interference and multipath are addressed in sections Multipath and Interference. Due to reduced visibility of satellites and reduced signal strength like described in Figure 1 and Figure 2 an increased measurement notehead be expected, which results in reduced accuracy, i.e., higher standard deviation. In serious cases a non-availability of GNSS-based positioning is possible.

- **Mountain and valleys**
  This environment usually has a lower probability for interference sources, but multipath effects still are common. As for settled regions, limitations in terms of satellite visibility are considerable but on or hand also heavily dependent on specific topographic features of analyzed area (e.g., position of higher mountains). Biggest issue can be found directly on mountain flanks and in valleys. effect intensifies as terrain gets steeper.

  Satellite view can be generally described like in ETSI TS 103 246 -3 V1.3.1 (2020-10) due to similarities to settled region on this topic. Thus, sky attenuation conditions described in Figure 1 and Figure 2 can be used for critical environments. Due to these similarities, effects also resemble, and thus an increased measurement noise can be expected, which results in reduced accuracy, i.e., higher standard deviation. In serious cases a non-availability of GNSS-based positioning is possible..

- **Different types of tunnels**
  This group contains besides "traditional" tunnel environment, thus a "complete" obscuration of general RF-environment and sky, also tunnel gallery and or more complex tunnels like environments with open elements in tunnel wall. This environment type usually does not describe an environment for a complete these cases but more as a segment of available environment. This applies also to simulations. An example for this can be found in European eCall regulation for automotive sector (DR 207/79) wherein Annex VI 2.2.4 a test with a temporal absence of GNSS signals to cover tunnels is described.

  General in these environments GNSS-based positioning systems cannot calculate a valid position solution (non-availability) because no satellite signals are available. With open elements in tunnel wall, for example in galleries, a possibility of reception of single satellite signals are possible. these signals can be used by certain positioning systems to support already trained sensor fusion-based positioning via advanced algorithms, but do not enable GNSS only positioning.

  Multipath can be heavily expected at entrances of tunnels, but during passage, through tunnel, it can be considered irrelevant (since reliable GNSS signals will not be trackable anyway). This changes up to a certain level with open elements in tunnel wall, but due to size, they still can be ignored. Topics regarding interference within tunnels are limited to interferences based on installed equipment from tunnel operator and usually can be found in area of unintentional interference due to damaged or misused equipment. Topic of GNSS repeaters or related techniques (pseudofiles, synthetic extension, etc.) needs to be addressed. Background is these techniques are getting more and more common. these techniques try to enable reception of GNSS signals in these non-available or reduced environments and thus transforming at least up to a certain level into open environments (see ETSI TS 103 246 -3 V1.3.1 (2020-10), FigureA.1).

3.3 Integrity

Integrity is an important cornerstone of satellite navigation and an aspect of reliability focused on correctness of output. Integrity is assurance that all functions of a system perform within operational limits. It is measure of trust that can be placed in solution provided by railway positioning system. Role of integrity is to provide timely warnings to railway domain users when some system anomaly results in unacceptable navigation accuracy [1]. As for autonomous driving, a key parameter for railway domain is integrity of position solution to provide some safe and real-time KPI such as:

- Position protection level (horizontal/vertical): Protection level (PL) is a value that bounds error of position or velocity components provided by positioning terminal [2] with a very high probability and an estimate of maximum error in associated position output. Position output is misleading if true error is greater than protection level. Protection level is a common quality metric for high integrity positioning systems. Protection levels may be provided for individual position vector elements (e.g., latitude) or combinations (e.g., horizontal). Protection level is a real-time and dynamic quantity that is valid for each measurement epoch.
- Alert Limit (horizontal/vertical): maximum position error that automated driving application in railway domain can tolerate and still deliver its function. If protection level is greater than alert limit, error cannot be guaranteed to be within tolerable level and thus position solution should not be used by automated driving application in railway domain.
- Tolerable Hazard Rate (THR) Level: defined as occurrence rate vehicle control systems fails to stop vehicle at desired location, or its speed exceeds prescribed value, is used to quantify safety requirements. In railway systems, [3] an overall THR better than 10-9/h or even 10-10/h is mandatory, and this can be attained only through a cross-check with a GNSS-independent

Protection level and its associated Integrity risk, in terms of reliability (verification of risk) but also its efficiency and usability (size of Protection level, which is directly related to their usability for intended application). Users have to be informed with timely warnings in this accuracy of service is not sufficient for intended operation. In this case, user is safe.

3.4 Sensor-Fusion solutions

As already indicated in last section, GNSS-alone positioning lacks requested accuracy and continuous availability in challenging environments. In these cases, satellite-independent systems are necessary to complement and ensure a continuous positioning solution of required quality. Most prominent sensors to complement GNSS in railway domain are Inertial Navigation Systems (INS), which shall be introduced shortly in Section 2.4.1.

Moreover, specialized mathematical methods are needed to combine measurements of these two (or multiple) sensors. This is necessary since GNSS and INS systems do not measure same physical quantities and thus observations from both sensors must be combined on a common mathematical level (called navigation equations). Process of finding optimal combination between different sensors is referred to as sensor fusion.

Therefore, appropriate mathematical algorithms have to be utilized, which can account for strengths and weaknesses of observed sensor data (in terms of stochastic information). Most common technique for this task in navigation applications is Kalman Filter, which we introduce in Section 2.5.

3.5 Inertial Navigation Systems (INS)

INS is a form of a dead reckoning navigation system that provides information about position, velocity, acceleration, and orientation using measurements taken from inertial sensors. It can be used as an autonomous system for navigation or is combined with complementary measurement systems (e.g., GNSS). Technically an INS represents combination of an IMU (Inertial Measurement Unit) and a computer running navigation equations using data collected by IMU. Later consist of sensors measuring angular velocities (gyros) and accelerations (accelerometers).

INS systems integrate rotation rates to obtain orientation changes and double integrate accelerations to obtain velocity and position increments. therefore, a relative orientation can be provided. Basic structure of an INS is visualized in Figure 1. Like every or measurement system, INS suffers from random and systematic errors. Due to errors in gyros, accelerometers, and with a mathematical background, an INS will have a drift in velocity, position, and attitude. To limit drift, an INS is usually aided by or sensors that provide direct measurements of integrated quantities. Any vehicle with an IMU and some aiding sensors can these aided INS to find its position, orientation, and velocity.

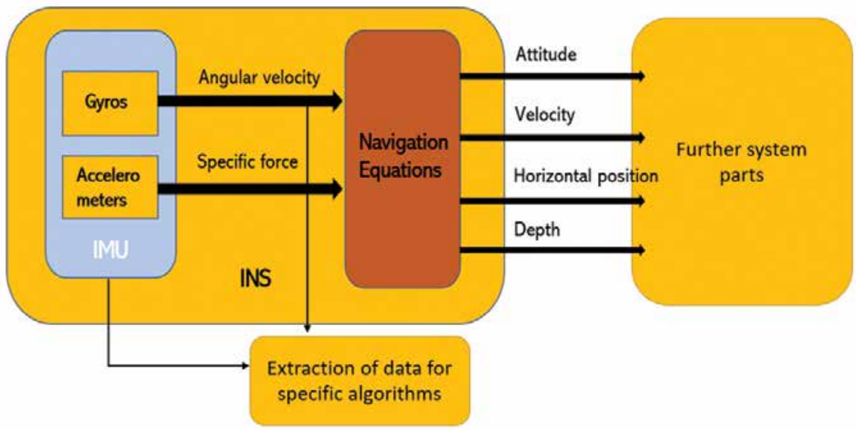


Figure 3: Schematic picture of an INS

3.6 Kalman filter fusion algorithm

Most prominent technique for sensor fusion in navigation applications is Kalman Filter. Therefore, some basic information on technique is provided in following. In a mathematical sense, Kalman Filter represents optimal parameter estimator regarding Minimum Mean Square Error Estimator (MMSE) criterium. This holds for linear systems with measurement errors following a Gaussian distribution. Estimations are based on a statistically optimal combination of real measurement data and statistical quality information (a-priori noise estimations, covariance-matrices, etc.) In algorithm, observations of different sensors can be introduced and combined at different levels of processing. In general, two different approaches can be distinguished:

- **Tightly coupled**

Tight coupling approach follows mathematics of a centralized filter which is realized through a combination at sensor level, i.e., at level of raw GNSS observations, not at level of actual parameters estimated (e.g., position). Therefore, it is possible to not only estimate positions/velocities in Kalman Filter but already raw GNSS observations (e.g., pseudo-range).

- **Loosely coupled**

Loosely coupled process represents most common approach for GNSS/INS coupling. Combination of measurements is realized at level of actual parameters to be estimated (positions/velocities/direction). Although this approach is easier to implement, it is also more prone to errors in actual raw data (pseudo-range, phase measurements, angular velocities, accelerations).

4. Assessment of GNSS-based systems

4.1 Key Performance Indicators

Key role of navigation within railway environment is to provide absolute positioning. Therefore, most Key Performance Indicators (KPI's) should be identified to measure performance of components and processes. For train Localization, performance of GNSS system delivering position is critical along with additional sensors.

4.2 GNSS related performances

Performance requirements are generally stated as requirements on outputs of a given system component, assuming that or components feeding it with input information do respect their performance requirements. [2] standard for assessing GNSS performance in context of Train transport systems is not ready currently. Therefore, existing standards which are initially defined for or domains which provide identification and definitions of positioning performance features and metrics can be adapted accordingly.

- Position: is location of positioning terminal (or, more specifically, of some reference point attached to it, such as antenna phase centre) expressed in some specified reference frame (e.g., WGS84) and system of coordinates (e.g., geodetic or Cartesian). Position output can include all position components (e.g., longitude, latitude, and height) or just a subset of m (e.g., longitude and latitude) depending on needs of application.
- Velocity: is velocity of positioning terminal relative to ground. In its more general form, it is a three-component vector which will most typically be expressed in a Cartesian coordinate system whose frame is centered at user position (e.g., local horizontal reference frame, with coordinates referring to North, East, and Up directions).
- Speed: is norm of velocity vector, and hence describes how fast user moves (relative to ground) irrespective of direction. It is of relevance in many applications and hence it shall be specifically addressed. When accompanied by heading, speed provides an equivalent description of velocity vector of a vehicle (provided that its motion is mainly horizontal, which is typically case with land vehicles). Depending on specific application, it can be convenient to present motion information to user in form of speed and heading, but in general, velocity vector is most informative.
- Accuracy: it depends on several factors (e.g., satellite visibility, constellation geometry (characterized by Dilution of Precision (DOP)), un-modelled

Dynamics	KPI	DUT Stage	Metrics
Static	Sensitivity	Acquisition	Signal Strength
		Tracking	
		Reacquisition	
	Accuracy	Acquisition	Mean and Max error
		Tracking	Mean and Max error
		Reacquisition	Radius 95% probable
	TTF	Acquisition	Mean TTFF and max
		Reacquisition	
Dynamic	Sensitivity	Tracking	Time
		Reacquisition	
	Accuracy	Tracking	Mean and Max error
		Reacquisition	Radius 95% probable
	Availability	Tracking	Position
		Reacquisition	

ionospheric and tropospheric errors, multipath, jamming,).
- Availability: despite global coverage of navigation systems, it is not always possible to obtain position, also due to some physical obstacles that limit satellite visibility.

4.3 Performance metrics

Performance metrics are precise definition of means of measuring a given performance feature of a given output of a system. This section defines positioning metrics related to position, velocity, and speed from existing standards.

1. According to CEN/EN 16803-1 [1] identification of performance features and definition of metrics are as follows:
   - provides identification and definitions of positioning performance features and metrics that characterize GNSS Based Positioning Terminals (GBPT) performance requirements.
   - these have to match a certain operational scenario, i.e., conditions in which GBPT is operating that may have a huge impact on its performances.
   - accuracy associated to position error, velocity error, or speed error,
   - integrity determined by protection level given an associated integrity risk.

2. According to ETSI TS 103 246-3, [2] standard defines three position horizontal accuracy and vertical accuracies performances for a moving vehicle in an open sky condition for urban canyon and asymmetric sky view scenarios requirements classes Performances for horizontal. Assessment of GNSS for train applications are based upon device under test. Appropriate metrics to quantitatively characterize KPIs have to be extracted from device under test used.

However, identified KPI must be measured also under two DUT dynamics: static and dynamic, at three signal-processing stages (states) of DUT: acquisition, tracking and reacquisition. Following table defines dynamics, associated KPI and metrics.

4.4 Assessment Methods

Under a statistical perspective, as means to assess above-mentioned KPIs with proper metrics extracted from receiver observables, following methods can be used. This section summarizes following three methods [5] used to provide a measure of system performance in navigation. These methods are appropriately used to compute performance metrics from receiver observables when accuracy is considered. Below accuracy metrics overall represent a measure of average positioning error with a certain percentage of confidence. Assuming Gaussian-distributed errors, direct conversion is possible among above-defined metrics.

- Circular Error Probable (CEP)

Circular Error Probable (CEP) is radius of circle that encloses 50 percent of probability of a hit in two dimensions, i.e., if a CEP of 5meters is quoted n 50% of horizontal point positions should be within 5metresof true position. Several methods are possible for computing CEP. This CEP is an integral of bivariate (two-variable) Gaussian probability function in a plane. radius of 95% with radius of 95% probability circle and it is computed as:

$$CEP = 0.5887(\sigma_y + \sigma_x)$$

Accurate when: $\frac{\sigma_y}{\sigma_x} > 0.3$

Radius of circle centered at true position, containing position estimate with probability of 50 %. parameters σ_y and σ_x are standard deviations of error along two perpendicular axes in a plane, and 0.5887 is a dimensionless constant was derived using a 50-percent CEP in integration of a bivariate Gaussian probability distribution x s y s

- Height Error Probable (HEP)
  HEP can be calculated to determine an altitude error independent of CEP and SEP. SEP combines both horizontal and vertical errors. Since vertical error is generally greater than horizontal error, SEP will be influenced dominantly by vertical error; therefore, by computing HEP, CEP, and SEP, one can better determine distribution of errors.

A 50-percent HEP is given as

$$HEP = 0.6745\sigma_H$$

derivation of this equation assumes a Gaussian probability function in vertical direction. parameter σ_H is standard deviation of error in height.

- Spherical Error Probable (SEP)

Above result can be extended to three-dimensional (3D) case: SEP. SEP is an integral of tri-variate (three-variable) Gaussian probability density function over a sphere, which is centred at mean. Two equations were found to compute 50-percent SEP. most common is:

$$SEP = 0.5(\sigma_x + \sigma_y + \sigma_z)$$

which allows to compute SEP to within 1 percent whenever $\frac{\sigma_y}{\sigma_x} > 0.5$

CEP, HEP, SEP, state nothing about quality or accuracy of data used in computing location of a target. these items are a measure of dispersion and of central tendency.

5. Conclusion

Under consideration of current approval processes in railway environment based on standards like EN 501026 RAMS-process (reliability, availability, maintainability, and safety) and available GNSS standards like EN 16803-1 and ETSI TS 103 246-3, the described approach presents a possible high-level process for assessment of GNSS bases systems. Sensor fusion is key for improvement of integrity and is assessed in more detail in the project CLUG. This together with other research activities of NavCert may lead to more specific standardization and regulation for smoother implementation of ERTMS L3.

