ENSURING FAIR ACCESS TO PRECISE POSITIONING BY IMPROVING GEODETIC DATA INTERCHANGE STANDARDS

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List of Definitions

Below we provide accepted definitions for the most frequently mentioned metadata elements required by the current GNSS end-user sectors as per Teunissen and Montenbruck (2017).

Accuracy	The degree of conformance of an estimated or measured position at a given time to a reference value.
Availability	A measure that relates to the percentage of time that a specified level of accuracy, integrity and continuity is available and useable within a specified area.
Integrity	A measure that relates to the extent to which the information supplied by the navigation system can be trusted, or to the ability of the navigation system to detect and provide timely warning to the user about when the specified accuracy should not be trusted.
Continuity	A measure that relates to the probability that a specified level of accuracy will be maintained throughout a given operation or experiment, assuming that the specification is met at initialization.
Coverage	An area serviced by the global satellite navigation system.
Reliability	Ability of a system to detect blunders in the measurements and estimate the effects of undetected blunders on the position solution.
Robustness	Ability of the GNSS system to withstand signal interference (e.g. jamming and spoofing).
Authentication	Technique to verify the receiving signal or navigation message.

List of Acronyms

AGRS	Australian Geospatial Reference system
AIMS	Australian Institute of Marine Sciences
ANDS	Australian National Data Service
ANSP	Airport Navigation Service Provider
AODN	Australian Ocean Data Network
ARDC	Australian Research Data Council
DANS	Data and Archiving Network Services
DELWP	Department of Environment, Land, Water and Planning
DFMC	Dual Frequency Multi Constellation
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
EDAS	EGNOS Data Access Service
EGNOS	European Geostationary Navigation Overlay System
EOSC	European Open Science Cloud
ESIP	Earth Science Information Partners
EWA	EGNOS Working Agreement
FAIR	Findable, Accessible, Interoperable, Reusable
GA	Geoscience Australia
GML	Geography Markup Language
GNSS	Global Navigation Satellite Systems
GSA	European GNSS Agency
ICSM	Intergovernmental Committee on Surveying and Mapping
IGS	International GNSS Service
IMO	International Maritime Organisation
ISO	International Standards Organisation
LPV	Localizer Performance with Vertical guidance
MCP	Marine Community Profile
MSM	Multiple Signal Messages
NOTAM	Notice to Airmen
NTRIP	Network Transfer of RTCM via Internet Protocol
OECD	Organisation for Economic Co-operation and Development
OGC	Open Geospatial Consortium
PCG	Permanent Committee on Geodesy
PNT	Position Navigation Timing
RNP	Required Navigational Performance
RINEX	Receiver INdependent Exchange
SBAS	Satellite Based Augmentation System
SDG	Sustainable Development Goal
SLR	Satellite Laser Ranging
SoL	Safety of Life
VLBI	Very Long Baseline Interferometry

Executive Summary

Current Global Navigation Satellite Systems (GNSS) enable existing and emerging industries to use real-time precise positioning data, allowing them to improve productivity, efficiency, safety and decision making. Standards play a crucial role when combining GNSS and geodetic data with data from other domains.

However, current standards for delivering geodetic data do not adequately serve the needs of users. The geodetic community is frequently called upon to provide accurate and reliable positioning, navigation and timing (PNT) data products and services to support a broad spectrum of government, industry, science and societal applications. In order to service these user demands in a robust way, geodetic data and the associated metadata need to be standardised, discoverable and interoperable (GA, 2016).

This report reflects on the results of the collaborative work between Curtin University, Geoscience Australia, the Department of Environment, Water, Land, and Planning (DELWP) of Victoria, and FrontierSI. The main objective of this work was to perform a scoping study on the current state of geodetic standards for information interchange, and their support of findability, accessibility, interoperability and re-usability (FAIR) of geodetic resources (i.e. precise positioning data, metadata and services).

The method used in this report was desk-based research, using a combination of referenced scientific literature and grey literature, such as organizational technical reports, white papers, analyses, websites and discussion, mostly sourced through agencies and societies for GNSS.

The main findings from the work presented in this report include:

- There is a need for increasing the FAIRness of current geodetic standards, and this is only possible through establishing detailed community-specific requirements for FAIR, and setting up a FAIRness compliance test for geodetic data and metadata records
- There is a need to ensure that precise positioning metadata supports precise positioning end-user requirements as identified in Chapter 1
- There is a need for a review and definition of how metadata (i.e. formats, metrics, mode of interaction) is delivered to human and machine users
- Definitions of which metadata are essential to be included with the data according to the way data is accessed (e.g. streamed to a receiver, offered for download or accessed via the Web)
- For each GNSS end-user sector, definitions of use cases and identified components of GNSS information flow are needed
- A review and revision of the rationale of the GeodesyML standard is warranted so as to reflect the current best practice of providing spatial data over the web

Findings in this report confirm that improvements are necessary in the current practice of specification and supply of required data and metadata to end-users. Follow-up work is underway at Curtin University, Geoscience Australia and FrontierSI, with the objective of enabling users of Positioning Australia services to receive FAIR and relevant precise positioning information in the future.

1. User requirements for precise positioning data

1.1. Introduction

With the increased proliferation of precise positioning and the availability of low-cost Global Navigation Satellite System (GNSS) receivers tailored to a plethora of applications, there is a need to conduct a review of current and emerging end-user sectors and their needs. Although there are several research publications related to the enhancement of GNSS technology to suit specific end-user applications (e.g. Velaga & Pangbourne, 2014; El-Mowafy et al. 2019), which provide first insights into end-user sectors (e.g. Tengku & Kealy, 2016; Kolomijeca et al., 2016; Ivánová et al., 2019), a thorough scientific end-user requirement analysis of emerging GNSS application sectors is still lacking. General requirements for the use of GNSS in various traditionally recognized application domains (e.g. surveying, agriculture, aerial, road, rail or maritime operations) are available in most GNSS textbooks, such as the "The Springer Handbook of GNSS" edited by Teunissen and Montenbruck (2017). Although general requirements per application domain as defined by GNSS professionals are still valid and useful, these are mostly based on theoretical expectations. Due to increased availability and access to GNSS technology, the end-user landscape has changed in recent years and new, previously undefined (or unnoticed) sub-sectors have emerged. An example of such a sub-sector includes passengers in the road and rail transportation sector, who demand live and accurate information on their smartphones, at their location, such as details of the next rail connection, updates on delays of public transportation, actual detours due to accidents and more.

It is worth noting that today's GNSS consumer sector is no longer solely passive; consumers (human and machine) are well-educated in the GNSS domain and expect active participation in selection of the best positioning information to suit their needs (GSA, 2020). Along with location information, users in emerging sectors request information about the quality of their precise positioning. Accuracy, availability and integrity of the GNSS data are a few examples of such GNSS quality metadata. Depending on the sector, quality requirements may vary significantly. For example, end-users from sectors that operate on larger spatio-temporal extent (such as the agriculture, maritime and rail sectors) demand information on coverage, whereas for other sectors such information might not be relevant. Similarly, the importance of different metadata elements varies per sector – for example, in surveying, high accuracy is paramount, whereas in sectors that have inherent safety components to them (including safety-of-life) such as rail, road and aviation, information authentication and integrity are more important.

The purpose of this report is to provide a summary of current GNSS end-user sectors and their requirements for spatial metadata. This report is the result of desk-based research, which has been compiled from scientific literature as well as from grey literature (organizational technical reports, white papers, analyses, websites and discussion fora) mostly found through agencies and societies for GNSS. Reports and literature used are included in the reference section, and the organizations and societies that were consulted are listed in Annex A.

1.2. Current users of precise positioning data and their expectations

Positioning technology has become omnipresent in current society, which is prompting precise positioning providers to review and analyse their end-user sectors and the particular needs of those sectors. If, in the past, end-users of precise positioning data were mostly surveyors, the current composition is richer and more colourful, including GNSS end-users from unexpected members of society (e.g. pensioners). Table 1 presents a categorisation of current GNSS end-users, the current GNSS high-end sector, and examples of typical end-user applications within each sector. This is a summary from an analysis of available resources discussing end-user requirements (Teunissen & Montenbruck, 2017; Ernst & Young, 2019; GSA, 2018; 2019a-h; 2020a-b; ACIL Allen Consulting Pty Ltd, 2013a-j). A more detailed list of applications per end-user sector is available in Annex B.

Table 1. Current GNSS end-user sectors and examples of potential applications within each sector.