Australian Height Datum: Celebrating 50 years

This paper celebrates the 50th anniversary of the Australian Height Datum (AHD), along with its achievements and longevity, outlines its shortcomings and looks ahead to a new era of vertical datum determination based on GNSS and airborne gravimetry

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The Australian Height Datum (AHD) celebrates its 50th anniversary this year and remains Australia's first and only legal vertical datum. Vertical datums define a reference for elevation comparisons and are essential for many applications relying on the flow of fluids. They are also of growing interest to a wider audience with an insatiable appetite for three-dimensional digital twins of the real world.

Surveyors typically work with two types of heights in Australia: ellipsoidal heights referred to the Geocentric Datum of Australia (GDA2020, see ICSM, 2020a) and physical heights referred to AHD. In New South Wales (NSW), both are available through the Survey Control Information Management System (SCIMS), the state's database containing approximately 250,000 survey marks on public record (Janssen et al., 2019).

Focussing on physical heights in NSW, this paper explores the achievements of AHD, outlines its shortcomings and looks ahead to a new era of vertical datum determination, based on Global Navigation Satellite System (GNSS) observations and airborne gravity measurements, culminating in the Australian Vertical Working Surface (AVWS, see ICSM, 2020b).

History of AHD

In May 1971, AHD (sometimes referred to as AHD71) was adopted by the National Mapping Council as the datum to which all vertical control for mapping was to be referred. In NSW, AHD replaced the Standard Datum, which was in use for some 80 years and defined by the value of Mean Sea Level (MSL) at the Fort Denison tide gauge, located on an island in Sydney Harbour and accessible via a survey plug that was installed in 1882 (and still exists) on the external wall of the former Department of Lands building in Sydney (Blume, 1975).

AHD was realised by setting MSL to zero at 30 tide gauges distributed around the coast of mainland Australia and adjusting 97,320 km of primary two-way spirit levelling across the country. MSL observations spanned three years (1966-68) for all but one tide gauge, with earlier data over four years (1957-60) used at Karumba in the Gulf of Carpentaria. A subsequent adjustment also included about 80,000 km of supplementary one-way and two-way spirit levelling, in addition to and dependent upon the primary levelling. For the first time, this provided a nationwide network of physical heights known as the Australian National Levelling Network (ANLN) – a stunning and quickly implemented achievement that required enormous effort. Prior to AHD, many disconnected local height datums were used in each Australian state and territory.

In order to produce the most useful outcome within the framework of funds and time available, third-order levelling was used for the primary survey (Granger, 1972; Lambert and Leppert, 1976). At the time, this certainly provided an adequate basis for the topographic mapping program, general engineering purposes and the coordination of levelling surveys undertaken during gravity observations.

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Anything more was considered as "striving against the forces of nature in order to achieve an impossible dream" (Lambert and Leppert, 1976).

An important time consideration was that third-order levelling could be accomplished with readily available equipment and by available professional staff found in both the government and private sector. Of course, third-order levelling was also much cheaper than first-order and second-order levelling. Considering the cost factor, as a rough rule of thumb, it was determined that an increase in a survey operation by a factor *n* involves an increase in time and funds of n^2. Furthermore, even if better levelling standards had been adopted, this accuracy would have been swamped in the warping of the level surface to hold MSL equal to zero at the 30 tide gauges.

Practical realisation of AHD in NSW

On the ground, AHD was realised by networks of approved survey marks. Some states organised their own ground marking and benefited as a result, others left this to contract surveyors. Typically, AHD marks were placed at intervals of one mile in regional areas and two miles in remote areas, usually following major roads. The network was far denser in towns and cities. The separation was also varied to place marks at easily identifiable locations (e.g. crossroads, property entrances, hill crests and bridges) in an era predating GNSS positioning or even full mapping of the state. Often, ANLN marks were located close to existing road mile posts for easier retrieval.

Marking typically consisted of five State Survey Marks (SSMs, brass plaque in concrete) followed by a Permanent Mark (PM, usually a stainless-steel rod with concrete collar), with this pattern being repeated for the entire level run. Sometimes, pairs of PMs on opposite sides of the road were placed to provide extra redundancy. Different level runs met and joined at junction points. Later, marking became more non-standard with entire runs sometimes consisting of only PMs or only SSMs and inter-station distances opting between miles or kilometres. Marks also varied with soil condition and when existing surveys were adopted or recycled.

Later, in the 1970s, NSW installed a series of Fundamental Bench Marks (FBMs) and Geodetic Bench Marks (GBMs). These were high-stability marks designed to physically hold and preserve AHD. Based on a European design, they were modified for Australian conditions, akin to trigonometrical (trig) stations for height. FBMs and GBMs consisted of two to three marks installed in clusters, with the primary mark being located under a standard cover box. Marks consisted of stainless-steel rods driven to refusal in auger holes that were backfilled with sand to decouple the mark from any local soil movement. An extensive network of FBMs and GBMs was envisaged, but the program was abruptly terminated due to budget constraints.

While AHD was designed as a third-order levelling network, NSW set a far higher standard and supplemented, strengthened and improved AHD by observing the nation's most extensive and ambitious network of first-order levelling (Figure 1), which extended throughout the eastern part of the state. While third-order levelling was performed by private sector contractors (whose participation was vital to the timely completion of AHD), first-order levelling was conducted by the Central Mapping

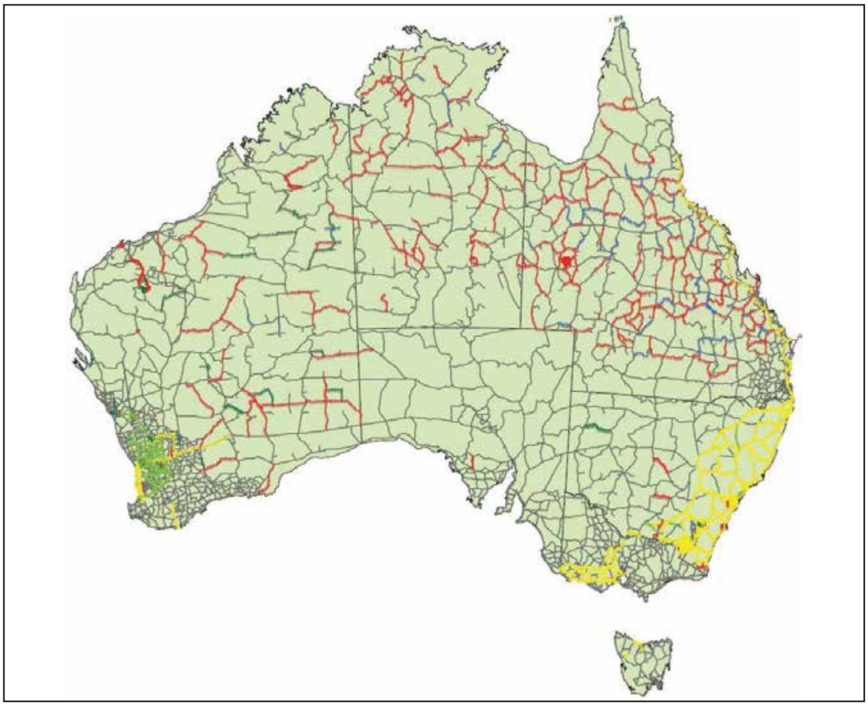

Figure 1: ANLN, showing first-order levelling sections (yellow), second-order sections (light green), third-order (fine grey), fourth-order (dark green), one-way third-order (red) and two-way levelling of undefined quality (blue) (Filmer et al., 2010).

Over the years, further level runs of various quality including one-way levelling were added to extend the network and investigate anomalies. An extensive capillary network of levelling to mountain-top trig stations was also established, typically one-way only, connecting to the nearest ANLN mark

Authority (CMA), now DCS Spatial Services, a business unit of the NSW Department of Customer Service (DCS).

Over the years, further level runs of various quality including one-way levelling were added to extend the network and investigate anomalies. An extensive capillary network of levelling to mountain-top trig stations was also established, typically one-way only, connecting to the nearest ANLN mark. To this day, discussions continue about the existence and nature of any systematic errors that may lay dormant in this then fit-for-purpose survey methodology. For DCS Spatial Services, the era of optically (or digitally) observing extensive levelling networks ended well before the start of the 21st century, and in-house geodetic levelling subject matter experts have since retired. Today, AHD is primarily derived from GNSS baseline networks, while digital levelling is only conducted for special projects, ad-hoc surveys or in some urban instances.

Adjustment of the ANLN

Prior to the adjustment, observed levelling data was corrected for the effect of non-parallelism of equipotential surfaces by applying the orthometric correction based on normal gravity (e.g. Granger, 1972; Roelse et al., 1975; Lambert and Leppert, 1976), which approximates true gravity. Orthometric corrections can be as large as several centimetres in mountainous regions where the level surfaces exhibit steeper slopes than in lowlands, e.g. 309 mm correction for the 146 km level run from Adaminaby into the Snowy Mountains versus 33 mm correction for the 155 km level run between Dubbo and Forbes.

AHD is considered a normal-orthometric height system because existing gravity observations were insufficient. Instead, a truncated normal-orthometric correction was applied to the spirit levelling observations, which only utilised normal gravity (referenced to the GRS67 ellipsoid approximating the Earth). For a detailed treatment of height systems and vertical datums in the Australian context, the reader is referred to Featherstone and Kuhn (2006) and Filmer et al. (2010).

The network of level sections and junction points was constrained at 30 tide gauges, which were assigned an AHD height of zero. In NSW, this included the tide gauges at Coffs Harbour, Sydney's Camp Cove and Port Kembla, while Eden was excluded at the request of the Victorian and NSW Surveyors-General due to poor data (Roelse et al., 1975). The selection of Camp Cove (established in 1916) over Fort Denison, the second continuously recording tide gauge established in Australia in 1886 with records dating back even further and a long association with levelling datums, was attributed to the difficulty in making the cross-water connection (about 600 m) and the existence of a tidal gradient between the entrance to Sydney Harbour and Fort Denison (Blume, 1975). While there were many interruptions to the national tide gauge network recordings due to theft, vandalism and faulty gauges, acceptable results were obtained from the 30 gauges eventually chosen (Granger, 1972).

The least squares adjustment propagated MSL heights, or AHD heights, across the levelling network. This adjustment occurred in two phases due to the computational limits of the impressive CDC 3600 computer used at the time. In phase 1, five regional adjustments were made within boundaries approximating state limits. In phase 2, these were combined to produce two solutions: a minimally constrained solution with one station held fixed to assess the quality of the levelling, and the final adjustment constrained to the 30 tide gauges, run on 5 May 1971 (Granger, 1972; Roelse et al., 1975; Lambert and Leppert, 1976). The minimally constrained solution indicated a standard deviation of about 0.3 m in the centre of Australia. Despite the best efforts of surveyors, gross, random and systematic errors crept into the level sections and were distributed across the network within the adjustment.

Lambert and Leppert (1976) noted the average loop closure was ± 6 mm/√km but the loop closures did not conform to a normal distribution. The average correction applied to the regional adjustments was ± 3 mm/√km. An assessment of the standard weight of the minimally constrained adjustment was ± 7 mm/√km for all states but NSW. Detailed analysis indicated that the data for the south-eastern corner of NSW was statistically inferior despite the existence of mostly first-order levelling. Reportedly, this indicated that, after several years, first-order surveys tend to deteriorate to much the same order of accuracy as third-order levelling.

Owing to their distance off the NSW coast, Lord Howe Island and Norfolk Island are not covered by AHD and continue to use local historical height datums, the origins of which require more detailed investigation, documentation and public communication. As an aside, the Tasmanian AHD (often referred to as AHD-TAS83 or AHD83) was realised separately by setting MSL observations for only one whole year (1972) to zero at the tide gauges in Hobart and Burnie. It was propagated using mostly third-order levelling and adjusted on 17 October 1983 (ICSM, 2020a).

Shortcomings of AHD

Over time, significant and well-documented shortcomings in the AHD realisation became apparent. In short, due to dynamic ocean effects (e.g. winds, currents, atmospheric pressure, temperature and salinity), tide gauge observations only spanning a period of three years and the omission of observed gravity, MSL was not coincident with the geoid at the tide gauge locations. The primary bias is due to the AHD realisation ignoring the effect of the ocean's time-mean dynamic topography, resulting in AHD being about 0.5 m above the geoid in north-east Australia and about 0.5 m below the geoid in south-west Australia. Together with uncorrected levelling errors, this introduced considerable distortions of up to about 1.5 m into AHD across Australia (e.g. Morgan, 1992; Featherstone and Filmer, 2012; Watkins et al., 2017). Many more investigations into the shortcomings of AHD can be found in the literature.

Observational blunders included those caused by observing in imperial units, where a whole foot was easily 'dropped' or 'picked up'. Random errors included those caused by metrification in Australia, having to use metres in calculations although the data was observed in feet. However, there were also downright fraudulent level runs, including the fable of the contractor who supposedly adjusted out a misclose of more than seven feet while enjoying a cold beer at a pub in outback NSW. The independent approach of a few surveyors who did not fully conform to the prescribed specifications also caused issues (Lambert and Leppert, 1976).

Despite all this, AHD has, overall, continued to be a practical height datum that is fit for purpose, providing a sufficient robustness for many surveying and engineering applications, particularly over smaller areas (less than 10 km).

> The small difference between the two datums has resulted in many surveyors being vocally critical of the new datum and the opinion has been expressed that the introduction of AHD was an unwarranted alteration to a long established and acceptable system

A new era of vertical datum determination

The era of GNSS technology ushered in the development of geoid or quasigeoid models to convert GNSS-derived ellipsoidal heights to physical heights, including the AUSGeoid models for Australia (Featherstone et al., 2019). This conversion is often needed because positions obtained by GNSS include heights referred to a reference ellipsoid. These heights are based purely on the geometry of the ellipsoid and therefore have no physical meaning, i.e. they cannot be used to predict the direction of fluid flow because they do not consider changes in gravitational potential. In practice, however, heights are generally required that correctly reflect the flow of fluids, e.g. for drainage and pipeline design.

Addressing the shortcomings of AHD in an era of ever-increasing usage and availability of GNSS and airborne gravity measurements, options for a potential new vertical datum were investigated at the national level (e.g. Featherstone, 2008; Filmer and Featherstone, 2012). This culminated in the development of AVWS as an alternative for users requiring higher-quality physical heights. AVWS allows early adopters to realise the full potential of modern technology, making height determination and transfer more efficient than with the traditional techniques used in the 1970s and 1980s.