Type of sector[1]	GNSS High-end sector	End-user application examples
Mass Market Consumer Applications	Agriculture	Livestock and produce provenance tracking
	Rail	Passenger Rail information management
	Road	Ride-sharing applications Live public transport tracking
	Maritime	Recreational Maritime Location of fishing grounds
	Aviation	Civil Aviation User-preferred routing
	Location-Based Services	Pedestrian navigation Smart parking
	Time & Synchronisation	Digital TV broadcasting Internet of Things applications
	Surveying	Personal-use & volunteered mapping
Workforce, Fleet, Traffic and Asset Management	Agriculture	Farm and livestock management Self-driving machinery monitoring
	Rail	Rail asset tracking Rail Infrastructure management
	Road	Road asset management Fleet management
	Maritime	Port operations Pilotage
	Aviation	Automatic GNSS satellite selection Drone management
	Location-Based Services	Taxi/rideshare fleet management Mobile workforce management and tracking
	Time & Synchronisation	Water and wastewater management Electricity and telecom transmission management
	Surveying	Asset positioning Mobile surveying equipment tracking
Liability-critical Applications	Agriculture	Park management
	Rail	Incident location registration Train integrity management
	Road	Tolling Operations Drivers surveillance (e.g. speeding, wrong way driving, geofencing)
	Maritime	Automatic collision avoidance Fisheries and parks management
	Aviation	Drone surveillance Airspace protection
	Location-Based Services	Mobile Payments (e.g. pay-per-use, location- based billing)
	Time & Synchronisation	Insurance Telematics
	Surveying	Engineering and construction surveying

[1] As per GSA's GNSS Market Report 2019

Safety-critical Applications	Agriculture	Manned and Unmanned Aviation
	Rail	Track-side personnel protection Rail emergency management
	Road	Connected and Automated Driving Automatic speed limitation
	Maritime	Connected and Automated Pilotage Search and rescue operations
	Aviation	Precision aerodrome approaches Unmanned aerial vehicle management
	Location-Based Services	Civic Emergency Response
	Time & Synchronisation	Electricity failure monitoring in critical zones
	Surveying	Machine control Alignment trajectory staking
High Precision Applications	Agriculture	Precision Agriculture Yield monitoring
	Rail	Door control supervision Emergency brake assistance
	Road	Autonomous vehicle navigation
	Maritime	Precision landing and navigation systems
	Aviation	Localized performance (with vertical guidance)
	Location-Based Services	Augmented reality support
	Time & Synchronisation	Scientific applications (e.g. metrology, geophysics) Navigation in sensor networks
	Surveying	Terrestrial, Aerial and Hydrographic Surveying Civil Construction, Engineering and Geomatics (incl. BIM and Smart Cities)
Timing Applications	Agriculture	Weather-monitored crop management
	Rail	Time-stamping of train location
	Road	Parking fee calculation Traffic warnings
	Maritime	Real-time management of rescue operations
	Aviation	Performance-based navigation Real-time re-routing
	Location-Based Services	Real-time locating systems Navigation during emergency
	Time & Synchronisation	Electrical network synchronisation Financial Services Energy and Telecom Services
	Surveying	Robotics

1.2.1. How do 'new' end-users consume GNSS?

To illustrate the current state of GNSS use, here is a glimpse into the new GNSS end-user segments through a few examples, along with responses by the GNSS-enabled suppliers:

The silver economy

As identified in the latest GNSS Market Report (GSA, 2019) of the European GNSS Agency (GSA), the growing aging population has created a new market segment, nicknamed 'the silver economy'. GNSS is increasingly used to ensure the wellbeing and comfort of this population segment, with applications such as 'PulsePoint Respond'[2] , which provides GNSS navigation for life-saving assistance to those suffering cardiac arrest, or Weenect[3] , which provides GNSS location alert to family members of an elderly person who might have wondered off unintentionally due to spatial disorientation caused by illness.

GNSS-powered emergency response

In regulations set down in 2019, the European Union defined that from March 2022, new smartphones placed on the European market will have to be capable of transmitting the 112 caller (a European alternative to the Australian 'triple zero' emergency call) location based on Wi-Fi and GNSS data (GSA, 2020h, EU, 2019). Also, GNSS technology is increasingly used in bushfire response and other emergency warning systems (Choi et al., 2016; GA, 2020) to navigate responders to desired locations, to survey the exact location of disaster events (Pauka, 2020), and to enable high-precision mapping of disaster impact by volunteers on the ground through community efforts, such as that of the Humanitarian OpenStreetMap Team[4].

1.2.2. End-user requirements for metadata and standards

Table 2 provides a summary of end-user[5] requirements for metadata as identified in the literature (Teunissen & Montenbruck, 2017; Ernst & Young, 2019; GSA, 2018; 2019a-h; 2020a-b; ACIL Allen Consulting Pty Ltd, 2013a-j). Further requirements are detailed in Annex B.

Table 2. Summary of metadata requirements per end-user sector.

	Agriculture	**Rail**	**Road**	**Maritime**	**Aviation**	**Location-Based Services**	**Time & Synchronisation**	**Surveying**
Metadata	Accuracy Availability Integrity Coverage Reliability	Accuracy Availability Integrity Coverage Reliability Robustness Continuity Authentication	Accuracy Availability Integrity Continuity Reliability Authentication Interoperability	Accuracy Availability Integrity Coverage Reliability Coverage	Accuracy Availability Integrity Continuity	Accuracy Availability Integrity Authentication	Accuracy Authentication	Accuracy Availability

From Table 2, it follows that users in all identified end-user sectors request information about the accuracy, availability and integrity of GNSS data, and depending on the sector there is a demand for additional details. For instance, sectors that need GNSS support in real-time, such as rail, road and location-based services, demand information about service 'authentication', which is not so relevant to the agriculture sector where coverage and reliability take precedence. Similarly, demands on the importance of metadata within the sector also vary. For example, in the application of GNSS enabled emergency response, the correctness of the signal matters more than achieving high accuracy.

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[2] https://www.pulsepoint.org/pulsepoint-respond

[3] https://www.weenect.com/en/gps-tracker-for-senior-citizens-alzheimer-weenect-silver.html

[4] https://www.hotosm.org

[5] Note: From the analysed reports, it is unclear exactly what types of users interact with GNSS services, but the impression from the analysis is that the users in question were most probably experienced GNSS users.

1.2.3. Insights to GNSS user satisfaction

GSA, along with the European Satellite Service Provider, have conducted user satisfaction reviews since 2014, several years after the launch of EGNOS, the European regional satellite-based augmentation system. From these satisfaction reviews, GSA aims to better understand the value of EGNOS to its users, as well as gather suggestions for improvements directly from those end-users (GSA, 2020c). Overall, EGNOS end-users express increased satisfaction with the system. For illustration, the yearly scores (out of 10) from 2014 until 2018 (the year of the latest user satisfaction report) are: 7.4, 7.6, 8.1, 8.1 and 8.3.

Table 3 presents a summary of recommendations and suggestions to EGNOS extracted from the user satisfaction reviews conducted in years 2014-2018 (GSA, 2020c). Suggestions listed in end-user satisfaction reviews are gradually incorporated into EGNOS system, and updates are available via the main EGNOS website.

Table 3. Recommendations from EGNOS user satisfaction surveys 2014-2018.

Aspect	Suggestion
Architecture/Evolutions	Increase accuracy and coverage
	Minimize the impact on users of GEO Swaps
	Provide emergency communication messages
	Inform in advance about signal outages
	Allow Pseudo-Random Noise (PRN) mask extension in standards and in EGNOS System Level
General Support	Provide multilingual user-support services (helpdesk, website)
EGNOS Documentation	Release documentation orientated to end-users, avoiding technical language
EGNOSS App	Provide user support with improved navigation in an app with dynamic map content
	Announce outages with accurate information on system recovery
	List planned outages with specific affected times
	Add historic ionospheric activity maps with Grid Ionospheric Vertical Error (GIVE) Indicators, vertical delay values and ionospheric activity time series plots for monitoring station locations
	Provide historical Notice to Airmen (NOTAM)
	Increase availability to 99.9%
	Increase continuity on Safety of Life (SoL) EGNOS Service
	Extend coverage area
	Enable dual frequency operations
	Documentation to support Required Navigation Performance (RNP) applications and RNP coverage maps
	Provide vertical deviation information for EGNOS Open Service (OS)
	Provide availability of service, based on user location
	Add maps of the 95% horizontal and vertical accuracy of GPS L1+EGNOS, and of the best available real-time multi-frequency GPS L1+L2+L5 standalone solution.
	Include predictability of the degraded signal's impact
	Provide more information on the quality of EGNOS OS in real-time, especially concerning the "vertical performance"
	Provide space weather alert

EGNOS Safety-of- Life (SoL) Maritime	Implement EGNOS L1 Maritime Service including integrity at system level compliant with International Maritime Organization (IMO) resolution A.1046 taking into account the evolution of DGNSS infrastructure Coordinate recognition of EGNOS navigation (as part of World Wide Radio Navigation System) with Maritime authorities (e.g. IMO) Redefine EGNOS integrity with respect to maritime needs
EGNOS SoL Rail	Continuous documentation of user requirements Evolve SoL service to cover European Rail Traffic Management System (ERTMS) requirements Create Minimum Operational Performance Specification (MOPS) like receiver specification guide for rail Specify liability of the service in terms of low integrity and availability
EGNOS SoL Aviation	Increase NOTAM Service coverage and reduce time to publish NOTAMs to 15min Provide support on Required Navigational Performance (RNP) specification Increase number of Localizer Performance with Vertical guidance (LPV) procedures to enable SBAS for variety of aviation users (pilots, training organizations, rotorcraft operators) Improve LPV-200 capabilities to foster EGNOS-based approaches to enable safer aircraft landing Ease the steps to establish EGNOS Working Agreement (EWA) and the use of aircraft navigation tools Support the use of SBAS in Dual Frequency Multi Constellation (DFMC) scenario Provide EWA with non-Airport Navigation Service Provider (ANSP) entities when implementing EGNOS enabled Performance-Based Navigation (PBN) operations in non-controlled air traffic service airspace Define solution for using SBAS in operations with vertical guidance with barometric procedures for both, final approach segment database present/not present Clarify EWA coverage in terms of liability/responsibility, economic and time-consuming costs Publish list of EGNOS compatible receivers for aviation market
EGNOS SoL Road	Express EGNOS's potential in its use for road applications, in particular those related to autonomous cars
EGNOS Time Service	Understand and evaluate user needs for EGNOS time service development
EGNOS Open Service (OS)	Extend OS Service area Increase EGNOS OS accuracy Develop the concept of integrity for drones Standardize the use of EGNOS in OS receivers ("EGNOS labelling") for different application fields Support users in EGNOS problems reporting Redefine EGNOS minimum reception signal level requirement to avoid reception problems for unamplified antennas or the possibility to define terrestrial relays Support multi-frequency EGNOS

EGNOS Data Access Service (EDAS)	Include virtual stations on EDAS for testing purposes Increase EDAS awareness for OS users (using smartphones and tablets) Provide support for post-processing and real-time systems Enable EDAS for unregistered users Include Multiple Signal Messages (MSM) on EDAS Publish mobile app in markets where users can connect and use EDAS corrections Increase support to RINEX v3 Make historical EGNOS data available Improve GNSS ephemeris data Provide EGNOS correction in RTCA format via Network Transport of RTCM via Internet Protocol (NTRIP) Improve SISNeT service robustness to be independent of outages Define mechanisms of EDAS access for relevant users from non-EU countries Increase the limit of concurrent connections for NTRIP access. Assess data gaps in the service, the quality of GLONASS data and the possibility to provide DGPS corrections for a denser network of stations Ease the connection to EDAS by implementing the HTTP/TCP/IP options of the NTRIP protocol.

1.2.4. Snapshot of GNSS trends for the next decade

GSA's GNSS EGNOS Market Report (GSA, 2019), published in October 2019, provided a forecast of expectations in terms of GNSS use, potential revenue and global societal impact. The methodology used in the report is a bespoke GSA Market Monitoring and Forecasting Process, which aims at providing trends per end-user application from detailed data (where available) on the number of devices shipped, value of the market, number of devices installed and number of potential users. This overview presents, via Table 4, summary statistics and main findings that inform expectations within the Australia/New Zealand context.

Table 4. Overview of findings in GNSS trends, including metadata requirements (GSA, 2019).

Aspect	Details
GNSS performance indicators (i.e. potential metadata requirements by end-user sectors listed above)	Availability Accuracy Continuity Integrity Time To First Fix (TTFF) Robustness to spoofing and jamming Authentication
Non-GNSS performance indicators	Power consumption Resilience Connectivity Interoperability Traceability

According to the GSA's Market report (GSA, 2019), the GNSS market is set to grow steadily in the next decade with a predicted total installed base for end-user sectors growing from 53.8 million in 2019 to 93.2 million in 2029. Consumer solutions (mobile phones, wearables) and road transportation will dominate revenues with a combined forecast total of 93.8%, whereas the sectors of agriculture and geomatics (surveying, cloud computing, sensor fusion) account for a forecast total of 50% of remainder revenue by 2029. Performance expectations from Galileo and EGNOS per sector type are quite similar, as identified above, with availability, accuracy, integrity, continuity and authenticity being commonly expected metadata in each end-user category, as per Figure 1. As presented in the GNSS market overview (GSA, 2019) and Figure 2, the Asia-Pacific region dominates the market.

	Mass Market Consumer Applications	Workforce, Fleet, Traffic and Asset Management	Liability-critical Applications[1]	Safety-critical Applications	High Precision Applications	Timing Applications (Financial services, Energy and Telecom)
Relevant market segments	Consumer solutions, Road, VFR General Aviation, Recreational Maritime, and Rail (e.g. passenger info)	Consumer solutions, Road, Rail and Agriculture (including farm and livestock management)	Road (e.g tolling operators, insurance telematics), Consumer solutions (e.g. mobile payments) and Maritime (e.g. fisheries, marine park management)	Manned Aviation and Drones, Road (Connected and Automated Driving), Consumer solutions (E112) Rail and Maritime	Agriculture, Geomatics and Maritime	Timing & Synchronization of Critical Infrastructures
Galileo	Availability, better resistance to multipath, Accuracy, TTFF	Availability, better resistance to multipath, accuracy, TTFF, Authentication	Authentication, Availability, Accuracy, Continuity	Availability, Accuracy, Compliance with safety requirements and standards Dedicated SAR service with return link	Accuracy, Availability, TTFF	Accurate time, Authentication
EGNOS	Accuracy, especially in remote areas	Accuracy, Integrity	Integrity, Accuracy, Continuity	Integrity, Accuracy, Compliance with safety requirements and standard	Absolute and pass to pass Accuracy	Improved quality of synchronization

[1] GNSS position is linked with payment for services or fine in case of infringement

Figure 1: Performance expectation per sector (from GSA, 2019).

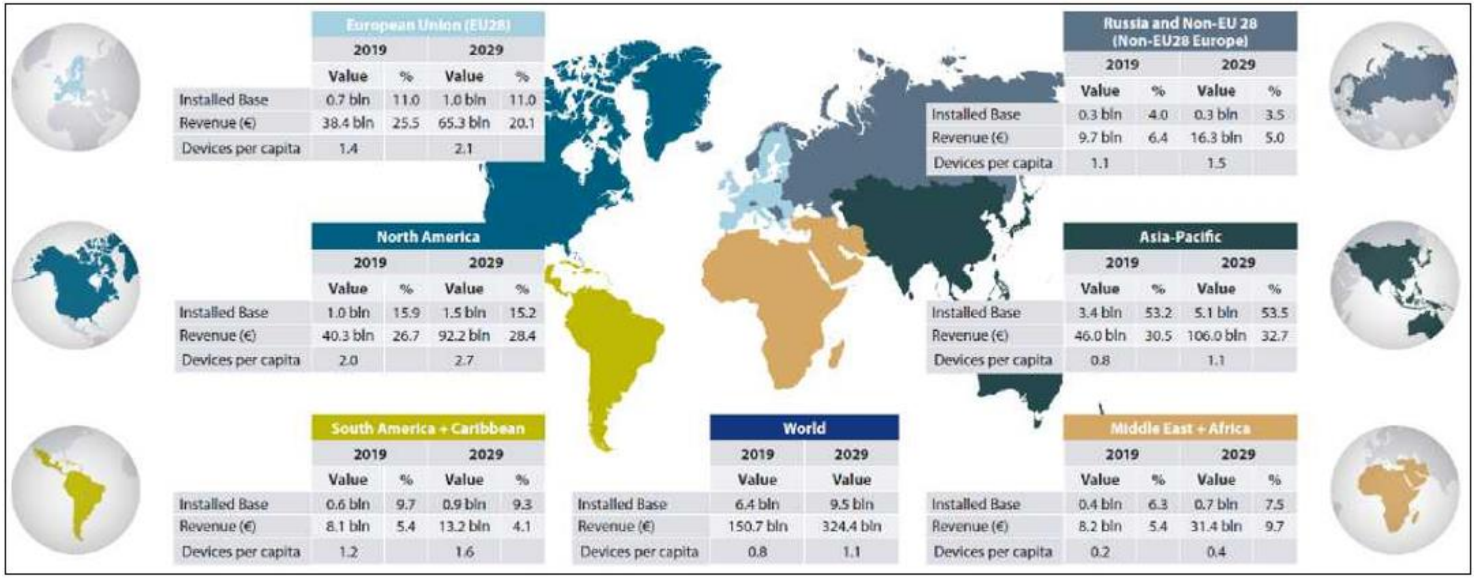

Figure 2: Global GNSS revenue from the installed base (from GSA, 2019).

GSA (2019) forecasts that added-value services such as data downloaded through cellular networks, subscription revenues from fleet management services, GNSS-attributable revenues of smartphone apps, and drone service revenues across a range of industries will account for more than half of total GNSS revenue.

Metadata requirements illustrate that current GNSS users are interested in understanding the quality of the precise positioning data they are receiving. This information is not present in the current formats, such as NMEA (NMEA, 2018) and RINEX (IGS, 2018). Information on spatial data quality such as accuracy, integrity and coverage can be encoded in additional metadata, however, this is not common practice at the moment and improvements to methods of supplying required metadata to end-users are necessary. Further investigation is required for an improved understanding of current GNSS end-users and their requirements. Questions that need to be addressed include the following:

- Are current GNSS users mostly human or machines?
- What is the level of GNSS expertise of current human GNSS users?
- How do human GNSS users interact with precise positioning data and evaluate its fitness for use?
- What types of machine users are there and what interface is used to interact with the GNSS service?
- For common machine users, is there any intelligence embedded to evaluate the requested metadata?

1.3. Standards: a key element in spatial information infrastructure

Along with organisational and technical rules, standards are one of the three pillars of any information infrastructure. This is no different in an information infrastructure serving end-users from the current high-end precise positioning sectors (as listed in Chapter 1).

Internationally, several groups are working on defining standards for geospatial and geophysical metadata, and the enhancement of their interoperability. However, there is no international strategy to ensure easy discovery of geodetic data, or to allow this data to be shared and combined with other data to improve access and maximise potential.

Technical Committee 211 for Geographic Information/Geomatics of the International Organization for Standardization[6] (ISO/TC211) and the Open Geospatial Consortium[7] (OGC) are the two main organisations for defining standards for geographic information and its exchange. More than 100[8,9] standards already exist or are under development[10], and many standards are successfully in use to facilitate 'geo-communication'.

In the geodetic community, the International GNSS Service[11] (IGS) is the main organisation for developing standards for GNSS message interchange. Several well-defined standards are already in use in the precise positioning domain, such as RINEX, IONEX and SINEX. These standards for GNSS message encoding and exchange are well known to many geodesists and surveyors.