Several countries have used, or are about to use, (nationwide) airborne gravity measurements to develop high-quality gravimetric quasigeoid models to modernise their national vertical datums. This includes the

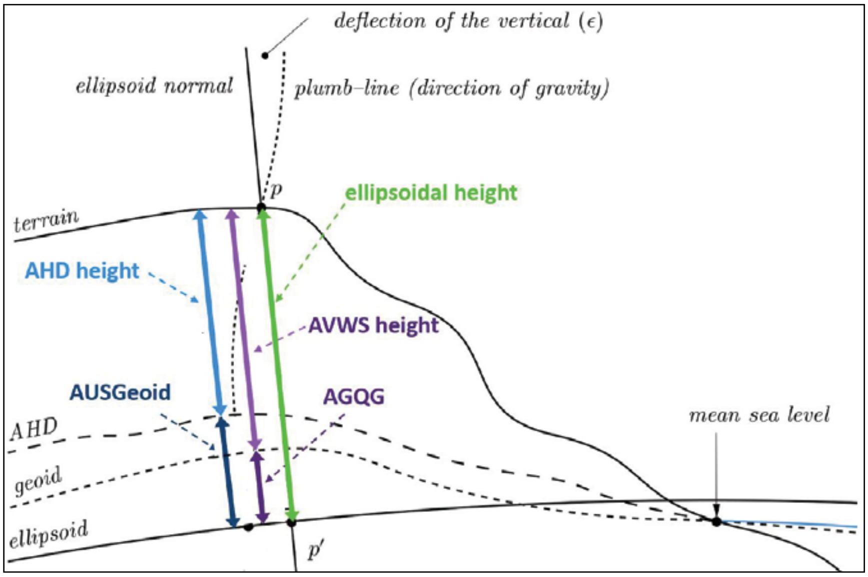

Figure 2: Converting ellipsoidal heights (green) to AHD heights (light blue) by subtracting the AUSGeoid model (dark blue) and to AVWS heights (light purple) by subtracting the AGQG model (dark purple) (ICSM, 2020b).

New airborne gravity data will significantly improve the gravity (and gravimetric quasigeoid) model and thus the accuracy of GNSS-derived physical heights. It will also be used by geoscientists to further their understanding of Australia's geological architecture

Canadian Geodetic Vertical Datum 2013 (CGVD2013), the New Zealand Vertical Datum 2016 (NZVD2016) and the North American-Pacific Geopotential Datum 2022 (NAPGD2022).

Gowans (2019) summarised the reasons for moving to vertical datums based on gravimetric quasigeoids: The maintenance of national levelling networks is no longer viable (too costly, too time consuming), and the results are too short-lived in countries subject to significant surface displacement. Gravimetric quasigeoid models are far more cost effective to maintain and less susceptible to surface movements. Their complete spatial coverage provides significant efficiency gains for industry when accessing the datum because propagating the datum from the nearest levelled benchmark(s) is no longer required. Basically, the datum is available everywhere, so there are no more 'black holes' as in AHD. However, digital levelling is still considered the most accurate technique for height transfer across short distances and will retain relevance in surveying for height-critical, local-scale projects. Since a model can only ever be as good as the data that informs it, the systematic acquisition of nationwide airborne gravity has proven to significantly benefit these quasigeoid models.

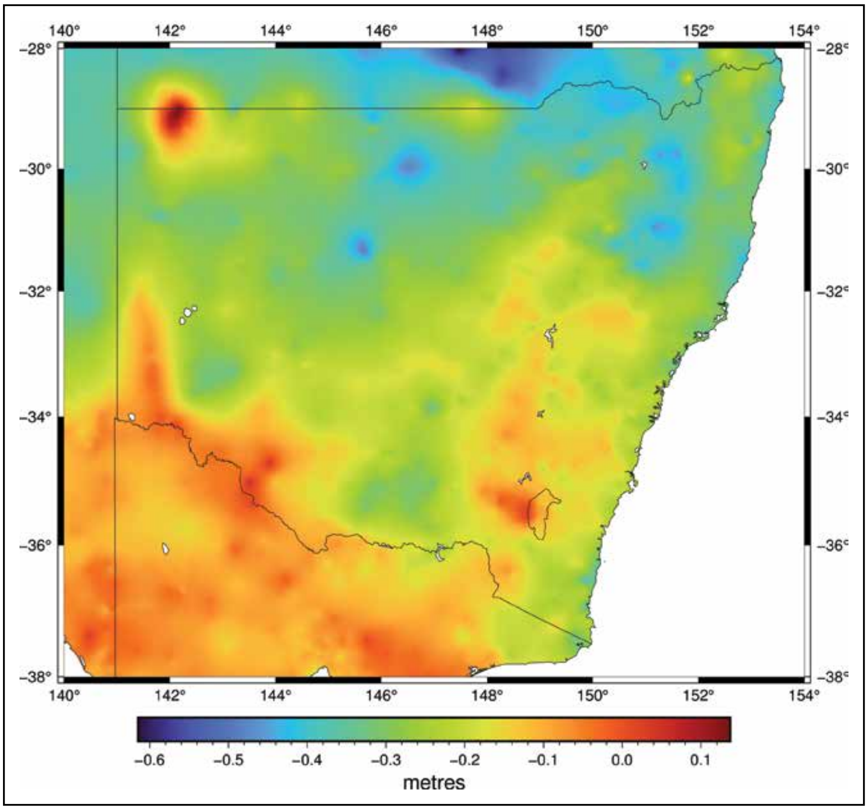

Figure 3: Differences in N values between AGQG_20201120 and AUSGeoid2020 across NSW, which is equivalent to the differences between AVWS heights and AHD heights.

In Australia, efforts are underway to collect airborne gravity data over targeted regions to improve the Australian gravimetric quasigeoid model. DCS Spatial Services is currently preparing a business case for the modernisation of its Foundation Spatial Data Framework (FSDF), which includes an option to secure funding for airborne gravity surveys across the entire state. New airborne gravity data will significantly improve the gravity (and gravimetric quasigeoid) model and thus the accuracy of GNSS-derived physical heights. It will also be used by geoscientists to further their understanding of Australia's geological architecture and how it has evolved over time, as well as advance the geoscience that assists management of earth resources, infrastructure and natural hazards.

AVWS

The Australian Vertical Working Surface (AVWS) is a new reference surface for physical heights in Australia, released on 1 January 2020. It provides an alternative for users requiring higher-quality physical heights (current accuracy about 4-8 cm) than those AHD can provide (accuracy about 6-13 cm) (ICSM, 2020b). GNSS users can access AVWS by applying the Australian Gravimetric Quasigeoid (AGQG) to their GDA2020 ellipsoidal heights, just like AUSGeoid2020 is used to obtain AHD heights (Figure 2). In practice, this means simply picking AGQG rather than AUSGeoid2020 as the geoid model in the GNSS rover or post-processing software.

The initial version, AGQG_2017 (Featherstone et al., 2018), is the gravimetric component of AUSGeoid2020, providing the offset between the ellipsoid and the quasigeoid without being contaminated by the distortions inherent in AHD. The current version of AGQG (AGQG_20201120) differs from AUSGeoid2020 by between -1.8 m and +0.7 m across Australia, resulting in AVWS (normal) heights differing from AHD (normal-orthometric) heights by the same amount when determined via GNSS and the respective models (J. McCubbine, pers. comm.). In NSW, users can expect differences of between -0.5 m and +0.1 m (Figure 3). Geoscience Australia is working with all jurisdictions to continuously improve AGQG as new gravity data (particularly airborne gravity) is included and modelling techniques are refined.

Recently, current and future user requirements for physical height determination and transfer in Australia were investigated (Brown et al. 2019a, 2019b; McCubbine et al., 2019). It was found that AHD is still deemed fit for purpose over short distances (less than about 10 km) for applications such as cadastral surveying, civil engineering, construction and mining. However, users working over larger areas wanted access to higher-quality heights to reap the full benefits of modern technology for environmental studies (e.g. flood or storm modelling), LiDAR surveys, geodesy or hydrography. The study recommended a two-frame approach for heights, with AHD remaining as Australia's legal datum and AVWS being provided as an alternative, analogous with the two-frame approach taken with GDA2020 (ICSM, 2020a) and ATRF2014 (ICSM, 2020c).

From a user perspective, AVWS provides improved access to physical heights, higher accuracy, increased efficiency, a surface without the known errors of the levelling network, better alignment with GNSS, and national consistency including a seamless onshore-offshore transition. Given that AVWS heights are not (currently) provided for benchmarks on public record, these AVWS heights can then be used as reference heights or starting points for spirit levelling surveys. While normal corrections should theoretically be applied to levelled height differences, this can generally be neglected in practice at the cost of introducing a small amount (sub-mm) of error (ICSM, 2020b).

Multiple height reference surfaces have been used in Australia for a long time to cater for certain applications, e.g. the Lowest Astronomical Tide (LAT) used for hydrographic applications. The introduction of AVWS simply adds to the spatial professional's toolbox but also highlights the importance of metadata clearly specifying which datum or reference surface one is working in.

The future of AHD

Nearly half a century ago, Blume (1975) noted: "With the adoption in New South Wales of the Australian Height Datum (AHD) 1971 as a new levelling datum, the previously used Standard Datum has been superseded. The small difference between the two datums has resulted in many surveyors being vocally critical of the new datum and the opinion has been expressed that the introduction of AHD was an unwarranted alteration to a long established and acceptable system." He continued: "Further investigation in connection with AHD is certain to continue and as a result of such research into tides, levelling, mathematical adjustments and revision, new values and possibly datums will arise. Because of the ever-changing level of the sea, any new datum would not necessarily agree with AHD, just as AHD did not agree with Standard Datum, which in turn did not agree with former datums based on sea levels. However, the need to replace AHD will doubtless require deep consideration in order to produce very strong and compelling reasons."

These sentiments are just as true today, and his crystal-ball wisdom about the debate the profession will soon begin regarding AHD and AVWS is visionary. A testimony to its true quality and immense expense, AHD has long outlasted its horizontal datum counterparts (i.e. AGD66, AGD84, GDA94), and it is unlikely that GDA2020 will still be operating in another 50 years. Acknowledging that there can be only one legal vertical datum, it remains to be seen what the future holds for legal heights in NSW and Australia.

While DCS Spatial Services does not expressly advocate or legislate adoption of AVWS at this time (currently it is neither implemented nor supported in SCIMS), it is collecting and maintaining new ellipsoidal height datasets with the aim to investigate and contribute to future applications of AVWS.

> The successful uptake of any alternative height surface(s), such as AVWS, will be decided by its users and their clients. They will soon play a key role in deciding the future of AHD and whether it will be able to celebrate its 75th or maybe even its 100th anniversary

Conclusion

AHD remains Australia's first and only legal vertical datum and is still deemed fit for purpose for most applications. This paper has celebrated the golden jubilee of AHD along with its achievements and longevity, outlined its shortcomings and looked ahead to a new era of vertical datum determination based on GNSS and airborne gravimetry. AHD has been a stalwart of Australian surveying, replacing a collection of various local vertical datums and the then 80-year old Standard Datum, and successfully satisfied users ranging from mums and dads to engineers and geodesists for 50 years.

It has been the only vertical datum for most surveyors during their professional careers. That some should raise an eyebrow at even the thought of changing it, is quite understandable. But it is, like some of us, showing its age and deteriorating, despite the best efforts to maintain it. As the sun has set on the age of long level runs across towns, cities, shires, states and the nation, users want physical heights delivered at the push of a button, anywhere and anytime. Positioning tools and sensors now collect data over larger and larger swaths, at increased precisions, and local distortions in the fundamental datum can no longer be tolerated.

There can be only one legal vertical datum, and currently there is no planned push to replace AHD. DCS Spatial Services has yet to implement AVWS but continues to investigate and contribute towards it. The successful uptake of any alternative height surface(s), such as AVWS, will be decided by its users and their clients. They will soon play a key role in deciding the future of AHD and whether it will be able to celebrate its 75th or maybe even its 100th anniversary.

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Alexander's wholeness as the scientific foundation of sustainable urban design and planning

This paper is attempted to argue for the wholeness as the scientific foundation of sustainable urban design and planning, with the help of the mathematical model and topological representation

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"... there is such a thing as living structure, and there is an objective distinction between systems which have relatively more living structure and systems which have relatively less living structure."

Christopher Alexander (2002–2005, Book 2, p. xvi)

As Christopher Alexander conceived and defined through his life's work – *The Nature of Order* – wholeness is a recursive structure that recurs in space and matter and is reflected in human minds and cognition. Based on the definition of wholeness, a mathematical model of wholeness, together with its topological representation, has been developed, and it is able to address not only why a structure is beautiful, but also how much beauty the structure has. Given the circumstance, this paper is attempted to argue for the wholeness as the scientific foundation of sustainable urban design and planning, with the help of the mathematical model and topological representation. We start by introducing the wholeness as a mathematical structure of physical space that pervasively exists in our surroundings, along with two fundamental laws – scaling law and Tobler's law – that underlie the 15 properties for characterizing and making living structures. We argue that urban design and planning can be considered to be wholeness-extending processes, guided by two design principles of differentiation and adaptation, to transform a space – in a piecemeal fashion – into a living or more living structure. We further discuss several other urban design theories and how they can be justified by and placed within the theory of wholeness. With the wholeness as the scientific foundation, urban design can turn into a rigorous science with creation of living structures as the primary aim.

1. Introduction

Modernist urban design, as well as modernist architecture, has been repeatedly criticized for lacking a robust scientific underpinning of its own. City rebuilding and planning are based on *"a foundation of nonsense"* (Jacobs 1961, p. 13), and their theories have been accused of being pseudoscientific (e.g. Cuthbert 2007, Marshall 2012). This situation constitutes one of the motivations of the present paper. However, there is a major difference between the 1960s and the 21st century, when a new scientific foundation for architecture and design was laid out by Alexander (2002–2005), although the mainstream architecture and urban design has yet to adopt the fundamental design thinking. This new scientific foundation is built on the concept of wholeness. The wholeness differs from the concept of wholeness as conceived in biology (Goldstein 1939, 1995), in Gestalt psychology (Köhler 1947), and in a variety of religious and therapeutic contexts, because it is mathematically defined as a recursive structure, recurring physically in space and matter, and can be reflected psychologically in human minds and cognition (Alexander

2002–2005; c.f. Section 2 for more details). In this connection, it is very much like wholeness in quantum physics as defined by Bohm (1980).

The wholeness was conceived, developed, and further refined during the 27 years between 1975 and 2002, and finally presented through his magnum opus entitled *The Nature of Order*, a four-volume book focusing on the art of building and the nature of the universe (Alexander 2002–2005). Although wholeness exists pervasively in our surroundings – artifacts, ornaments, rooms, buildings, gardens, streets, cities, and even the entire Earth's surface – it is rather obscure, not so obvious to be seen. Because of this obscure nature of wholeness, Alexander (2002–2005) used hundreds of pictures, paintings, and drawings to illustrate the deep structure of wholeness. As he admitted, there was no mathematics at that time that was powerful enough to capture the wholeness of space. A mathematical model of wholeness has since been developed that it is able to address not only why a structure is beautiful, but also how much beauty the structure is (Jiang 2015). This situation constitutes another major motivation and catalyst of the present paper. The mathematical model is based on a topological representation of wholeness e.g., topology of streets as well as that of cities (Jiang 2018). The topology refers to the topological relationship among geometrically coherent entities rather than geometric primitives of points, lines, polygons, and pixels.

Under the new circumstance, this paper is intended to advocate the wholeness as the scientific foundation of sustainable urban design and planning. The wholeness or living structure, which can be pervasively seen in traditional cities or traditional societies in general (Alexander 2002–2005, Hakim 2009), should become a shared notion of quality of what architects and urban designers are collectively aiming for. With the living structure as the shared notion of quality, the goodness of buildings and cities is considered to be a matter of fact – rather than opinions or personal preferences as currently conceived – and the successes and deficiencies of buildings and cities can be judged objectively or structurally. Although this sounds radical, it is indeed what Alexander (2002–2005) has been advocating and fighting for throughout his entire career (Alexander et al. 2012).

The contribution of this paper is three-fold. First, our argument is based on the newly developed mathematical model of wholeness and its topological representation. Through the model, the concept of wholeness – or Alexander's design philosophy – becomes more accessible thus less obscure to urban design and planning professionals, as well as to other researchers. Second, we argue that living structure is governed by two fundamental laws – scaling law and Tobler's law – that are also what underlies the 15 structural properties (Appendix A), which further serve as transformational properties to transform a space to a living structure. Third, we illustrate that urban design and planning are considered to be wholeness-extending processes through two design principles of differentiation and adaptation, and further discuss on how other urban design theories can be justified and placed within the theory of wholeness, thus wholeness being really a larger theory.

The remainder of this paper is structured as follows. Section 2 introduces the concept of wholeness and two fundamental laws – scaling law and Tobler's law – that govern the deep structure of wholeness. Section 3 presents the mathematical model of wholeness, which is well supported by the topological representation of wholeness, capturing two spatial properties: "far more smalls than larges" (scaling law or spatial heterogeneity) on the one hand, and "more or less similar" (Tobler's law or spatial dependence) on the other. By focusing on how to generate a living structure for a design purpose, Section 4 discusses two design principles – differentiation and adaptation – that are in line with the two fundamental laws of wholeness. Section 5 examines how classic urban theories can be placed within the theory of wholeness in order to further argue why the wholeness can serve as the scientific foundation of sustainable urban design and planning. Finally, Section 6 concludes the paper and points to future work.

2. The wholeness and its two fundamental laws: Scaling law and Tobler's law

The wholeness is defined as a recursive structure that recurs in space at different levels of scale; the wholeness is *"a real structure", "nearly a substance",* not just *"a general appreciation for the unity"* (Alexander 2002–2005, Volume 4, p. 319). The wholeness is made of "far more low-intensity centers than high-intensity ones". The centers are geometrically coherent entities in that space, and they can only be defined by other centers – centers are made of other centers reflexively or recursively. This is somehow like the situation of fax machines. A single fax machine is useless and it has to rely on the other fax machines for its usefulness; the more other fax machines there are, the more useful the fax machine is. All centers at different levels of scale tend to nest or overlap each other to form a complex whole. The intensity of the centers in that space is actually their degree of coherence or life or beauty, which is another name of wholeness (Alexander 2002–2005). In other words, life or beauty or coherence is a quality of space – *"what we perceive as the quality of buildings and artifacts"* (Alexander 2002–2005, Volume 1, p. 110) – that comes about because of the wholeness. A structure with a high degree of wholeness is called a living structure, while a structure with a low degree of wholeness is called a dead or nonliving structure.

Space is neither lifeless nor neutral, but is a living structure – like a growing plant – that is capable of being more living or less living. This new view of space, as conceived by Alexander (2002–2005), represents a paradigm shift from Newtonian and Leibnizian views of space, which are framed under the mechanistic world picture of Descartes (1637, 1954). In contrast, the new view of space is

We argue that urban design and planning can be considered to be wholeness-extending processes, guided by two design principles of differentiation and adaptation, to transform a space – in a piecemeal fashion – into a living or more living structure.

framed under a modified picture of the universe – Alexandrine organic world picture. Under the organic world picture, Alexander (2002–2005, Volume 1, p. 4) made two bold claims: (1) *"all space and matter, organic or inorganic, has some degree of life in it, and that matter/space is more alive or less alive according to its structure and arrangement"*, and (2) *"all matter/space has some degree of "self" in it, and that this self, or anyway some aspect of the personal, is something which infuses all matter/space."* Either of these two claims would radically change our picture of the universe from the mechanistical one to the personal one.

The mechanistic world view makes good architecture virtually impossible because of the lack of a universal standard about the goodness of architecture. As Alexander remarked (2002–2005, Volume 1, p. 16), "*The picture of the world we have from physics, because it is built only out of mental machines, no longer has any definite feeling of value in it; value has become sidelined as a matter of opinion, not intrinsic to the nature of the world at all*". A good building is therefore conventionally considered to be an opinion or personal preferences. This view about goodness of building is very bad for urban design and architecture, because under the view it is virtually impossible to make great buildings or cities. In this respect, the wholeness or living structure provides a universal standard or a shared criterion for the goodness of buildings, cities, or artifacts.

Beauty or life or coherence is essentially structural, not merely an impression or cognition. To illustrate, Figure 1 illustrates some structures with different degrees of wholeness. For example, compared to the two rectangles, the one with a tiny dot has a higher degree of wholeness than the empty one. This is because the rectangle with a tiny dot is able to induce about 20 centers, among which the "far more low-intensity (or life) centers than high-intensity ones" constitute a complex network (Jiang 2015, p. 479–480, Alexander 2002–2005, Volume 1, p. 81–82). In comparison with the empty rectangle and the ellipse, the reader might prefer the ellipse to the rectangle. However, structurally speaking, or as a matter of fact, the empty rectangle has a high degree of wholeness than the ellipse. Why? The empty rectangle has five centers – the rectangle itself and its four corners – whereas the ellipse is able to induce no other center, except for the ellipse itself as the only center. More importantly, the degree of wholeness of a structure is assessed not only in terms of things within it, but also in terms of things surrounding it. The ellipse is not well shaped in terms of its surrounding, since it induces concave rather than convex space. This is the same for the circle, when compared with the square in the second row. This is the reason why the square column is usually more coherent than the round column (Alexander 2002–2005, Volume 1, p. 129). Having argued that both ellipse and circle are not well shaped, we are not suggesting that ellipses or circles should not be used in buildings.

Instead, our point is that if the ellipse and circle are used, there should be some measure to avoid concave space at their surroundings, so that the part of space in the surroundings still looks convex rather than concave. The octagon has a higher degree of wholeness than the square, because the former is more differentiated than the latter. This is the exact reason why the columns with the octagonal chamfer are more coherent than the square columns (Alexander 2002–2005, Volume 1, p. 113). If the circle and the ellipse are transformed to the decagon and the 10-sided polygon

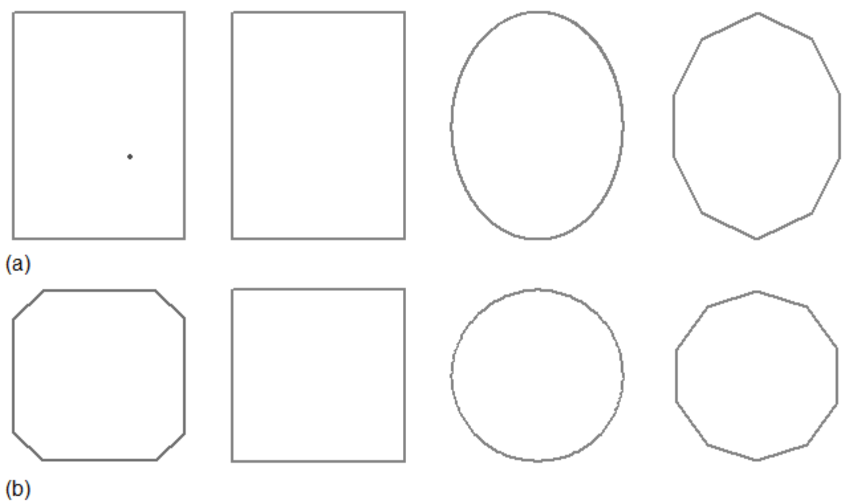

Figure 1: Illustration of physical and mathematical nature of wholeness. (Note: For the first three columns, the degree of life or wholeness in each row of (a) and (b) decreases from left to right. The reason why the ellipse and the circle have the lowest degree of life concerns their surroundings that are not well-shaped, concave rather than convex. If both the ellipse and circles became polygons while still retaining the overall shapes, the effect will be dramatically different – their degree of life will become far more than the corresponding rectangle and square.)

Table 1: Comparison between scaling law and Tobler's law
(Note: These two laws complement each other and recur at different levels of scale in living structure.)

Scaling law	Tobler's law
far more small things than large ones	more or less similar things
across all scales	available on one scale
without an average scale (Pareto distribution)	with an average scale (Gauss distribution)
long tailed	short tailed
interdependence or spatial heterogeneity	spatial dependence or homogeneity
disproportion (80/20)	proportion (50/50)
complexity	simplicity
non-equilibrium	equilibrium

in the fourth column of Figure 1, their degree of wholeness would be improved significantly. This is a very powerful and subtle way of making and intensifying centers, similar to the flutes of the columns in the Temple of Hera at Paestum (Alexander 2002–2005, Volume 1, p. 131–132). As a general rule, more coherent centers tend to lead to a living structure, given that these centers are adapted to each other. For example, the decagon is more alive than the circle because the former tends to induce more centers.

A living structure possesses many, if not all, of the structural properties (Appendix A), so the degree of wholeness of a structure can be judged in terms of how many properties it has. Usually, the more these structural properties, the higher degree of wholeness, meaning more alive or more beautiful or more coherent something is. In many cases, one can simply count the number of local symmetries to determine which of the two structures has a higher degree of wholeness. Underlying the 15 properties are two fundamental laws – scaling law and Tobler's law (1970) – that well complement each other (Table 1, Jiang 2018b) for better understanding and accounting for living structure in our surroundings. Scaling law states that there are "far more small centers than large ones" across all scales ranging from the smallest to the largest. The very first property, *"levels of scale"*, essentially reflects the scaling law. For example, there are "far more low buildings than high ones", and further there are "far more short streets than long ones" in it. Salingaros and West (1999) formulated a universal rule for the distribution of sizes. This universal rule is essentially based on power laws, but scaling law could imply power laws, lognormal, exponential functions or even skewed normal distributions. Tobler's law is widely known as the first law of geography, indicating that nearby centers tend to be "more or less similar". Many of the 15 properties reflect Tobler's law, such as, alternating repetition, local symmetries (at a same scale rather than different scales), deep interlock and ambiguity, contrast, gradients, and simplicity and inner calm; see Appendix A for more details. The 15 properties are often shown in various living structures, yet they should not be followed literally, and they are an outcome rather than a recipe.

The wholeness is not only physical, but also psychological, reflected in our minds and cognition. Due to this cognitive nature of wholeness, we can rely on the human observer as a measuring instrument to objectively judge the degree of life or beauty. Two structures are put side by side and the subject is requested to pick the one that better represents himself. This is the so-called mirror-of-the-self experiment (Alexander 2002–2005, Volume 1, p. 314–350, Wu 2015, Rofé 2016). Although engaging with the human observer, the purpose of the mirror-of-the-self experiment is *not* to seek inter-subjective agreements like ordinary psychological or cognitive tests, but to seek the objective existence of the wholeness. Guided by the 15 properties or tested through the mirror-of-the-self experiment, we can objectively –yet relatively just as we evaluate temperature for warmness – judge the degree of beauty of a pair of structures. The feeling of wholeness is objective, thus invariant among people across different faiths, ethics, and cultures; *"Ninety percent of our feelings is stuff in which we are all the same and we feel the same things"* (Alexander 2002–2005, Volume 1, p. 4). This ninety percentage should not be understood literally, but rather metaphorically, indicating a majority rather than a minority. In addition to the mirror-of-the-self experiment, we can also determine the degree of wholeness, through the mathematical model of wholeness (Jiang 2015). Through the model, we are able to give an accurate account of why a structure is beautiful and how beautiful it is. This is achieved firstly through a topological representation of the wholeness (e.g. Jiang 2018a), and then by using Google's PageRank scores (Page and Brin 1998) and the ht-index (Jiang and Yin 2014) to characterize the beauty of individual centers and the whole. The topological representation of cities as a coherent whole (Jiang 2018a) reflects both scaling law – at the global scale or across all scales – and Tobler's law at each of these scales.

3. A mathematical model of wholeness

The wholeness is made of recursively defined centers, which further constitute a topological structure of relationship of these centers. Based on the topological representation of numerous nested and overlapped centers and their relationships, the mathematical model of wholeness is able to compute the degree of life or beauty for individual coherent centers, as well as for that of the whole. To illustrate, we use a simple mandala as a working example (Figure 2). As shown in Figure 2a, there are many centers – more precisely, "far more small centers than large ones" – and, importantly, small centers are embedded in large ones. We can see many of the 15 structural properties, such as *"levels of scale"*, *"strong centers"*, and *"thick boundaries"*, so there is little doubt that this is a living structure. Figure 2b shows the topological representation of these centers. Note that the node locations of the topological representation in Figure 2b have no effect on computing the degree of wholeness.

The topological representation of these centers is a de facto complex network (Jiang 2015), on which Google's PageRank scores (Page and Brin 1998) are used to indicate the degree of wholeness for individual centers. The degree of wholeness or life or beauty is represented by node sizes: the larger the nodes, the higher the degree. For all of the centers as a whole, there are obviously "far more low-intensity centers than high-intensity ones". The extent to which there are "far more smalls than larges" indicates the degree of wholeness of the whole, and it is measured by the ht-index, a head/tail-breaks-induced index for measuring the complexity or scaling hierarchy of a structure or pattern (Jiang and Yin 2014). The degree of beauty for the mandala as a whole is 5, indicating that the scaling of "far more low-intensity centers than high-intensity ones" recurs four times.

The topological representation of wholeness is a graph theoretic representation of centers, rather than an ordinary graph representation among geometric primitives of points, lines, polygons, and pixels (Bian 2007, Longley et al. 2015), for these geometric primitives are not coherent wholes or centers. Current representations of space in mathematics and physics and geography (including geographic information science as well) reflect essentially local scales; *"It is precisely this assumption about space which is being challenged by the idea of the field of centers"* (Alexander 2002–2005, Volume 1, p. 460). In terms of Alexander (2002–2005, Volume 1, p. 458–459), *"The extraordinary thing does not lie in the 'system' of these centers, not in the fact that they cooperate to form a system. ... What is extraordinary here is something else. ... The life of any given center depends on the whole field of centers in which this center exists. This means that the most fundamental property of each center – its degree of life – is defined not by the center itself but by its position in the entire field of centers. ... This is the thing which is peculiar. It is a type of behavior which is not typical of Newtonian space at all. Indeed, it is a type of behavior which is also not typical of relative space, nor even of quantum mechanical space. ... Thus the intensity of a center can never be understood as a local property of that center itself, merely in terms of its own local structure. ... This is the essence of the recursive definition of a center."*

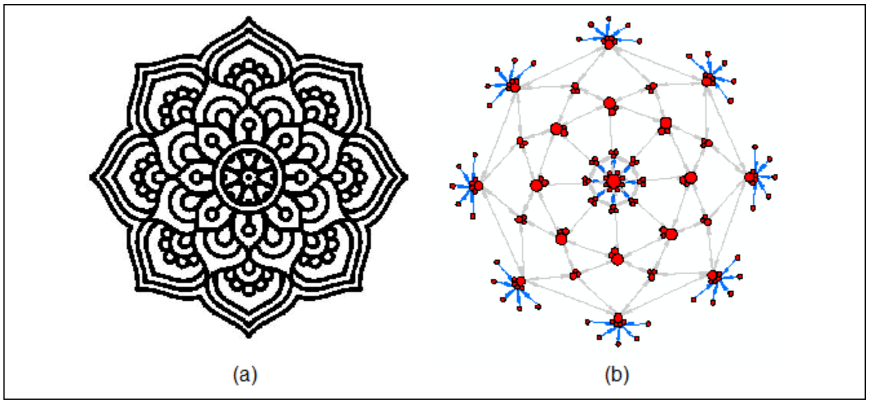

Figure 2: (Color online) A simple mandala (a) and its topological structure of wholeness (b) (Note: The structure of wholeness is essentially topological (b) and it captures the overall character of the mandala, whereas the mandala has geometric details of locations, sizes, shapes, and directions (a). With the topological representation to the right, the node locations have no meaning at all, and only relationship matters. There are two kinds of relationship, indicated by two colors: gray for an undirected relationship and blue for a directed relationship. The node sizes indicate the degree of wholeness or life or beauty or coherence.)