All standardisation organisations mentioned above deal with spatial information interchange. However, there is a surprising divide between the users of ISO and OGC standards, and users of IGS standards. Uncovering reasons for this is beyond the scope of this report. Here, we only provide a few success stories as evidence of efficient use of a wide variety of international standards for spatial information interchange (see Annex C). Five examples are used to demonstrate how standards are helping in efficient spatial information discovery (Annex C.1), retrieval (Annex C.3), encoding (Annex C.2 and Annex C.4) and seamless GPS information interchange (Annex 0).

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[6] https://committee.iso.org/home/tc211
[7] https://www.ogc.org
[8] https://www.iso.org/committee/54904/x/catalogue/p/1/u/0/w/0/d/0
[9] Current list of published OGC standards for geographic information https://www.ogc.org/docs/is
[10] Current list of ISO standards under development: https://committee.iso.org/sites/tc211/home/projects.html
[11] http://www.igs.org

2. FAIRness of current geodetic standards

To support new and existing precise positioning users and to maximise data potential, it is essential that geodetic data is Findable, Accessible, Interoperable and Reusable (FAIR). These four foundational principles are aimed at guiding producers and publishers to improve the sustainable use of their digital resources (e.g. data, software, services). Implementing FAIR principles in publishing increases the value of digital resources, and the reuse of these resources by humans as well as machines (Wilkinson et al., 2016; Ivánová et al., 2019; Coetzee et al., 2020). Sharing precise positioning data, information and services in a FAIR way is a practice that will fill critical knowledge gaps required to address the 2030 Agenda for Sustainable Development Goals (SDGs) adopted by the United Nations in 2015 (UN, 2015).

2.1. What is FAIR and why does it matter?

The formulation of FAIR guiding principles dates back to 2007, when the Organization for Economic Co-operation and Development (OECD) published their principles and guidelines for access to publicly funded research data (OECD, 2007). Currently, several funder data policies exist (Hodgson and Molloy, 2015) to ensure intelligently open, accessible and reusable publicly funded research (The Royal Society, 2012). FAIR principles apply to digital resources regardless of their public availability and it is not required that these resources be open (EC, 2018). However, as a best practice in Open Science, FAIR and open should be considered as complementary by data practitioners, and resources created from public funds need to be as open as possible (EC, 2018).

Several organizations and communities exist to promote FAIR practices – these include Go FAIR[12], CODATA[13] and the Research Data Alliance[14]. The geoscience community champions the FAIR cause by creating and contributing to FAIR data repositories, for instance to the Australian Ocean Data Network Portal[15] (which is a domain specific resource dedicated to register marine and climate scientific data), or to a generalist Figshare[16] (which is an online open access research repository to store research outputs and artefacts). Upskilling geoscientists in FAIR practice (e.g. via webinars on FAIR at DataONE[17]) is paramount as several scientific journals, such as *Nature* and *Scientific Data*, only accept FAIR supplementary material related to their publications and only when these are submitted to a FAIR data repository (Stahl et al., 2019).

In 2017, the European Commission invited member nation governments, industry and the scientific community to support their progression towards open science and FAIR scientific practice. In their action plan towards this goal they highlighted that turning digital objects into FAIR requires substantial change in practice, technologies and their implementation. The action plan summarized the requirements and priorities as follows (EC, 2018), :

- Central to the realisation of FAIR are **FAIR Digital Objects** which can only exist in a **FAIR ecosystem** (see Section 2.1.2 for more details)
- The definition of **interoperability frameworks** for data formats, metadata standards, infrastructure and data exchange is fundamental
- **FAIR** must be in operation **for humans** as well as for **machines**

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[12] https://www.go-fair.org

[13] http://www.codata.org

[14] https://www.rd-alliance.org

[15] https://portal.aodn.org.au

[16] https://figshare.com

[17] https://www.dataone.org/webinars/enabling-fair-data and https://www.dataone.org/webinars/quantifying-fair-metadata-improvement-and-guidance-dataone-repository-network

- To ensure the requirements in the preceding three dot points are achievable, capacity building in data science and data stewardship is essential
- Metrics, indicators and funding act as important **incentives** for open science and FAIR

The European Union has estimated that the cost of not having FAIR research data (e.g. costs for licences, access fees, or unnecessary data duplication) could amount to at least €10.2bln (≈ AUD$16.5bln) annually, as direct costs from un-FAIR research data only. Furthermore, €16bln (≈ AUD$26bln) annually is estimated in addition as the impact on research quality and economic turnover (PwC EU Services, 2018).

2.1.1. The FAIR guiding principles

According to Wilkinson et al. (2016), resources are FAIR when they are findable, accessible, interoperable and reusable. More specifically, this means that FAIR resources are:

Findable when:

F1. (meta)data are assigned a globally unique and persistent identifier

F2. data are described with rich metadata (defined by the R1 below)

F3. metadata clearly and explicitly include the identifier of the data it describes

F4. (meta)data are registered or indexed in a searchable resource

Accessible when:

A1. (meta)data are retrievable by their identifier using a standardized communications protocol

A1.1. the protocol is free, open and universally implementable

A1.2. the protocol allows for an authentication and authorisation procedure, where necessary

A2. metadata are accessible, even when the data are no longer available

Interoperable

I1. (meta)data use a formal, accessible, shared and broadly applicable language for knowledge representation

I2. (meta)data uses vocabularies that follow FAIR principles

I3. (meta)data include qualified references to other (meta)data

Reusable

R1 (meta)data are richly described with a plurality of accurate and relevant attributes

R1.1. (meta)data are released with a clear and accessible data usage license

R1.2. (meta)data are associated with data provenance

R1.3. (meta)data meet domain relevant community standards

In more detail, data are **findable** when they are sufficiently described by their metadata and when they are registered and indexed in a searchable resource that is known and accessible to potential users (EC, 2018; Wilkinson et al., 2016). For example, resources registered in Geoscience Australia's data and product catalogue can be considered findable because they comply with the requirements F1-F4 described above to a large extent (see Section 2.6 for details).

Digital resources are **accessible**, when anyone (human or machine) with access to the Internet understands exactly how to access the digital resource via provided metadata, and the conditions on its reuse (EC, 2017;

Wilkinson et al., 2016). Common misinterpretation of this concept is the expectation that accessible (and hence FAIR) digital objects should be 'open' and/or 'free'. This is not what FAIR guiding principles define. The only condition for FAIR digital objects is the clarity and transparency on the conditions of access and reuse of these objects (Mons et al., 2017). For example, resources registered in Geoscience Australia (GA)'s data and product catalogue can be considered accessible because they comply with the requirements A1-A2 described above to large extent (see Section 2.6 for details).

Referring to the semantic interoperability of digital resources, these are **interoperable** when they use a "normative and community recognised specifications, vocabularies and standards that determine the precise meaning of concepts and qualities that the data represent" (EC, 2018, p.19). Although presence of these vocabularies and standards in a format compatible with the semantic web would undoubtedly increase their interoperability (van der Brink et al., 2019; Mons et al., 2017), this requirement does not mean that vocabularies and standards used to describe the resource have to 'be on the web'. Use of a well-defined community profile (e.g. GA Metadata Profile Extension for ISO 19115-1:2014, version 2.0) and providing metadata in a machine-readable format (e.g. XML) ensure sufficient interoperability of a resource (e.g. those resources registered in GA's data and product catalogue).

License information and a description of the provenance are the two crucial factors determining the **reuse** of a digital resource by both humans and machines (Mons et al., 2017; EC, 2018). This requires that the license description and provenance information need to be provided in a suitable format (e.g. XML or RDF). Resources in GA's data and product catalogue comply with this principle only partially – although both the license information and the provenance information are provided, both are available only in a human-readable format (i.e. free-text on a web-page), and as such would impede full 'understanding' of these by a machine.

2.1.2. FAIR Digital Objects and FAIR ecosystem

FAIR principles do not just apply to data, but to all digital objects. **FAIR Digital Objects** represent data, software, protocols and other resources with the following characteristics:

- They are accompanied by persistent identifiers (PIDs)[18] and metadata rich enough to enable them to be found, used and cited
- They are represented in common, ideally open, format and using vocabularies adopted by the community (to enable interoperability)
- They explain dependencies and licensing

A **FAIR ecosystem** comprises services and infrastructure for FAIR and it contains the following components:

- Policies
- Data management plans
- Identifiers
- Standards (including standards for vocabularies, data access and exchange)
- Repositories (ideally certified with CoreTrustSeal[19]; example of CoreTrustSeal repository is CSIRO's Data Access Portal[20])

[18] An example best practice for persistent identifier definition is available from the Australian Government's Linked Data Working Group – http://www.linked.data.gov.au/governance
[19] https://www.coretrustseal.org
[20] https://data.csiro.au/collections

Metadata specifications, repositories and registries, actionable policies and data stewardship management plans govern FAIR Digital Objects and ecosystems. Implementing FAIR Digital Objects and developing a FAIR ecosystem requires two high-priority activities (EC, 2018):

1. Development, refinement and adoption of shared vocabularies, ontologies, metadata specifications and standards central to interoperability and reuse of FAIR Digital Objects, and
2. Increased provision and professionalization of data stewardship, data repositories and data services.

Moreover, a FAIR interoperability framework has to be defined to ensure best practice across stakeholders in the community (e.g. in geodesy, the community represents both producers and users of geodetic data).

2.2. FAIR is a scale

Implementation of FAIR varies by the community in which the data needs to be FAIR, and to what degree. In this sense, FAIR needs to be understood as a scale, and hence various degrees of FAIRness for different types of digital objects are possible. One example, presented by Jones and Slaughter (2019), is illustrated in Figure 3, which shows the variability in FAIR score across more than 600,000 metadata records stored in repositories of the Data Observation Network for Earth (DataONE). As the example in Figure 3 indicates, most DataONE resources are findable and accessible (i.e. comply with most 'F' and 'A' requirements as defined in Section 2.1.1), and with only a few extremes, the 'F' and 'A' compliance scores mostly vary between 75 and 100 per cent. However, when it comes to resources interoperability and reusability (the 'I' and 'R' in FAIR), the scores are significantly lower. This might be due to missing FAIR checks, incomplete essential metadata, and other reasons which are currently a subject of further investigation (Jones & Slaughter, 2019).

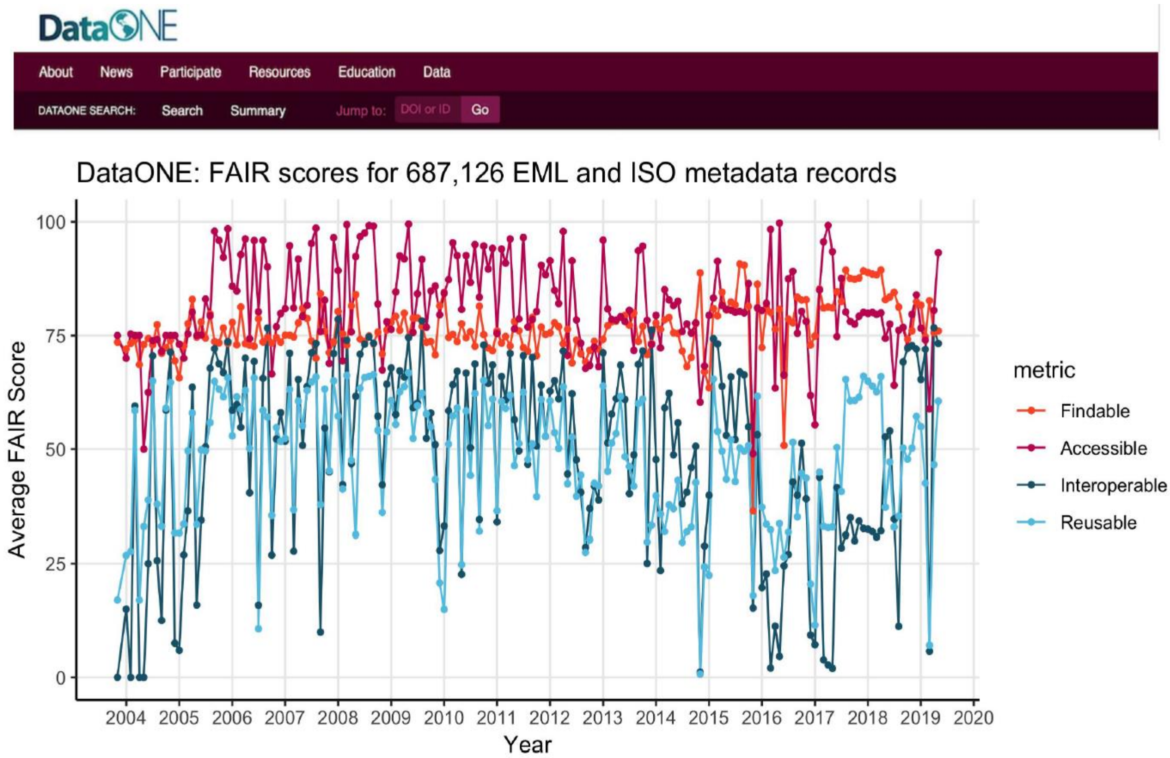

Figure 3: Monthly average FAIRness scores across metadata records (Jones & Slaughter, 2019)

In another report, Mons et al. (2017) argue that more than 80% of the datasets in current practice are 're-useless', which is the term to associate with a low FAIR score. Re-useless data include datasets with unknown or unclear provenance, published on obscure or unstable links without machine-resolvable persistent and unique identifiers (Mons et al., 2017).

2.3. Few examples of FAIR resources

In this section, a brief review of available international and Australian FAIR resources is reported, including FAIR data infrastructures, FAIR data repositories, FAIR metrics, and tools to measure FAIRness of digital objects.

2.3.1. FAIR international

Since its definition in 2016 (Wilkinson et al., 2016), FAIR principles have been rapidly adopted within international scientific communities. Several initiatives govern FAIR regionally and a global trend has been defined (Wilkinson et al., 2016; Mons et al., 2017; Stahl et al., 2019). Current FAIR initiatives around the world include the following:

FAIR in Europe: the European Open Science Cloud

The European Open Science Cloud (EOSC)[21] is an infrastructure and repository for research data, which supports science producers and science consumers in a federated access to data and services across Europe with a FAIR Data Action Plan as one of the initial drivers in its establishment (Hodson et al., 2018). The first phase of EOSC implementation (EOSC, 2017) is proposed to be achieved in four steps:

1. Define and apply FAIR appropriately
2. Develop and support a sustainable FAIR ecosystem
3. Ensure FAIR data and certified services to support FAIR
4. Embed a culture of FAIR into research practice

The EOSC is still under development with a strategic implementation plan for 2019-2020 already in place (EC, 2019). The mode of development is a European joint venture funded through European Commission research projects within the Horizon2020 research framework.

FAIR in North America: DataONE and its take on FAIR

The Data Observation Network for Earth (DataONE)[22] is a US distributed framework and sustainable cyberinfrastructure established in 2012 to support the needs of science and society for open, persistent, robust and secure access to well-described and easily discoverable Earth observation data. DataONE currently hosts 57TB of data content (≈ 1.2m data and over 800,000 metadata records) with an average activity of around 200,000 downloads per month[23]. The DataONE community subscribes seriously to the FAIR cause mainly by ongoing improvement of their metadata (Jones & Slaughter, 2019; Jones et al., 2019). There are series of webinars, workshops and best practice related to FAIR for DataONE members and the community is instrumental in the wider consortium of Earth System Information Partners (ESIP)[24], whose mission is to connect earth data and information to the community of science, education and practice.

FAIR in Africa: The African Open Science Platform

Similar to the rest of the world, the data science community in Africa is also progressing towards implementing FAIR principles into their best practice. They started by adopting the Dakar declaration on open science in Africa (Sci-GaIA, 2016) with the aim of creating a FAIR compliant open scientific platform for the access and sharing of scientific data. The development is in progress with strategic resources in place (AOSP, 2018). The FAIR cause in Africa is supported and promoted by various international communities, including Go-FAIR[25] and the FAO[26].

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[21] https://ec.europa.eu/research/openscience/index.cfm?pg=open-science-cloud
[22] https://www.dataone.org
[23] Up-to-date metrics available from: https://www.dataone.org/numbers
[24] https://www.esipfed.org
[25] https://www.go-fair.org/implementation-networks/overview/in-africa
[26] http://aims.fao.org/activity/blog/fair-data-what-and-why-easier-said-implemented

2.3.2. FAIR Australia

The need for FAIR digital resources has been recognized in Australia since the inception of the concept in 2016. The two main bodies advocating FAIR cause in Australia are the Australian Research Data Council (ARDC)[27] and the Australian National Data Service (ANDS)[28]. Both organizations champion the FAIR cause and offer support for the data-user community by participating in international initiatives that define FAIR, providing best practice guidelines and tools for assessment of FAIRness, and facilitating the organization of workshops and seminars to upskill the community, thus ensuring maximum recognition of Australian research through adoption of FAIR principles.

Within the Earth science community, a recently formed partnership, the Earth and Environment Information Science Partners (E2SIP)[29] is one of the strongest advocates for the FAIR cause. With their US counterpart, ESIP, E2SIP is involved in defining and establishing FAIR principles within the Australian geo-community. An example of one of their latest efforts is the inclusion of sessions on FAIR data management and stewardship in GEO Week 2019.[30] For the Australian National Computing Infrastructure, FAIR principles are essential for enabling data-intensive science, and there is a need for a data quality strategy to ensure consistency both within the computing infrastructure and in the offering of procedures for quality control/assurance and benchmarking performance testing (Evans et al., 2017).

One example where the FAIR principles advocated by ARDC, ANDS and E2SIP have offered an improvement in service is the Australian Ocean Data Network (AODN), a portal of meteorological and oceanographic data curated by the Australian Institute of Marine Sciences (AIMS). AIMS have considerably improved the FAIRness score of their repository by improving the content and web access to their metadata, linking to standardized metadata vocabularies, and defining persistent identifiers to their resources (ARDC, 2019). This experience allows Australian researchers to contribute to international efforts such as establishing global ocean FAIR services (Tanhue et al., 2019).

2.3.3. FAIR assessment metrics and tools

As mentioned in Section 2.2 , FAIRness of digital objects is measured along a scale – there is no unFAIR data and unFAIR digital object (Mons et al., 2017), with possibly one exception: when a digital object is "not even findable" it is deemed unFAIR (Mons et al., 2017, p.52). Various resource or domain-specific metrics can be used in addition to universal FAIRness metrics as listed in Section 2.1.1 (Wilkinson et al., 2018). Another clarification worth noting is that a FAIR assessment metric and any results stemming from its application must also be FAIR and accessible via an open standard, and there is a need for governance to both enable their careful evolution and address valid disagreements (Wilkinson et al., 2018).