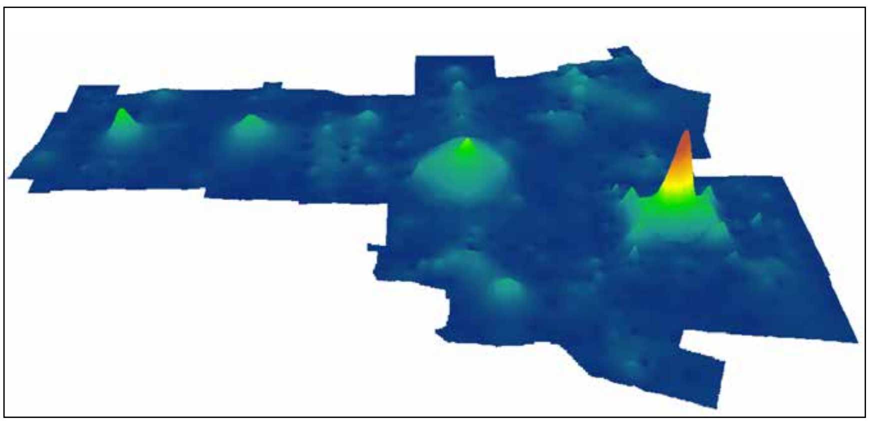

Figure 3: (Color online) The field of centers of the Alhambra plan (Note: The field or surface of centers was interpolated from the degrees of life of the individual centers, calculated from the mathematical model of wholeness (Jiang 2015). The spectral colors show the degree of life with red for the highest, blue for the lowest, and other colors for those between the highest and the lowest.)

It is not easy to identify centers from a whole and they must be in line with our cognition. In a city, street segments are not centers since they are not congruent with our cognition, but individual streets generated from the street segments can be considered to be coherent centers. In a city image, individual pixels are not centers, but individual meaningful places are centers, since they tend to meet both scaling law and Tobler's law. There are "far more small cities than large ones" recurring at the country scale, so all cities in a country constitute a coherent whole (Jiang 2018a). This topological representation of cities can be considered to be the randomized or statistical model of central place theory (CPT) (Christaller 1933, 1961); see Section

5 and Figure 5 for further details. Just like a city or country, the entire Earth's surface is a living structure, since there are "far more small countries than large ones" recurring at the global scale.

The mathematical model of wholeness implies a new mathematical structure of space, in which the intensity or life of a center is a global effect rather than a local effect. The global effect implies that every center can – through the underlying structure of wholeness – affect other centers that are not nearby. As an example, the living structure or wholeness of the Alhambra plan is a field of centers (Figure 3), in which the intensity is a global effect. Changing one local part would likely affect all other centers in the space, and even beyond towards a larger whole that contains the space. This global effect reflects in both the topological representation and the way in which the intensity or life is calculated.

4. Wholeness-extending process: Differentiation and adaptation

Having discussed the physical and mathematical nature of the wholeness, as well as its reflections in our minds and hearts, urban design is essentially concerned with how to create the kind of structure in our built environment. When they are used to generate living structure or wholeness, the 15 properties (Appendix A) become transformation properties. All the 15 transformation properties can be summarized by two design principles – differentiation and adaptation – through which a space or structure is recursively differentiated to induce many nested and overlapped centers that are well adapted to each other to be a coherent whole. In Figure 1, the tiny dot is able to differentiate that paper, and induce about 20 centers (Alexander 2002–2005), and eventually to create a more coherent whole than that of a blank paper. In the same way, the decagon and the 10-sided ellipse shape are able to create more centers than their counterparts of the circle and the ellipse. Therefore, this process is also called the centering process, or structure-preserving process. Throughout the four volumes, in particular Volume 2 entitled *"The Process of Creating Life"* and Volume 3 entitled *"A Vision of a Living World"*, Alexander (2002–2005) provided hundreds of practical examples on how to generate– in a piecemeal fashion – living structures at different levels of scale of built environment. In particular, the column example provides a step-by-step recursive process for transforming a simple cylinder into a living column (Alexander 2002–2005, Volume 1, p. 128–130, Figure 4).

Let us use 10 numbers that follow exactly Zipf's law (1949): 1, 1/2, 1/3, …, and 1/10 as a working example to further illustrate two design principles or underlying the wholeness-extending transformations. The 10 numbers meet the scaling law statistically or the transformation property of *"levels of scale"*. Why? The mean of the 10 numbers is 0.29, which partitions the 10 numbers into two parts: the first three, as the head (accounting for 30%), are greater than the mean, and the remaining seven (70%) as the tail are less than the mean. For the three numbers in the head, their mean is 0.61. This mean further partitions the three numbers into two parts: 1 (33%) as the head is greater than the mean 0.61, and 1/2, and 1/3 (67%) as the tail are less than the mean. As seen from the above head/tail breaks process (See below the recursive function, Jiang 2013a), the notion of "far more smalls than larges" recurs twice, so there are three hierarchical levels among the 10 numbers: [1], [1/2, 1/3], [1/4, 1/5, …, 1/10].

Recursive function of head/tail breaks

```
Function Head/tail Breaks:
     Rank the input data from the largest to the smallest
     Break the data around the mean into the head and the tail;
     // the head for those above the mean
     // the tail for those below the mean
     While (length(head)/length(data)<=40%):
         Head/tail Breaks (head);
End Function
```

What we wanted to do is to locate these ten numbers – in a step by step fashion – in a square space to constitute a coherent whole. As shown in Figure 5 (first row a), we first put the largest number in the middle of square, and then two middle ones near the largest, and finally the remaining seven smallest. This is one of the coherent wholes for the 10 numbers in the space using the two design principles. On the one hand, the square is recursively differentiated: first two parts by the green line, and later seven parts by blue lines, with "far more smalls than larges" across the three scales. On the other hand, the induced centers, or the partitioned parts, are well adapted to each other with "more or less similar" at each scale, thus meeting Tobler's law. In comparison, we created another pattern shown in Figure 4 (second row b). The scaling law remains unchanged for it is determined by the same 10 numbers. However, the induced centers of the second pattern at the smallest scale are not well adapted to each other, thus violating Tobler's law to some extent, as can be seen from the partitions by the blue lines. More importantly, across the middle and smallest scales,

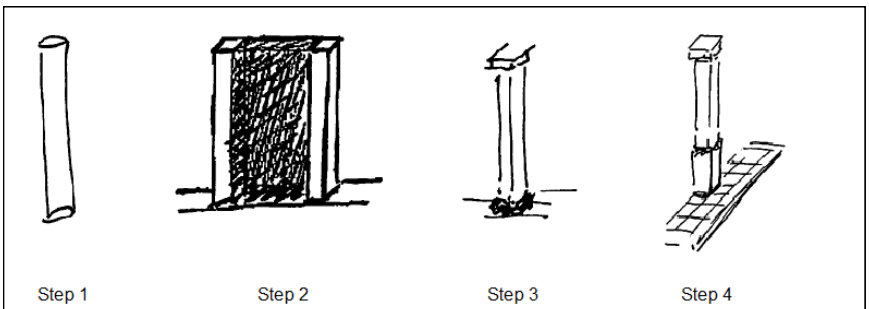

Figure 4: A cylinder is transformed – in a step by step recursive fashion – into a living column

centers are not well adapted to each other; the left green contains six blue points, whereas the right green contains only one blue point. Therefore, the second pattern – by violating Tobler's law – is apparently less coherent or less beautiful or with less life than the first. This coherence difference between the two patterns or structures is partially reflected in the calculated degrees of beauty shown in the last column of Figure 5, where the largest dot in row a is apparently a bit larger than the largest dot in row b.

What was just discussed is, of course, a very simple example, which relies on topological representation for illustrating different configurations. Actual architectural and urban design is far more complicated than this example, but the underlying design principles of differentiation and adaptation remain the same; more specifically, the 15 transformation properties (Appendix A) remain the powerful means to reach a living structure. The wholeness-extending process is the only way to create living structures. Based on the wholeness theory, urban design should be considered to be a piecemeal and iterative growth process; every transformation is based on what exists, identifying latent centers and further extending or enhancing these centers to be more living.

Relying on human feeling or the feeling of wholeness, right decisions, at each iteration, can be made to ensure that the degree of wholeness is increased rather than decreased. With the help of the mathematical model of wholeness, computer algorithms can be developed to guide the generation of living structures. Urban design is the process of continuously generating living centers: "far more small centers than large ones", with "more or less similar centers" nearby through differentiation and adaptation. This wholeness based urban design *"is different, entirely, from the one known today"*, and *"the task of creating wholeness in the city can only be dealt with as a process"* (Alexander 1987, p. 3). The 15 transformation properties (Appendix A) provide not only clues or hints, but also effective means for urban design processes.

Many efforts have been made to advocate the wholeness-oriented transformations for sustainable urban design. Salingaros (2012, 2013) developed 12 lectures on architecture for algorithmic sustainable design, and a unified architectural theory for transforming our built environment for the better through adaptive and sustainable design. Mehaffy and Salingaros (2015) explored many complexity science ideas, such as fractals and complex networks, which have close links to the wholeness for designing a living planet. Importantly, fractal or living structure is found to have a healing effect for human health and well-being (Ulrich 1984, Taylor 2006, Salingaros 2012b). The wholeness constitutes some key conceptual insights for the new urban renaissance for making or re-making better built environments (Mehaffy 2017, Salingaros 2019). The wholeness-oriented making or design is not just a vision, but a mission that many of urban designers are aiming for. Based on the legacy of Alexander and his life-long pursuit of beauty (Salingaros 2018), the Building Beauty program (https://buildingbeauty.org/) has started this mission in educating the next generation of architects and urban design professionals. All of these efforts will hopefully transform urban design towards a well-respected discipline – design science.

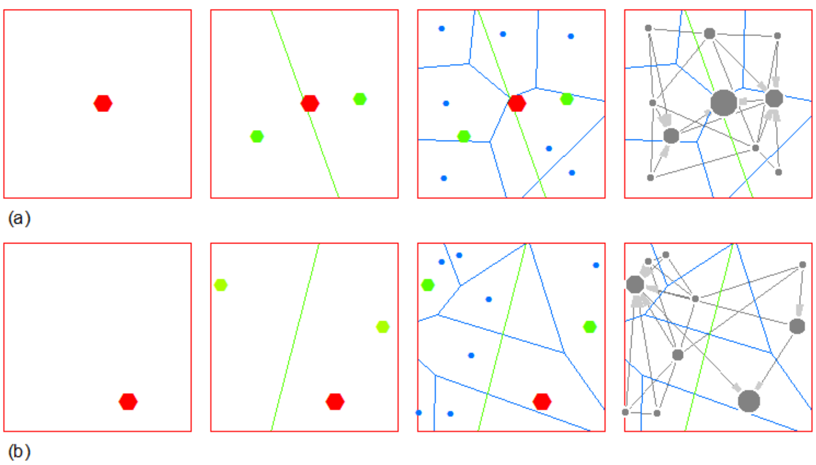

Figure 5: (Color online) Unfolding of two different configurations (Note: There are 10 cities with sizes that follow Zipf's law exactly: 1, 1/2, 1/3, ..., and 1/10. The first three panels from the left indicate how the two structures are unfolded or transformed. Statistically, both structures are living structures, since they contain "far more smalls than larges". However, geometrically – or topologically, to be more precise – the pattern of the second row (b) is less coherent or less beautiful than that of the first row (a). This fact can be seen from several aspects: (1) the largest red dot in row (b) is far from the center, so it tends to detract rather than to reinforce the whole; (2) the two green dots are not well located as these two in row (a), so detract rather than reinforce the two green sub-wholes; (3) at the lowest hierarchy, or the blue Thiessen polygons in row (b), look too diverse rather than "more or less similar" as in row (a), so violating Tobler's law; and (4) the two lowest hierarchical levels are not well adapted: six blue dots under the left green dot's polygon, while only one blue dot under the right green dot's polygon.)

5. The wholeness accounting for other urban design related theories

The wholeness serves as the scientific foundation for sustainable urban design and planning because it reveals not only the nature of beauty: being objective and structural, but also the nature of space: neither lifeless nor neutral, but a living structure. More importantly, it can be used to account for many other urban design and planning theories such as the image of the city (Lynch 1960), space syntax (Hillier and Hanson 1984), the city as an organized complexity (Jacobs 1961), and the CPT (Christaller 1933, 1966). Strictly speaking, none of these theories really focuses on urban design and planning. Instead, they concentrate largely on understanding the complexity of cities, rather than on making or re-making cities. This is the same for fractal geometry. Fractal geometry is mainly for understanding complexity of fractals rather than for making fractals, even with limited making, often resulting in fractals of "*pretty, yet pretty useless*" (Mandelbrot 1983); fractal geometry is unable to quantify goodness of fractals. In contrast, living geometry – another name of the wholeness theory – aims not only for understanding complexity, but also for actively creating complex or living structure; living geometry *"follows the rules, constraints, and contingent conditions that are, inevitably, encountered in the real world"* (Alexander et al. 2012, p. 395). This section will further discuss on wholeness and its relationship to the other urban design related theories.

Why the image of the city can be formed in our minds and hearts has little to do with who we are or what gender or ethnic background we have; it is primarily to do with the underlying living structure of "far more smalls than larges". The largest in the top head constitutes the image of the city (Jiang 2013b). The largest refers to not only largest sizes, but also the most connected, or the most meaningful. In other words, the living structure of "far more smalls than larges" can be in terms of geometric sizes, topological relationships, or semantic meaning. For example, a place that does not have the highest buildings or the most connected streets constitutes part of the mental image of the city because it bears the most meaning for a person. Given this new interpretation, it is not so much about geometric or visual shapes, so called the city elements including nodes, paths, edges, districts, and landmarks (Lynch 1960). Among the five city elements, only landmarks make good sense for the image of the city, and other four are irrelevant (Jiang 2013b). In this connection, I would like to refer to this statement again: *"Ninety percent of our feelings is stuff in which we are all the same and we feel the same things"* (Alexander 2002–2005, Volume 1, p. 4). While individuals do have their own image of the city, but that accounts for only ten percent of feelings. Recently, Shushan et al. (2016) bring further empirical evidence for what we discuss here by using virtual environments to verify the image of the city in both heterogeneous and homogenous environments, which represent respectively living and dead structures.