Several FAIR assessment tools are available online, including:

- **ANDS's FAIR Data Self-assessment Tool**[31] – this tool has been designed for librarians and IT staff, but can be used by others to determine the FAIRness of their digital resources
- Two tools from the Dutch Data and Archiving Network Services (DANS) for digital research data:
    - **DANS Fairdat[32]** – a prototype FAIR assessment tool for evaluating the 'F', 'A' and 'I's score for digital resources

[27] https://ardc.edu.au
[28] https://www.ands.org.au
[29] http://www.c3dis.com/1945
[30] https://www.earthobservations.org/geoweek19.php?t=programme
[31] https://www.ands.org.au/working-with-data/fairdata/fair-data-self-assessment-tool
[32] https://www.surveymonkey.com/r/fairdat

  - **DANS Fair enough?**[33] – a short checklist to evaluate the FAIRness of digital resources
- The **CSIRO's 5-star Data Rating tool**[34] – a comprehensive self-assessment tool based on a rating scheme against the social, technical and informational attributes of data, and including assessment against FAIR principles
- **FAIR Metrics Questionnaire**[35] – a questionnaire for manual evaluation of the FAIRness of digital resources prepared by the FAIR Metrics group, the team around the founders of the FAIR concept (Wilkinson et al., 2018)

These five FAIR assessment tools have been used to assess the FAIRness score of data and metadata for precise positioning data encoded in current standards (RINEX & GA-ISO 19115-1) and example data and metadata encoded in the current version of the standard intended for use in the future (GeodesyML v0.5). The results are provided in Section 2.5.

The FAIR assessment tools listed above provide a method of self-assessment against predefined general FAIRness criteria, namely those listed in Section 2.1.1. More comprehensive online evaluation tools are emerging with the **MetaDIG**[36] engine, originally developed by the National Centre for Ecological Analysis and Synthesis, for evaluating compliance of any metadata against any standard (with ISO 19115, the international standard for geographic information metadata, included by default). This open-source tool is available for download and installation, with future plans being to expose the evaluation as a web-service (Jones & Slaughter, 2019; Jones et al., 2019).

2.4. FAIR and the 'geocommunity'

Although FAIR is a common keyword at most important geo events and venues (e.g. GEO Week 2019, AGU 2019 Fall meeting, ESIP 2019 Summer and Winter meetings), implementing FAIR principles is not yet common practice within the geospatial community. There are dozens of standards available for defining and sharing geospatial data, including the ISO 19100 series and OGC specifications, as well as several community profiles and best practices. However, in most cases these standards fall short in ensuring the FAIR distribution of geospatial resources. The good news is that the 'geocommunity' recognizes the need for FAIR digital resources. For example, at the end of 2019, the OGC changed its mission from being an organisation driven to enable the geospatial web into being an organisation driven to make geospatial (location) information and services FAIR, i.e. Findable, Accessible, Interoperable, and Reusable. The concept of FAIR is not explicitly referenced by ISO or in the ISO 19100 set of standards for geographic information, but mechanisms for geographic information discovery ('F'), access ('A'), interoperability ('I') and reuse ('R') are available. However, even if standards for ensuring FAIRness of digital resources are available, the selection of an appropriate set of standards and the provision of information beyond the mandated minimum remains a decision for the digital resource producer.

2.5. Geodetic data and metadata standards evaluation support for FAIR

In this section, an overview of current standards for geodetic data and metadata and their support for FAIR is provided. The analysis is a result of desk-based research during which all standards in the list were reviewed and elements/definitions supporting the FAIR guiding principle as defined in Section 2.1.1 were searched for. The focus is upon the following aspects:

1. Support of geodetic standards for FAIR

[33] https://docs.google.com/forms/d/e/1FAIpQLSf7t1Z9IOBoj5GgWqik8KnhtH3B819Ch6lD5KuAz7yn0I0Opw/viewform
[34] http://oznome.csiro.au/5star
[35] https://github.com/FAIRMetrics/Metrics/blob/master/Evaluation_Of_Metrics/Supplementary_Information_FM_Evaluation_Results.pdf
[36] https://github.com/NCEAS/metadig-engine

2. Support of core metadata elements in GA's profile of ISO 19115-1 – the standard currently used for disseminating metadata about precise positioning data to end-users (Section 2.6)
3. The FAIRness score for precise positioning data and metadata as currently provided (Section 2.6.1.1 and Section 2.6.1.2 respectively)
4. The FAIRness score for precise positioning data and metadata intended to be provided in the future (Section 2.6.2)
5. A summary of assessment for items 2-4 using the MetaDIG engine

NOTE: The ISO 19100 series contains several standards defining various aspects of geospatial metadata and several are relevant to the provision of information about geodetic resources. A comprehensive overview of geospatial metadata standards is provided by Brodeur et al. (2019), and a list of standards for metadata related to geographic information, along with short descriptions, is presented in Annex E.

Table 5 provides an overview of both current geodetic standards (i.e. standards from the ISO 19100 series directly relevant for the geodetic domain) and their support for FAIR. For each of the four principles of FAIR, a supported standard is indicated by a green tick. It is noted that standards from the ISO 19100 group support findability, accessibility, interoperability and reusability of geographic information inherently as a suite designed to encompass all aspects of the data lifecycle. However, due to the wide-reaching scope of the ISO 19100 series, the standards do not need to be implemented as a full collection and only relevant standards to the specific domain are typically selected. Hence, it is up to providers to select the appropriate collection and make sure a FAIR description of their resources is provided.

Table 5. Overview of standards for geodetic data and metadata and their support for FAIR.

Standard	FAIR Support			
	F	A	I	R
ISO 6709: 2008 Standard representation of geographic point location by coordinates ISO 6709:2008/COR 1: 2009			✓	✓
ISO 19111: 2019 Geographic information – Spatial referencing by geographic identifiers			✓	✓
ISO 19115-1: 2014 Geographic information – Metadata – Part 1: Fundamentals ISO 19115-1: 2014/AMD 1:2018 Geographic information – Metadata – Part 1: Fundamentals, Amendment 1 ISO 19115-2:2019 Geographic information – Metadata – Part 2: Extension for acquisition and processing ISO 19115-3: 2016 Geographic information – Metadata – Part 3: XML schema implementation for fundamental concepts ISO 19139-2: 2012 Geographic information – Metadata XML schema implementation – Part 2: Extension for imagery and gridded data	✓	✓	✓	✓
ISO 19116: 2019 Geographic information – Positioning services	✓	✓	✓	✓
ISO 19118: 2011 Geographic information – Encoding			✓	
ISO 19119: 2016 Geographic information – Services	✓	✓	✓	
ISO 19127: 2019 Geographic information – Geodetic register		✓	✓	
ISO 19132: 2007 Geographic information – Location-based services – Reference model		✓	✓	✓
ISO 19133: 2005 Geographic information – Location-based services – Tracking and navigation			✓	✓
ISO 19134: 2007 Geographic information – Location-based services – Multimodal routing and navigation			✓	✓
ISO 19145: 2013 Geographic information – Registry of representations of geographic point location		✓	✓	

ISO 19148: 2012 Geographic information – Linear referencing			✓	✓
ISO 19155: 2012 Geographic information – Place Identifier (PI) architecture ISO 19155-2: 2017 Geographic information – Place Identifier (PI) architecture – Part 2: Place Identifier (PI) linking	✓	✓	✓	
ISO 19156: 2011 Geographic information – Observations and Measurements			✓	✓
ISO 19157: 2013 Geographic information – Data Quality ISO 19157:2013/AMD 1: 2018 Geographic information – Describing data quality using coverages ISO 19157-2: 2016 Geographic information – Data Quality – Part 2: XML schema implementation	✓	✓	✓	✓
ISO 19161:2020 Geographic information – Geodetic references – Part 1: The international terrestrial reference system (ITRS)		✓	✓	
ISO 19162: 2019 Geographic information – Well-known text representation for coordinate reference systems			✓	✓
ISO 19165-1: 2018 Geographic information – Preservation of digital data and metadata – Part 1: fundamentals ISO 19165-2 (under development) Geographic information – Preservation of digital data and metadata – Part 2: Content specification for earth observation data and derived digital products	✓	✓	✓	✓
ISO 19168-1 (under development) Geographic information – Geospatial API for Features – Part 1: Core	✓	✓	✓	
ISO/NP 24245 Space systems – GNSS device codes			✓	
ISO/NP 24246 Space systems – Requirements for GNSS positioning augmentation centres			✓	
ISO 18197: 2015 Space systems — Space based services requirements for centimetre class positioning				✓
SpatioTemporal Asset Catalogue (STAC)[37]	✓	✓	✓	✓
ICSM Survey control standards				✓
ICSM Metadata profile	✓	✓	✓	✓
W3C DCAT	✓	✓	✓	✓
INSPIRE(/OGC) GeoDCAT-AP	✓	✓	✓	✓

2.6. Core metadata from GA Profile Extension for ISO 19115-1:2014, version 2.0[38]

The core metadata elements from the GA Metadata Profile of ISO 19115-1: 2014, along with their support for FAIR guiding principles as listed in Section 2.1.1, are overviewed in this section, with the whole metadata set and each individual metadata element being reviewed. In Table 6, a 'Y' indicates that an element supports the principle (together with additional explanation in bottom section of the table), whereas a 'Y/N' indicates partial support. Blank fields indicate an absence of explicit support of the FAIR principle.