Space syntax is a theory developed by Hillier and Hanson (1984) for urban morphological analysis using graph theoretic representations. The fundamental idea of space syntax is that a space is too big or too complex to be well perceived entirely, so it is partitioned into many small-scale spaces that can be perceived entirely or from a single vantage point of view. All the small-scale spaces constitute an interconnected whole represented by a graph. There are different representations of space, which can be put into two major categories: geometric and topological. The major difference between the two representations lies on whether they capture the underlying living structure of "far more small centers than large ones": topological representation can, while geometric representation cannot. The topological representation is among meaningful geographic features such as streets and cities (Jiang 2018a, 2018b), while the geometric representation is among meaningless geometric primitives of points, lines, or polygons. For example, a city can be topologically represented as an interconnected whole consisting of "far more less-connected streets than well-connected ones". A city can also be topologically represented by axial lines – a so-called axial map – which is not as good as the streets in terms of capturing the underlying living structure. From the perspective of wholeness, a spatial representation that captures the underlying wholeness tends to have high prediction rate for human activities or urban traffic. Geometric representations are unable to capture the living structure because they concentrate on geometric primitives of points, lines, or polygons, each of which makes little sense in our minds and hearts.

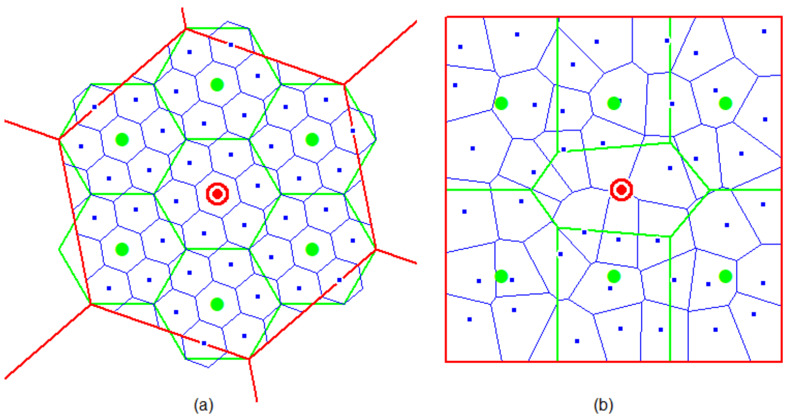

Figure 6: (Color online) A diagram of the classic CPT (a) and its statistical counterpart (b) (Note: The major difference between the classic CPT (a) and its statistical counterpart (b) is that in the former, every city is supported by exactly other six cities, while in the latter, the number of supporting cities vary from one to another. The diagram to the left is the case of k = 7 (Christaller 1933, 1961), in which there three hierarchical levels indicated by three colors with red being the highest, blue the lowest, and green between the highest and the lowest. The randomized or statistical counterpart to the right (b) is a topological representation of wholeness. Given the set of city locations, the city sizes have three hierarchical levels indicated by three colors, which are derived using head/tail breaks (Jiang 2013a). At each hierarchical level, space is differentiated by individual cities and represented by Thiessen polygons. For more details on the topological model, one can refer to Jiang (2018a).)

What was just discussed is, of course, a very simple example, which relies on topological representation for illustrating different configurations. Actual architectural and urban design is far more complicated than this example, but the underlying design principles of differentiation and adaptation remain the same; more specifically, the 15 transformation properties (Appendix A) remain the powerful means to reach a living structure

A city is essentially the problem of organized complexity, as Jacobs (1961) claimed in the classic work *The Death and Life of Great American Cities*. This complexity science perspective on cities helps better understand not only how a city looks, but also how a city works. For example, a city is not a tree (Alexander 1965), but a semilattice, which exhibits scaling hierarchy of "far more smalls than larges"; a city is self-organized with emergences developed from the bottom up. The understanding of cities from the complexity science perspectives helps in planning and designing cities to become living structures. However, the generative science, including *A New of Kind of Science* (Wolfram 2003), is largely limited to the understanding of complexity, and hardly touches the fundamental issue of making or design of living structure (Simon 1962). Critically, science as it is currently conceived lacks a standard or criterion about goodness of structure, being judged as opinions and individual preferences; therefore, it is no wonder that urban design – or geography in general – has always been a minor science. Urban designers and researchers try to apply ideas of major sciences such as physics, biology, and computer science in order to make their work seemingly "scientific". If the wholeness were adopted as the scientific foundation, and if space were properly understood as a living structure, urban design and planning – or geography in general – would *"play a revolutionary role in the way we see the world … and will perhaps play the role for the world view of the 21st and 22nd centuries, that physics has played in shaping the world view of the 19th and 20th"* (Alexander 1983, cited in Grabow 1983, p. xi); see Volume 4 of Alexander (2002–2005) for detailed arguments on the modified world view that is organic in essence.

CPT is a geographic theory that seeks to account for spatial configuration of cities (or human settlements in general) in terms of their numbers, sizes, and locations in a region or country (Christaller 1933, 1966, Chen and Zhou 2006, Jiang 2018a, 2018b). This spatial configuration is essentially a structure of wholeness of different sized cities at different hierarchical levels, and governed by two fundamental laws of living structure: scaling law and Tobler's law. On the one hand, there are "far more small cities than large ones" across all scales ranging from the smallest to the largest; on the other hand, there are "more or less similar sized cities" on each scale. Both laws complement each other to characterize all the cities as a coherent whole (Jiang 2018a). However, like many other classic fractals such as the Koch (1904) curve and the Sierpinski (1915) carpet, the classic CPT is too restricted – thus less living – to be a useful model in reality; every city is surrounded by six other cities at a low level (Figure 6a). Instead, the topological representation of wholeness provides a realistic model – thus more living – that can be applied directly to cities, and it is a de facto randomized or statistical model of the classic CPT (Figure 6b). In other words, the topological model is to the CPT model what the coastline model – or statistical fractal in general (Mandelbrot 1967, 1983) – is to the Koch curve (Koch 1904). To this point, we can better understand that the two configurations shown in Figure 5 are actually based on the topological model, and why one is more coherent than another from the perspective of CPT.

6. Conclusion

Relying on the mathematical model and in particular the topological representation of wholeness, we have argued and demonstrated the mathematical and physical structure of wholeness, and how sustainable urban design can be viewed as the wholeness-extending processes. Wholeness is structural and objective, and pervasively exists in our surroundings, such as artifacts, ornaments, buildings, gardens, streets, and cities; and it can trigger positive feelings – life and beauty – in our minds and hearts. There are two design principles – differentiation and adaptation – that guide the wholeness-extending processes for transforming, in a recursive step-by-step manner, a space into a living or a more living structure. Both differentiation and adaptation are what underlie the 15 transformation properties (Appendix A) that were distilled from traditional and vernacular buildings, as well as from nature. In this sense, the wholeness is what Alexander discovered in nature and in traditional buildings or artifacts, rather than his invention. What also underlie the 15 structural properties (Appendix A) are two fundamental laws – scaling law and Tobler's law – respectively for characterizing living structure with "far more small centers than large ones" across all scales, and "more or less similar centers" on each scale.

As the scientific foundation of urban design, wholeness can be used to effectively justify and account for other urban design theories. The image of the city arises out of the underlying living structure of the city; in other words, a city lacking the living structure would not be able to form the mental image in human minds. Why space syntax works relies on the fact that the topological representation – rather than the geometric representation – is able to capture the underlying living structure of space. A city is essentially the problem of organized complexity (Jacobs 1961) or living structure. The classic CPT model and its variant – the topological representation – can be well justified and accounted for by wholeness. Urban design can, should, and must become part of new complexity science (Alexander 2003), which aims for not only understanding, but also for generating the complex or living structure of our built environments. Our future work will point to the development of computer algorithms for automatically generating living structure for sustainable urban design and planning.

Acknowledgement:

This paper is a reprint of the open-access journal paper (Jiang 2019). It should be noted wholeness is believed to be an ancient idea that human beings used – unconsciously or subconsciously – in design for centuries. The discovery of living structure or the formulation of the wholeness by Christopher Alexander is new, yet not so new, beginning in the 1980s. This situation can be compared to fractal thought, which is an ancient design idea used in many traditional designs across many cultures and countries, but fractal geometry was established in the 1970s. This paper was partially supported by the Swedish Research Council FORMAS through the ALEXANDER project with grant number FR-2017/0009 (2017-00824).

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Appendix A: A brief introduction to the 15 properties

The 15 properties, also called structural or transformational properties as sketched in Figure A1, are what Alexander first discovered after he developed the pattern language work, because the pattern language failed to create living buildings or cities. He thought the 15 properties must be the fundamental stuff that makes a building or city alive. Later on, he further realized that it is wholeness or living structure, or wholeness-extending process that is what underlies living environments. To make the paper self-contained, this Appendix briefly introduces the 15 properties, and associate them with two fundamental laws: scaling law and Tobler's law.

1. Levels of scale: This first property is essentially scaling law of “far more small centers than large ones”. Or

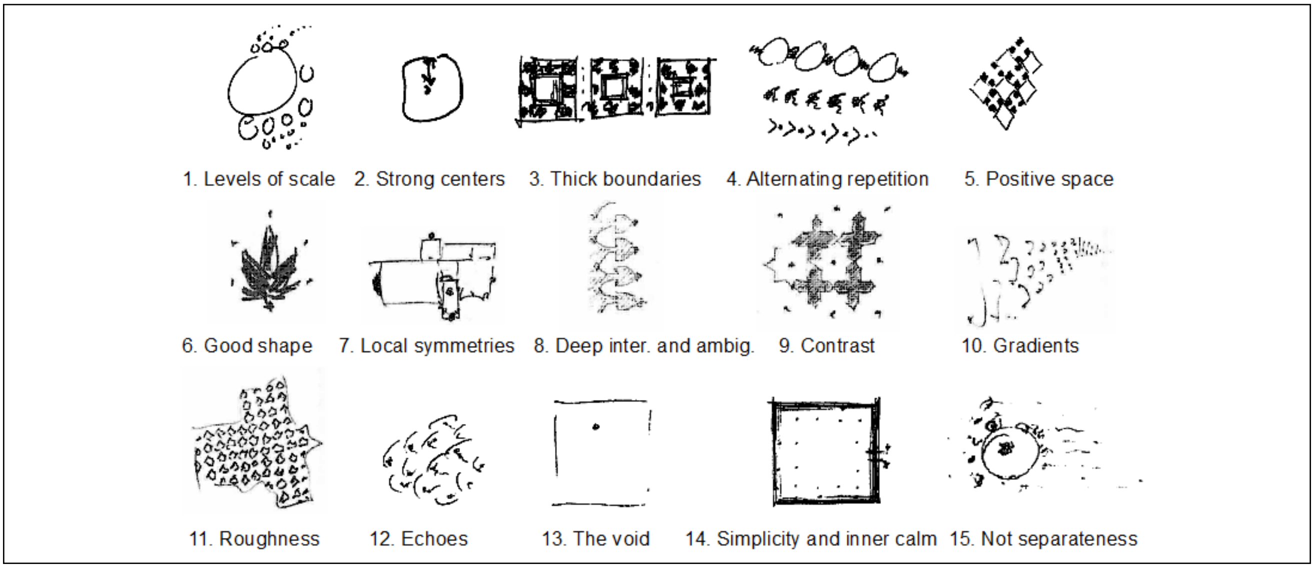

Figure A1: The 15 properties of wholeness (Alexander 2002–2005)

alternatively, all centers ranging from the smallest to the largest form a scaling hierarchy, thus meeting scaling law.

2. Strong centers: A strong center is a geometrically coherent unit or sub-whole human beings can easily identify, and it is supported by other surrounding centers. The surrounding centers tend to meet Tobler's law at each level of scale, and scaling law across different levels of scale.

3. Thick boundaries: A center often differs or separates from other centers by thick boundaries. Or a thick boundary defines a coherent center or sub-whole, which meets not only scaling law, but also Tobler's law.

4. Alternating repetition: Alternating repetition of centers tend to be more living than monotonic repetition of centers. These different or alternating centers tend to meet Tobler's law, for they are more or less similar in size.

5. Positive space: Space can be seen from both figure and ground, each of which should be well shaped, by which it means convex rather than concave. In cities, both buildings and the space between the buildings should be well shaped, somehow like a piece cloud in which both white parts and blue parts are well shaped. For a positive space that can be partitioned into many pieces, both scaling law and Tobler's law apply to these pieces.

6. Good shape: A shape is good, if it consists of good shapes. It is essentially a recursive rule for assessing good shapes. A good shape can have multiple levels of scale, thus meeting scaling law.

7. Local symmetries: Local symmetries differ from global symmetry which is defined at the global level of scale. Local symmetries refer to symmetries at smaller levels of scale. At each small level, centers are "more or less similar" – meeting Tobler's law, whereas at the global level or across scales, there are "far more small centers than large ones" – meeting scaling law.

8. Deep interlock and ambiguity: Centers interpenetrate deeply each other, forming deep interlocks, and creating ambiguity among centers. Those interlocked tend to meet Tobler's law.

9. Contrast: Contrast recurs between adjacent centers, which tend to be "more or less similar", thus meeting Tobler's law.

10. Gradients: The gradients property is a field-like character of the center, and it is better characterized by Tobler's law, since nearby centers are "more or less similar".

11. Roughness: Roughness is a key feature of fractals or living structures, yet the degree of roughness tends to meet Tobler's law on a same level, and scaling law across different levels.

12. Echoes: This property of echoes resembles very much to the self-similarity of fractals. It can occur within a sub-whole or across different sub-wholes.

13. The Void: A void is an empty center at the largest scale, surrounded by many small and smaller centers, with which the void meets scaling law.

14. Simplicity and inner calm: This property reflects "more or less similar things" – or even exactly the same things – on a scale within a living center, thus meeting Tobler's law. It should be noted that this property is on a scale rather than across all scales. When applied to all scales, it becomes minimalism. In other words, this property should be avoided at the global scale.

15. Not separateness: A center is not separable from its surrounding centers. This property has multiple meanings: e.g., centers of a living whole cannot be separated, multiple levels of scale are not separable, a whole is not separable to its larger whole, and the remaining 14 properties are hard to separate from each other. The first and the last properties are probably the most important of all.

NavVis IVION Core

NavVis, an innovator in mobile mapping and reality capture launched of NavVis IVION Core.

Previously known as NavVis IndoorViewer, NavVis IVION Core is a reality capture platform where you can manage your 3D scans with intuitive tools for creation, collaboration, and publication. NavVis IVION Core makes mobile mapping workflows more efficient, speeds up model creation and delivery, and adds value to your data. *www.navvis.com*

Bentley Systems acquires of sensemetrics and Vista Data Vision

Bentley Systems has announced its acquisitions of sensemetrics and Vista Data Vision leading providers of software for Internet of Things (IoT) applications used extensively in infrastructure. Sensemetrics and Vista Data Vision will expand the scope of the Bentley iTwin platform to add intrinsic IoT capabilities for infrastructure digital twins to incorporate real-time sensor data.

sensemetrics and Vista Data Vision are particularly complementary to Seequent, a global leader in 3D modeling software for geosciences, which Bentley recently announced its agreement to acquire, subject to regulatory approvals in New Zealand and the United States. *www.bentley.com*

GeoCalc SDK version 8.1

Blue Marble Geographics announced the immediate availability of version 8.1 of the GeoCalc® Software Development Kit (SDK). It provides developers with the advanced coordinate transformation toolkit behind Blue Marble's Geographic Calculator. The new release uses the v10.018 EPSG repository. It has added support for two newly released magnetic models, the World Magnetic Model 2020 (WMM2020) and the International Geomagnetic Reference Field 13th generation (IGRF13). *www.bluemarblegeo.com*

IDS GeoRadar announces IQMaps enhancement

IDS GeoRadar, part of Hexagon, has announced that it has enhanced IQMaps, its post-processing software application for advanced GPR data analysis. The updated version includes new functionalities that improve the visualisation of radar data and extend the application fields to void detection and archaeology. The software now allows for the simultaneous export of multiple radar maps with user defined lengths with detected features on these maps also exported in .csv format. This allows for more streamline reporting and statistical analysis. *https://idsgeoradar.com*

Jack Dangermond honored by IGU with Planet and Humanity medal

International Geographical Union (IGU) has recently awarded Jack Dangermond the Planet and Humanity Medal. The award honors individuals who have made outstanding contributions to peace, welfare, or sustainability. The IGU is an international, non-governmental, professional organization devoted to the promotion and development of the discipline of geography through initiating and coordinating research and teaching globally. This award is only given every four years and normally to leaders in the public sector or with science leadership backgrounds. Past awardees have included Al Gore, Nelson Mandela, and Mikhail Gorbachev. This year marks the first time the medal has been given to someone from the private technology sector.

Jack Dangermond founded Esri in Redlands, California in 1969, and it is now the leading GIS software company in the world. *www.esri.com*

GIS-based mapping of Microbial Diversity of river Ganga

CSIR-National Environmental Engineering Research Institute (CSIR-NEERI), Nagpur has conducted the first ever GIS-based mapping of Microbial Diversity of river Ganga, as reported by a news website. The project of mapping the entire stretch of Ganga is funded by the National Mission for Clean Ganga (NMCG), and is done by a selected team along with four other institutes, which includes Motilal Nehru National Institute of Technology (MNNIT), Allahabad, Charotar University of Science and Technology, Changa, PhiXgen Pvt Ltd, Haryana and Xcelris Labs Ltd, Ahmedaba.

The main objective of the mapping of river Ganga is to create a database which will be available for everyone on GIS and CSIR-NEERI websites. The data is open for all and can be used by government, researchers, experts and students for their work or research. The team checked BOD, COD, pH, DO, Heavy Metals parameters for water quality check. *www.csir.res.in*

xyzt.ai introduces xyzt.ai explorer

xyzt.ai a Leuven-based technology start-up offering an innovative visual analytics SaaS platform for big location data, recently launched of xyzt.ai explorer, a 30-day free trial that lets you discover its full performance at no cost.

Big Data analytics requires two components working seamlessly together: good quality data and the right tool to visualize and analyze billions of data points. Therefore xyzt.ai partnered with Spire Maritime, a leader in maritime data and start.io, a leader in mobile data, and included data samples to provide easy access to high-quality data. *www.xyzt.ai*

GeoMax introduces new X-PAD 365 service platform

GeoMax Positioning, part of Hexagon, introduces the new X-PAD 365 web-based cloud platform that addresses data management and collaboration challenges surveyors and construction professionals meet every day. The web-based platform provides online file management, allowing users to access and store data in the cloud. Users of GeoMax X-PAD Ultimate and X-PAD Fusion can share data instantaneously with their colleagues in the office or the field. *https://geomax-positioning.com*

Freestyle 2 handheld scanner for construction by FARO

FARO Technologies, Inc., recently released the Freestyle 2 Handheld Scanner for Construction. This fast, portable, and targeted 3D data capture device can scan even the tightest spaces more easily than ever. For the construction industry, accurate dimensions and locations are needed when coordinating with scope done earlier in the project, such as underground stub-ups, water utility ties-ins or duct riser penetrations, to ease the handoff between contractors. The new Freestyle 2 addresses these and other common challenges. *www.faro.com*

New NASA Earth System Observatory

NASA will design a new set of Earth-focused missions to provide key information to guide efforts related to climate change, disaster mitigation, fighting forest fires, and improving real-time agricultural processes. With the Earth System Observatory, each satellite will be uniquely designed to complement the others, working in tandem to create a 3D, holistic view of Earth, from bedrock to atmosphere.

The observatory follows recommendations from the 2017 Earth Science Decadal Survey by the National Academies of Sciences, Engineering and Medicine, which lays out ambitious but critically necessary research and observation guidance.

Areas of focus for the observatory include:

- Aerosols: Answering the critical question of how aerosols affect the global energy balance, a key source of uncertainty in predicting climate change.
- Cloud, Convection, and Precipitation: Tackling the largest sources of uncertainty in future projections of climate change, air quality forecasting, and prediction of severe weather.
- Mass Change: Providing drought assessment and forecasting, associated planning for water use for agriculture, as well as supporting natural hazard response.
- Surface Biology and Geology: Understanding climate changes that impact food and agriculture, habitation, and natural resources, by answering open questions about the fluxes of carbon, water, nutrients, and energy within and between ecosystems and the atmosphere, the ocean, and the Earth.
- Surface Deformation and Change: Quantifying models of sea-level and landscape change driven by climate change, hazard forecasts, and disaster impact assessments, including dynamics of earthquakes, volcanoes, landslides, glaciers, groundwater, and Earth's interior.

NASA is currently initiating the formulation phase for the observatory. Among its first integrated parts is NASA's partnership with the Indian Space Research Organisation (ISRO), which brings together two different kinds of radar systems that can measure changes in Earth's surface less than a half-inch. This capability will be utilized in one of the observatory's first missions intended as a pathfinder, called NISAR (NASA-ISRO synthetic aperture radar). This mission will measure some of the planet's most complex processes such as ice-sheet collapse and natural hazards such as earthquakes, volcanoes, and landslides. NISAR can assist planners and decision makers with managing both hazards and natural resources in the future. *www.nasa.gov/earth*

Velodyne Lidar launches Intelligent Infrastructure Solution

Velodyne Lidar, Inc. has launched its Intelligent Infrastructure Solution designed to solve some of the most challenging and pervasive infrastructure problems. This new solution combines Velodyne's lidar sensors and Bluecity's artificial intelligence (AI) software to monitor traffic networks and public spaces. It generates real-time data analytics and predictions, helping to improve traffic and crowd flow efficiency, advance sustainability and protect vulnerable road users. *https://velodynelidar.com*

Woolpert and Planet partnership

Planet and Woolpert have expanded their long-standing partnership to provide high-frequency satellite data and high-resolution aerial data and imagery to federal, state and local governments around the world. The partnership combines the global coverage and efficient data delivery from Planet with the diverse geospatial expertise and client-facing relationships of Woolpert to comprehensively support clients' mapping needs. *www.planet.com*

NorSat-3 Maritime Tracking Microsatellite launched

The Norwegian Space Agency successfully launched the NorSat-3 maritime tracking microsatellite built by Space Flight Laboratory (SFL) in Toronto. It was launched on April 28, 2021, aboard Vega Flight VV 18 from the Guiana Space Center in French Guiana.

NorSat-3 carries two instrument payloads. The primary device is an Automatic Identification System (AIS) receiver, which acquires messages from civilian maritime vessels to provide information on ship locations and marine traffic. The microsatellite is also equipped with an experimental navigation radar detector developed by the Norwegian Defence Research Establishment (FFI) to augment the AIS receiver. *www.utias-sfl.net*

First LiDAR Pre-processing Software Engine

Outsight, a 3D Spatial Intelligence solutions provider, has launched the Augmented LiDAR Box (ALB). It's the first real-time LiDAR Software Engine that allows application developers and integrators to seamlessly use LiDAR data from any hardware supplier. Created as a turnkey solution, the ALB enables leveraging 3D Spatial Intelligence's unique value while avoiding the complexity of processing 3D data in real-time. Being a LiDAR-agnostic solution, it saves the customer the hassle of assessing and choosing the most appropriate LiDAR for each application. *www.outsight.ai*

EGNOS and Galileo on the ambitious Digital Rail agenda

The European Year of Rail brings attention to a number of topics important for improving the role of rail within the EU transport ecosystem. The recently published Policy paper "Challenges for European rail – getting solutions on track" by Jacques Delors Institute, highlights the main challenges and opportunities for the railway system evolution in Europe, focusing on increasing the rail attractiveness and make it the transport of choice for the decades to come.

EGNOS and Galileo are an integral part of the Digital Rail agenda, both freight and passenger transport rely on the European satellite navigation system, improving service provision with more than 150 000 freight wagons in Europe equipped with GNSS-based localization to provide accurate information about the wagon position. Precise location is used for asset and fleet management purposes, becoming a crucial element for efficient supply chain operations, and service to customers with estimated time of goods arrival.

The European GNSS Agency (GSA) continues to support projects and initiatives leading towards potential adoption of EGNOS and Galileo within European Rail Traffic Management System (ERTMS), aiming to decrease the costs linked to the ERTMS deployment and its carbon footprint by reducing the dependency on physical trackside elements that need to be manufactured, installed and maintained for proper train localization.

Last year, the GSA and ESA supported the ERTMS Users Group´s Change Request 1368, aiming to introduce EGNOS as the first step towards future safe use of GNSS for train signaling within ERTMS.

GNSS has the potential to enable a cheaper, more flexible and greener ERTMS, possibly offering also its faster deployment beyond the EU mainline corridors. Outside of Europe, GNSS is already used for fail-safe train localization (e.g. within the Positive Train Control (PTC) in the USA). The role and priorities of the sectorial associations, and especially the EU rail system integrators, will be a key factor for GNSS success within the ambitious Digital Rail agenda, allowing a faster progress towards closing technological gaps and agreeing on the final and best approach towards GNSS inclusion in ERTMS. *www.euspa.europa.eu*

ESA selects SpacePNT

The European Space Agency (ESA) has selected SpacePNT to develop an advanced spaceborne GPS/GALILEO receiver to demonstrate for the first time, onboard the ESA-SSTL Lunar Pathfinder Spacecraft in orbit around the Moon, the use of terrestrial satellite navigation signals (i.e., GALILEO, GPS) for the purpose of real-time and autonomous orbit determination and Positioning, Navigation and Timing (PNT). The contract includes the development, qualification, and delivery of one proto-flight model (PFM) and two engineering models of NAVIMOON receiver.

The NAVIMOON receiver implements very high sensitivity algorithms able to receive and process signals extremely attenuated coming from the spillover around the Earth of the signals transmitted by satellite navigation (SatNav) systems (GALILEO, GPS). Furthermore, it combines these signals' measurements with advanced on-board orbital forces filters to achieve directly onboard the spacecraft and in real-time an unprecedented target orbit determination accuracy of 100 m rms at Moon altitude, which is well below the typical accuracy that can be achieved today with terrestrial radio ranging that involve the use of costly deep space station ground infrastructures.

Given the high interest in Moon exploration and colonization (over 50 commercial and governmental missions have been announced between now and 2024), it is expected this NAVIMOON receiver technology will play a significant role in the next decade not only on Earth-Moon transfer orbits, but also to provide enhanced PNT services for the Moon users with the deployment of a lunar constellation that will allow the provision of lunar navigation in Moon-obstructed areas.

For this project, SpacePNT will partner with EECL from UK that will work as sub-contractor and will bring their significant space expertise for the electronics design, manufacturing, and qualification. *https://spacepnt.com*

NASA tests system for aircraft positioning in supersonic flight

NASA recently flight tested a visual navigation system designed to enhance precise aerial positioning between two aircraft in supersonic flight. The Airborne Location Integrating Geospatial Navigation System (ALIGNS) was developed to prepare for future acoustic validation flights of the X-59 Quiet SuperSonic Technology airplane. It is designed to reduce the loud sonic boom, heard on the ground when an aircraft flies at supersonic speeds, to a quiet thump – a technology that will be demonstrated when the X-plane flies over communities starting in 2024.

First, NASA will need to fly the X-59 as part of an acoustic validation phase, to confirm that the aircraft is as quiet as it's designed to be. This is where ALIGNS comes in. To validate the X-59's acoustic signature, the team at NASA's Armstrong Flight Research Center in Edwards, California will need to both measure and visualize its shock waves, which are waves of pressure produced by aircraft as they fly faster than the speed of sound and are heard as sonic booms. Getting accurate measurements of the X-59's unique shock waves will require a chase aircraft, flying in exact positions relative to the X-59 while both aircraft fly at supersonic speed.

A shock-sensing probe, mounted to the nose of an F-15, will be the primary tool in measuring the X-59's shock waves. For the probe to take accurate measurements, the F-15 will need to fly in and out of the X-59's shock waves at precise distances.

"ALIGNS is software that is designed to create a virtual point on the shock wave that is produced from the target aircraft. The pilots will get directional cues on the ALIGNS display to help them steer the F-15 to that specific point in space," said ALIGNS Principal Investigator Troy Robillos.

"ALIGNS is absolutely going to help us get this done," says NASA test pilot Jim 'Clue' Less. "We've flight tested it, we're going to continue to make it better, and we'll be ready."

Matt Kamlet
NASA Armstrong Flight Research Center. *www.nasa.gov*

STL is an Accurate and Reliable Source for Wide-Area Delivery of Coordinated Universal Time

Satelles, Inc., innovative provider of highly secure satellite-based time and location services, recently announced an important new finding by the U.S. National Institute of Standards and Technology (NIST) about Satellite Time and Location (STL). Following a detailed performance study in 2020, NIST determined that STL is a reliable source of timing that is highly consistent with Coordinated Universal Time (UTC) and is based on a signal that is independent from the GPS and other Global Navigation Satellite Systems (GNSS). The STL service was able to deliver this consistent performance in a deep indoor environment where GNSS signals did not reach.

The results of the study were shared by Dr. Elizabeth Donley, Chief of the Time and Frequency Division at NIST, when she presented at the recent Workshop on Synchronization and Timing Systems (WSTS) conference organized by the Alliance for Telecommunications Industry Solutions (ATIS).

Dr. Donley articulated the details of the study conducted by NIST last year in which a GPS-disciplined clock (GPSDC) and a Satelles EVK-2 evaluation unit with a quartz oscillator comparable to that in the GPSDC were both compared to UTC(NIST), the national time scale in the United States, for a period of 50 days. In this evaluation, the GPS device received its signal from an outdoor antenna whereas the Satelles device was connected to an indoor antenna in a deep indoor environment where GNSS signals were not able to reach.

Time deviation (TDEV) calculations estimated the stability of the two signals with respect to the UTC(NIST) time scale. Based on one day of averaging, the GPS instability was less than two nanoseconds, and the STL instability was only slightly higher at under three nanoseconds (view chart). These measurements demonstrated that STL delivers stability that is comparable to GNSS and does so in an indoor location where GPS signals usually cannot penetrate.