Table 6. Core GA ISO 19115-1 metadata profile and their support for FAIR.

		Supports elements for FAIR (Y=Yes, N=No, blank = support not explicit)														
		Findable				Accessible				Interoperable			Reusable			
		F1	F2	F3	F4	A1	A1.1	A1.2	A2	I1	I2	I3	R1	R1.1	R1.2	R1.3
Metadata in full		Y	Y	Y	Y/N	Y	Y	Y		Y/N	Y/N	Y/N	Y/N	Y	Y/N	Y
Metadata element	**Element's obligation**															
Metadata Identifier	Mandatory	Y				Y	Y	Y	Y	Y	Y					Y

[37] https://stacspec.org
[38] http://pid.geoscience.gov.au/def/schema/ga

Default Locale (Metadata)	Conditional		Y							Y	Y					Y
Parent Metadata	Conditional		Y							Y	Y	Y/N				Y
Contact	Mandatory		Y							Y	N					Y
Date Info (Metadata)	Mandatory		Y							Y	Y					Y
Metadata Standard	Optional		Y							Y	Y					Y
Metadata Profile	Optional		Y							Y	N					Y
Metadata Constraints	Mandatory		Y							Y	N			Y		Y
Resource Scope	Mandatory		Y							Y	N					Y
Title	Mandatory		Y							N	N					Y
Date (Resource)	Mandatory		Y							Y	Y					Y
Identifier (Resource)	Mandatory		Y	Y							Y					Y
Abstract	Mandatory		Y							N	N					Y
Resource Point of Contact	Mandatory		Y							Y	N					Y
Topic Category	Mandatory		Y							Y	N					Y
Resource Maintenance	Mandatory		Y							Y	N					Y
Resource Constraints	Mandatory		Y							Y	N			Y		Y
Default Locale (Resource)	Conditional		Y							Y	Y					Y
Descriptive Keywords	Mandatory		Y							N	N					Y
Resource Lineage	Mandatory		Y							N	N				Y/N	Y
Reference System	Conditional		Y							N	N					Y
Geographic Extent	Conditional		Y							Y	N					Y
Temporal Extent	Conditional		Y							Y	N					Y
Resource Format	Conditional		Y							Y/N	N					Y
Distribution Format	Conditional		Y							Y/N	N					Y

Notes:
F4 - The resource is not discoverable by mainstream search engines, but it can be harvested via CSW requests.

I1 - Metadata format is XML, but many elements are in free-form text using domain specific language and not connected to any universal vocabularies. I2 - Metadata uses standard vocabulary (ISO 19115-1) combined with the domain specific language. However, as ISO 19115-1 vocabulary is not accessible online, this vocabulary is not FAIR. I3 - There is a link to parent metadata, but is it a URI, or any other machine-readable identifier. R1 - Metadata is richly described and follows community standard (ISO 19115-1). However, some crucial elements (abstract and lineage) are in free-text and vocabulary used for description is not linked to any global vocabulary (e.g. DCAT or PROV), and these limitations hamper the fully automated re-use of the (meta)data. R1.2 - Provenance information is present (LI_Lineage is Mandatory, but it is described in free-text).

2.6.1. FAIRness of geodetic metadata and data records as currently provided to the end-users

Sections 2.6.1.1 and 2.6.1.2 provide an overview of FAIRness status of metadata and data record, respectively, as measured with selected online FAIRness self-assessment tools (as listed in Section 2.3.3 and Table 7). The evaluation method was manual; the FAIR self-assessment tool was applied in the testing of each of the records covered in the sections below. Together with the FAIRness score, details of the metadata or data record and the web-access parameters of the record for each section are provided.

2.6.1.1. An example GNSS metadata record

- Metadata record: Metadata of 'Geodesy – Continuously Operating'
- Metadata URL: https://ecat.ga.gov.au/geonetwork/srv/eng/catalog.search#/metadata/74501

Table 7. FAIRness scores for an example metadata record.

Tool	Tool URL	GA record FAIR score
ANDS FAIR Data Self-assessment Tool	https://www.ands-nectar-rds.org.au/fair-tool	Approx. over 60% (no numeric result)
DANS-Fairdat	https://www.surveymonkey.com/r/fairdat	4.67 out of 5 calculated as (F+A+I)/3; NOTE: the tool does not test 'R'.
DANS-Fair enough?	https://docs.google.com/forms/d/e/1FAIpQLSf7t1Z9IOBoj5GqWqik8KnhtH3B819Ch6lD5KuAz7yn0I0Opw/viewform	13 out of 13 points
The CSIRO 5-star Data Rating tool	http://oznome.csiro.au/5star/	3.48* out of 5*
FAIR Metrics Questionnaire	https://github.com/FAIRMetrics/Metrics/blob/master/Evaluation_Of_Metrics/Supplementary_Information__FM_Evaluation_Results.pdf	12 pass; 8 fail; 1 problematic; 1 not applicable (out of 22 questions in total)

As mentioned in Section 2.3.3, assistance was made available from the developers of NCEAS's MetaDIG (Jones et al., 2019), which is a robust metadata evaluation tool able to test against customized FAIRness evaluation criteria. This tool currently operates in compliance with specific metadata and FAIRness requirements and it is able to test records compliant with ISO 19115 and encoded in XML as per ISO 19139. Hence, it was possible to test the metadata record of GA's 'Geodesy – Continuously operating'. Indicative results from MetaDIG are not very optimistic for GA's record, which failed most currently available checks (see details in Annex D). However, as mentioned earlier in Section 2.3.3, the reasons for this score might be differences in the standard used for specifying the rules. MetaDIG works with ISO 19139 and GA's metadata record complies with the GA Metadata Profile of ISO 19115-1: 2014. While both standards are very similar, they also differ in a number of ways.

2.6.1.2. An example GNSS data record

- Data record: daily observation from one station (Albany) of 'Geodesy – Continuously Operating' product (file: **alby1570.19d.Z**)
- Data URL: ftp://ftp.ga.gov.au/geodesy-outgoing/gnss/data/daily/2019/19157/alby1570.19d.Z

Table 8. FAIRness scores for an example data record.

Tool	Tool URL	GA record FAIR score
ANDS FAIR Data Self-assessment Tool	https://www.ands-nectar-rds.org.au/fair-tool	No numeric result, only colour indicator showing approx. **25%**
DANS-Fairdat	https://www.surveymonkey.com/r/fairdat	**1.67 out of 5** calculated as (F+A+I)/3; NOTE: the tool does not test 'R'.
DANS-Fair enough?	https://docs.google.com/forms/d/e/1FAIpQLSf7t1Z9IOBoj5GgWqik8KnhtH3B819Ch6lD5KuAz7yn0I0Opw/viewform	**7 out of 13** points
The CSIRO 5-star Data Rating tool	http://oznome.csiro.au/5star	**0.78* out of 5***
FAIR Metrics Questionnaire	https://github.com/FAIRMetrics/Metrics/blob/master/Evaluation_Of_Metrics/Supplementary_Information__FM_Evaluation_Results.pdf	**6 pass**; 15 fail; 0 problematic; 1 not applicable (**out of 22** questions in total)

2.6.2. FAIRness of geodetic data records as intended to be provided in the future

The long-term intent is to improve the standards used for exchange of geodetic data. The result of previous efforts in this direction is version 0.5 of the GeodesyML[39] encoding standard, and it is interesting to note if and how FAIRness score improves, should the geodetic data and metadata be encoded in compliance with GeodesyML. GeodesyML has the capacity to encode data together with associated metadata.

In the sections below, FAIRness scores are presented for two records of the position of reference sites within the Australian network of Continuously Operating Reference Stations (the dataset parts of which were tested in Section 2.6.1). These were found within examples of data records in GeodesyML's repository[40]. The evaluation method involved manual use of the FAIR self-assessment tools (as listed in Section 2.3.3), and during the evaluation several assumptions were made, these being listed for each record below.

2.6.2.1. 20na_20161027.xml Data Record

- Data record: example from GeodesyML's GitHub repository (file: **20na_20161027.xml**)
- Data URL (this is a placeholder URL for testing purposes only; assumption is that GeodesyML's will be present on the web in one way or another, i.e. findable via a URL[41]):
- **ASSUMPTIONS** on GeodesyML (derived from other GA records):
  - data records accessible via URL
  - metadata available as ISO 19115 GA profile
  - accessible without restrictions, e.g. via CC-BY 4.0 license
  - accessible via standard API (e.g. OGC)

[39] http://geodesyml.org
[40] https://github.com/GeoscienceAustralia/GeodesyML/blob/master/examples
[41] https://github.com/GeoscienceAustralia/GeodesyML/blob/master/examples/0.5/20na_20161027.xml

- data directly available via GA's catalogue

Table 9. FAIRness scores for 20na_20161027.xml - data example encoded in GeodesyML.