STL delivers a positioning, navigation, and timing (PNT) service from satellites in low Earth orbit (LEO) to back up or augment GPS and other GNSS. *www.satelles.com*

IIT Roorkee launches free online course on GNSS

IIT Roorkee is launching a free online course on GNSS and Applications on the NPTEL platform. The 4 weeks long course is going to provide a basic understanding about digital elevation models (DEMs) and their application in Civil Engineering and Earth Sciences.

Participants will be given insights into various DEMs, their source, generation techniques, derivatives, errors and limitations.

The courses will begin on 26th July 2021 and will end on 20th August 2021. The registrations are currently open till 2nd August 2021 and can be done through SWAYAM platform. *www.iitr.ac.in*

S Korea develops autonomous UAV navigation technology

Agency for Defense Development (ADD) controlled by the Defense Ministry, South Korea, through a four-year project, has developed an autonomous navigation technology for drones. The technology allows UAVs to autonomously set an optimized and safe path to their destination. It uses a sensor to collect external information and automatically generates an algorithm for navigation. *www.ajudaily.com*

Tailor-made flight control solution for VTOL platforms

In recent years, the UAV / RPA industry has seen an increasing amount of interest in using VTOL platforms, a hybrid between fixed-wing and rotary-wing platforms, due to the versatility they offer to the operators. In order to bring this new flight control solution to reality, both development teams in fixed wing and rotary wing have worked together to create the most advanced VTOL solution on the market. Technological capabilities already existing in other solutions such as referenced navigation or the development of missions in environments without GNSS signal and under threat of jamming attack have been incorporated in an organic way to facilitate a complete and reliable system. *www.uavnavigation.com*

HCSS introduces new version of Aerial

HCSS recently introduced a new version of HCSS Aerial, a drone-based data analytics platform. This upgrade is the sixth major release of the software since the product was launched in March 2020 and incorporated direct customer feedback. This new version of HCSS Aerial contains design visualization and digital inspection enhancements. *www.hcss.com*

uAvionix adds ping200XR with Integrated GPS

uAvionix has added a new low-SWaP transponder to the line-up of UAS communications, navigation, and surveillance (CNS) solutions. The ping200XR integrates the full capability of the ping200X TSO Certified Mode S ADS-B OUT transponder with the high integrity truFYX TSO certified GPS position source into a single, easy-to-install enclosure. *www.uavionix.com*

Hexagon partnerships with Fatigue Science

Hexagon's Mining division has partnered with Fatigue Science, a leader in fatigue and performance predictive analytics and fatigue management information systems. Combined with its real-time operator alertness and collision avoidance solutions, Hexagon will now be able to help customers further protect and optimize their people and equipment with Fatigue Science's Readi platform for predictive fatigue management.

Hexagon and Fatigue Science are at the forefront of innovation to help mines increase output and prevent accidents caused by fatigued and/or distracted operators of vehicles and equipment. *www.hexagon.com*

Arrival selects HERE SDK for its Electric Vehicles

Arrival, the company reinventing the automotive industry with its entirely new approach to the design and assembly of electric vehicles (EVs), has selected HERE Technologies to power its in-vehicle Human-Machine Interface (HMI) navigation solution. HERE's software development kit (SDK) provides real-time visibility into the geographic location of mobile assets and offline capabilities that include route calculation, location search and turn-by-turn navigation. *360.here.com*

TomTom EV Technology suite

TomTom has unveiled a roster of enhancements to its electric vehicle (EV) suite including upgraded range and routing features, and industry-leading data on charging points. This follows recent announcements of collaboration with Hubject and Eco-Movement – that will improve the EV driving experience. The new TomTom Routing and Range will be available in select electric models from TomTom customers already later this year via an over-the-air-update, and will be further enhanced with the introduction of the cloud-native TomTom Navigation for Automotive. *www.tomtom.com*

Raytheon gets $228 million contract extension for GPS ground system

Raytheon received a $228 million contract to continue development of a ground system for GPS satellites, the Space Force's Space and Missile Systems Center announced April 30. The contract is for work on the operational control system for the newest version of GPS 3 satellites made by Lockheed Martin. The estimated $6 billion ground system known as OCX has been in development since 2012.

The Space Force extended Raytheon's contract until 2025. This next phase of the program is for the OCX follow-on, or OCX 3F, which requires Raytheon to integrate the newest version of GPS satellites called GPS 3F.

Raytheon currently is working on OCX upgrades expected to be delivered in 2022, including hardened cybersecurity, anti-jam capabilities, and new software compatible with the military's M-code secure signals and with Europe's Galileo global navigation system. *https://spacenews.com*

Grandmaster clock with multi-band GNSS receiver

ADVA has launched its OSA 5405-MB, the industry's first ultra-compact outdoor PTP grandmaster clock with multi-band GNSS receiver and integrated antenna. Part of the OSA 5405 Series of smart synchronization devices for indoor or outdoor deployment, the OSA 5405-MB ensures timing accuracy by eliminating the impact of ionospheric delay variation. This empowers communication service providers (CSPs) and enterprises to deliver the nanosecond precision needed for 5G fronthaul and other emerging time-sensitive applications. The multi-band GNSS receiver and integrated antenna enable the OSA 5405-MB to meet PRTC-B accuracy requirements (+/- 40nsec) even in challenging conditions. For the first time, the technology is available in an edge timing device with minimal footprint, helping operators achieve unprecedented accuracy and reliability as they roll out wide-spread small cell networks. *www.adva.com*

Stamp size RTK positioning and heading receiver

SkyTraq has announced a 17mm x 22mm size PX1172RH surface mount multi-band multi-GNSS receiver module for RTK positioning and heading applications. With dual antenna input, the receiver delivers sub-degree heading & pitch or heading & roll angles on top of centimeter-level positioning. The PX1172RH works with dual frequency GPS/QZSS L1/L2, GLONASS L1/L2, Galileo E1/E5, and BDS B1/B2 global navigation satellite signals concurrently to enable robust positioning and heading performance under more challenging partial-sky environments and to provide fast RTK convergence in seconds. The PX1172RH is ideal for precision guidance applications. *www.skytraq.com.tw*

Key contract won by Thales Alenia Space

Thales Alenia Space, a joint venture between Thales (67%) and Leonardo (33%), as prime contractor for Galileo First Generation's Ground Mission Segment, has been selected by the European Space Agency (ESA), on behalf of the European Commission in the Horizon 2020 Satellite Navigation Program (HSNAV), to develop the Advanced Orbit Determination and Time Synchronisation (ODTS) Algorithms Test Platform (A-OATP). This new contract will support the implementation and experimentation of the navigation algorithms that will be used for Galileo Second Generation. *thalesaleniaspace.com*

Septentrio launches AsteRx-i3

Septentrio has launched the AsteRx-i3—a new product line of high-performance GNSS plus inertial navigation system (INS) receivers. The AsteRx-i3 product family brings to market an array of next-generation receivers from plug-and-play navigation solutions to feature-rich receivers with raw measurement access. OEM boards are available for rapid integration as well as ruggedized receivers enclosed in a waterproof IP68 housing. *Septentrio.com*

Hexagon's Mining division awarded significant project

Hexagon's Mining division has been awarded a multi-solution project at Toka Tindung gold mine in North Sulawesi, Indonesia. The phased deployment will see Hexagon systems for fleet management, operator alertness, blast monitoring and enterprise analytics implemented by the company's Indonesian staff at the mine between now and October 2021. Toka Tindung is operated by subsidiaries of PT Archi Indonesia, one of the largest gold producers in Indonesia and Southeast Asia. *hexagon.com*

New GAJT-410MS protects against RF interference and jamming in marine environments

NovAtel is proud to release GAJT-410MS, the latest addition to their proven GPS Anti-Jam Technology (GAJT), into the commercial and defense marine markets. This low size, weight and power (SWaP) variant protects civil and military operations from interference and jamming, with jammer direction-finding capabilities for enhanced situation awareness in the marine environment.

The GAJT-410MS provides dynamic protection on both GPS L1 and L2 bands, as well as Galileo E1, QZSS L1 and L2 and SBAS L1 to combat intentional and unintentional interference. If a vessel experiences jamming, the device's direction-finding capabilities provide improved situation awareness of their RF environment to identify and locate the source of the jamming signals. This commercial off-the-shelf, non-ITAR solution is easy to install or retrofit onto existing fleets, enabling assured PNT for continuous operations, cybersecurity and safe navigation at sea. *novatel.com*

Unearth joins Trimble's GIS Partner Program

Trimble has announced that Unearth Technologies, a provider of map-based project tools that help built-world industries to manage physical assets, has joined Trimble's Mapping & GIS Partner Program. Unearth's map-based project management software connects field and office teams by providing a unified platform for data collection and work management. As part of the program, Unearth has implemented the Trimble® Precision software development kit (SDK) to enable field teams to perform high-precision Global Navigation Satellite System (GNSS) data capture in real-time, directly from their Android and iOS apps. *www.trimble.com*

GMV is selected by ESA as a supplier of the RFCS

GMV has been selected to lead the consortium that will supply a Radio Frequency Constellation Simulator covering both the 1st and 2nd Galileo Generation. Galileo First Generation (shortened to G1G), running since December 2016, consists of space infrastructure (26 satellites to date) and ground infrastructure.

Under the G2G RFCS contract GMV teams in Portugal and Spain together with our key partners □OROLIA and TECNOBIT□ are developing a constellation simulator covering both Galileo generations and Galileo Open Service and Public Regulated Service. The RFCS will simulate the progressive deployment of the G2G with its new signals and will be a key element to support the development of Galileo 2nd Generation infrastructure and for the testing of experimental user receivers.

In addition to the simulation of the constellation and radio frequency signals emitted by the satellites, the RFCS will cover many user characteristics such as dynamic behavior, signal impairments such as multipath and interference but also solution hybridization (e.g. inertial sensors) and signal distortions. *gmv.com*

eCognition Suite Version 10.1

Trimble Geospatial has announced the availability of the latest version of the Trimble® eCognition® Suite. eCognition Suite 10.1 includes a variety of great new tools and features that will streamline existing workflows and open the doors for new types of data analysis. For example, it is now possible for users to import pre-trained 3rd party TensorFlow models for execution directly in Developer. *www.trimble.com*

Microsoft cloud identity app uses GPS

Microsoft has added identity and access management capabilities employing GPS among other factors to its Azure Active Directory, a cloud identity solution, to counter sophisticated hacking techniques. Two-factor authentication is no longer sufficient to defend against malicious entry. The GPS-based named locations and filters look at a range of signals for authorized user access.

New GPS SmartSole begins testing and certification

GTX Corp, a pioneer in the field of location based wearable GPS human and asset tracking systems and a supplier of Health and Safety personal protective medical equipment, has announced it will begin testing its new Cat M1 LTE SmartSoles across North America, Europe and Australia, and will begin the regulatory certification process for FCC/IC and CE.

The patented and award-winning GPS SmartSoles were designed to address the unprecedented crisis related to Alzheimer's and autism challenges that the World continues to face. *GTXCorp.com*

NSSLGlobal partnership with DDK Positioning

NSSLGlobal has entered a strategic alliance with DDK Positioning (DDK), to incorporate enhanced GNSS positioning navigation and timing solutions into its maritime portfolio.

NSSLGlobal will now provide, install and service DDK's GNSS Precise Point Positioning (PPP) solution which enhances the ability of its customers to precisely locate and track their assets. DDK's independent GNSS technology is provided exclusively through Iridium's global satellite constellation. *www.nsslglobal.com*

Trimble introduces VRS Now correction services to Norway

Trimble has announced the expansion of its VRS Now® correction services across mainland Norway and most outer islands. As part of an ongoing global correction service strategy, the company is adding over 400,000 square kilometers (156,000 square miles) to its European footprint, which now totals 2.5 million square kilometers (975,000 square miles). VRS Now delivers reliable, easily accessible, centimeter-level accuracy that is ideal for professionals in the surveying, GIS and mapping, construction and agriculture industries, as well as many emerging autonomy applications in the automotive and robotics industries. *tpsstore.trimble.com*

oneNav unveils L5 mobile GNSS receiver

oneNav has announced that it has closed a $21 million Series B funding round, led by GV, with participation from Norwest Venture Partners and GSR Ventures, bringing total funding to $33 million. The company also unveiled the world's first pure L5 mobile GNSS receiver, which provides the highest location accuracy with half the footprint of existing solutions.

oneNav has also signed a strategic partnership agreement with In-Q-Tel Inc., providing U.S. intelligence and defense agencies with a first-of-a-kind GNSS technology solution. *nenav.ai*

Orolia selected to deliver the next generation Galileo GNSS simulator

Orolia has been selected by the European Commission and the European Space Agency (ESA) to provide the core GNSS simulation engine for the Galileo Second Generation (G2G) RF Constellation Simulator (G2G RFCS).

Orolia has been selected to participate in the G2G RFCS activity, which will support G2G signals evolution requirements. The primary objective of the G2G RFCS initiative is to design, develop, manufacture, and test an enhanced radio frequency constellation simulator dedicated to Galileo engineering and experiments. This simulation technology will enable scientists and industries to verify, demonstrate, and validate the future G2G configuration. *www.orolia.com*

Automotive GNSS positioning module for ADAS and autonomy

NovAtel has introduced the PIM222A, part of a new family of automotive GNSS positioning products for advanced driver assistance systems (ADAS) and autonomy.

Built with automotive-qualified hardware in a package that is easy to integrate, the PIM222A leverages SPAN technology from NovAtel to provide accurate position data in urban environments that challenge GNSS availability. Deeply coupled GNSS receivers and inertial measurement units (IMUs) ensure continuous availability of position, velocity and attitude, even when satellite signals are briefly blocked.

The PIM222A, which was created in collaboration with STMicroelectronics, is a lightweight, power-efficient, solder-down module that maximizes flexibility for integration. The receiver design can be applied to low-, medium- and high-production volumes while retaining a rich array of features, including options such as multi-frequency, multi-constellation, RTK and dual-antenna precision. *www.novatel.com*

TRIUMPH-3 - The latest-generation receiver from JAVAD

TRIUMPH-3 is capable of efficient tracking even in difficult conditions. It can track all current signals and is ready for any future satellites. No need to pay RTN service providers! Your RTK system communicates via integrated UHF, 4G/LTE, Wi-Fi, and Bluetooth channels.

Receive faster and more reliable RTK solutions with your own base station nearby. TRIUMPH-3 is designed to operate as a base together with TRIUMPH-LS and TRIUMPH-LS Plus to efficiently accomplish any geodetic job. *www.javad.com*

'Operate-anywhere' portable shallow-water tracking system

Sonardyne has launched a new, entirely portable configuration of its shallow water Ultra-Short BaseLine (USBL) system Micro-Ranger 2.

The one-box USBL solution is able to track up to 10 targets out to 995 m. Inside the case is a Micro-Ranger Transceiver (MRT) with 10 m of cable, a GNSS antenna with 5 m of cable, and two Nano transponders and command hub. A built-in battery provides more than 10 hours of continuous use, enough for a full day of activity out on the water. The case can also accept external power from a boat or shore supply.

Sonardyne have also recently introduced an upgraded and extended Nano range which; improves the acoustic performance of the Nano transponder, extends its operational depth range and increases its acquiescent battery life to 90 days. *www.sonardyne.com*