Tool	Tool URL	GA record FAIR score
ANDS FAIR Data Self-assessment Tool	https://www.ands-nectar-rds.org.au/fair-tool	No numeric result, only colour indicator showing approx. **50%**
DANS-Fairdat	https://www.surveymonkey.com/r/fairdat	**4 out of 5** calculated as (F+A+I)/3; NOTE: the tool does not test 'R'.
DANS-Fair enough?	https://docs.google.com/forms/d/e/1FAIpQLSf7t1Z9IOBoj5GgWqik8KnhtH3B819Ch6lD5KuAz7yn0I0Opw/viewform	**8 out of 13** points
The CSIRO 5-star Data Rating tool	http://oznome.csiro.au/5star	**3.13* out of 5***
FAIR Metrics Questionnaire	https://github.com/FAIRMetrics/Metrics/blob/master/Evaluation_Of_Metrics/Supplementary_Information_-_FM_Evaluation_Results.pdf	**5 pass**; 16 fail; 0 problematic; 1 not applicable (**out of 22** questions in total)

2.6.2.2. MOBS.xml Data Record

- Data record: example from GeodesyML's GitHub repository (file: **MOBS.xml**)
- Data URL (this is a placeholder URL for testing purposes only; assumption is that GeodesyML's will be present on the web in one way or another, i.e. findable via a URL): https://github.com/GeoscienceAustralia/GeodesyML/blob/master/examples/0.5/MOBS.xml
- **ASSUMPTIONS** on GeodesyML (derived from other GA records):
  - data records accessible via URL
  - metadata available as ISO 19115 GA profile
  - accessible without restrictions, e.g. via CC-BY 4.0 license
  - accessible via standard API (e.g. OGC)

Table 10. FAIRness scores for MOBS.xml – an example data record encoded in GeodesyML.

Tool	Tool URL	GA record FAIR score
ANDS FAIR Data Self-assessment Tool	https://www.ands-nectar-rds.org.au/fair-tool	No numeric result, only colour indicator showing approx. **80%**
DANS-Fairdat	https://www.surveymonkey.com/r/fairdat	**4 out of 5** calculated as (F+A+I)/3; NOTE: the tool does not test 'R'.
DANS-Fair enough?	https://docs.google.com/forms/d/e/1FAIpQLSf7t1Z9IOBoj5GgWqik8KnhtH3B819Ch6lD5KuAz7yn0I0Opw/viewform	**8 out of 13** points
The CSIRO 5-star Data Rating tool	http://oznome.csiro.au/5star	**3.13* out of 5***
FAIR Metrics Questionnaire	https://github.com/FAIRMetrics/Metrics/blob/master/Evaluation_Of_Metrics/Supplementary_Information_-_FM_Evaluation_Results.pdf	**5 pass**; 16 fail; 0 problematic; 1 not applicable (**out of 22** questions in total)

Differences between 20na_20161027.xml and MOBS.xml:

- MOBS.xml contains data quality info (increases the R score):

- Line 79: record of tracking change (this is lineage)
- Line 91: ME (firmware?) upgrade (this is lineage)
- Line 213: position record quality (this is extra metadata)
- Lines 266-297: record of GNSS receiver updates (this is lineage)
- Lines 895-961: complete history (lineage) of the record)

- MOBS.xml is linked to other data (increases the I score) – e.g.:
  - Line 767-779 and 798-810: links to associated documents available via URL

The results indicate that there is significant improvement in the FAIRness score (from 25% to 80% with the ANDS Tool) when data is encoded in GeodesyML instead of using legacy encoding standards. Note that the results above do not measure if current positioning data provides end-users with the expected information. As explained in detail in Section 3.3, most of the information expected by users is still missing in current (meta)data. Nevertheless, the improved FAIRness score means that GeodesyML is designed to support FAIR and if developed further, it may well be the standard which enables precise positioning end-users FAIR access to precise positioning data.

Preliminary findings show that data discovery and access is still a very challenging, and at times close to an impossible exercise. There are several reasons for this, as outlined below:

- There are gaps in content and understanding of metadata provided by geospatial data producers and those expected by the community of practice (e.g. end-users of the spatial resource, or other stakeholders of the spatial data infrastructure)
- The format of metadata is not interoperable for all metadata consumers (e.g. non-expert human user and machines)
- Metadata are often incomplete, leading to a description of the resources insufficient for decision on spatial resources' fitness for use
- Metadata are declared in a local jargon (e.g. language of geodetic science, which might not be fully comprehensible by users from other sectors)
- Metadata provided in a free-form text is not linked to any open vocabulary, which makes it impossible for machines to parse and use these metadata automatically
- Metadata are provided at the dataset series level and not at the data level, which naturally results in highly generalized metadata sets with crucial metadata information missing
- Metadata included with the data as traditionally provided (e.g. with RINEX data format) are incomplete with regard to the end-user expectations listed in Section 1.2
- Metadata are detached from the data, which hampers effective decisions on fitness for use

Moreover, as can be observed from the results in Tables Table 6 to 10, geodetic standards are progressing towards better compliance with FAIR principles. The deficiencies causing low FAIR score are similar to those indicated by Jones and Slaughter (2019) and Mons et al. (2017). Current data and metadata records miss elements of interoperability and reusability, which include machine-readable records of the provenance, machine-readable license information, links to well-defined and established domain vocabularies of a resource. More work is required to both create a definition of detailed, community-specific requirements for FAIR and set-up a FAIRness compliance test for geodetic data and metadata records.

3. Towards FAIR geodetic standards

Introducing FAIR in the geospatial domain is especially relevant for foundational geospatial data, such as required inputs for precise positioning. This is urgent, as within the next five years GNSS with corrections from internet or satellite communications will permit national coverage of positioning services with real-time accuracy of several centimetres or better. Such developments will open up a wide range of positioning applications for new and emerging industries (e.g. intelligent transport systems, precision agriculture, location-based services) and enable existing industries to improve their productivity, efficiency, safety and decision making.

However, in order to support new and existing users and to maximise data potential, it is essential that geodetic data and services are not only FAIR, but also provide relevant metadata which is accessible by precise positioning end-users in an expected way and expected format. This is currently not the case for various reasons: firstly, there are gaps in content and understanding of the metadata provided by geospatial data producers and that expected by the end-users; and secondly, the provided metadata is sometimes incomplete, which renders end-users incapable of making reliable decisions regarding the suitability of the data.

In this chapter, GNSS end-user requirements as detailed in Chapter 1 are revisited in order to provide a description of how current standards support the fulfilling of these requirements, and to propose what can be done to fill the critical gaps in current standards to support high-use precise positioning sectors.

3.1. Support of end-user requirements in current geodetic standards

Users in application domains of precise positioning make decisions on the fitness for use of geodetic data based on quality metadata (Ivánová et al., 2013). The requirements for metadata in current precise positioning end-user sectors are shown in Table 2, and a review was provided on how current standards support these requirements. The results are shown Table 11 (please note that for brevity, the table lists standards by their number, the full titles being available in Table 5).

It is evident from Table 11 that current standards do not support the full extent of precise positioning end-user requirements. There is practically no support beyond accuracy and coverage elements in current standards. This is not a surprise *per se* as the standards listed above are general and are defined intentionally to allow their implementation in the widest possible array of geospatial applications. For example, the ISO 19115 standard for metadata is intentionally generic to satisfy metadata requirements and needs of various disciplines. This standard is equally applicable to sharing data of regional interest[42], as it is to specific and local interests[43]. The ISO 19115 standard supports, by default, only quality elements that are defined in its data quality normative references, ISO 19157 or 19133. Hence the support for accuracy and coverage and not for robustness and continuity (concepts well-known and quantifiable in the field of geodesy, but not elsewhere). The same holds for the ISO 19119 standard for services where there is support for generic quality parameters recognized and measurable in most types of services (such as availability and reliability), but not for specific quality indicators of geodetic services (such as authentication and continuity).

[42] Example dataset of protected areas across Scandinavia – ISO 19115 compliant metadata is accessible here.
[43] Example dataset of one gravity point in Western Australia – ISO 19115 compliant metadata is accessible here.

Table 11. End-use requirement support of current standards for precise positioning data.

Standard	Support for metadata elements (✓= support explicit, blank = support not explicit)							
	Accuracy	Availability	Integrity	Coverage	Reliability	Robustness	Continuity	Authentication
ISO 6709	✓							
ISO 19111	✓							
ISO 19115	✓			✓				
ISO 19116	✓		✓	✓				
ISO 19118								
ISO 19119		✓		✓	✓			
ISO 19127	✓							
ISO 19132	✓							
ISO 19133	✓	✓		✓				
ISO 19134								
ISO 19145								
ISO 19148								
ISO 19155				✓				
ISO 19156	✓			✓				
ISO 19157	✓			✓				
ISO 19161				✓				
ISO 19162	✓			✓				
ISO 19165-1								
IS—19168--1								
ISO/NP 24245								
ISO/NP 24246	✓		✓					
ISO 18197	✓							
STAC								
ICSM Survey control standards	✓							
ICSM Metadata profile	✓			✓				
W3C DCAT								
INSPIRE(OGC) GeoDCAT-AP				✓				
OGC TimeSeriesML								

3.2. Critical gaps in current geodetic standards

Tables 12- 20 present a tabulated review of the analysis of critical gaps in current geodetic standards that restrict the FAIRness of precise positioning data in high-use sectors. Each table presents the following information:

In grey columns:	Detailed end-user requirements (including expected measure and magnitude for each requirement) as listed in Chapter 1 and sourced from the GNSS end-user reports prepared by the GSA (GSA, 2018; GSA, 2019a-g), and GNSS handbook (Teunissen & Montenbruck, 2017).
In green columns:	Supporting standards for encoding of data, specifying and encoding quality and other metadata. Here, for brevity, standards are listed only by their number, the full title being available in Table 5.
In red columns:	Gaps in current standards supporting end-user requirements.
In yellow columns:	Proposed improvements in these standards.

From the tables, it is evident that several standards are already available to support the encoding of geographic data, quality information and metadata, as shown by well-populated columns under the green headings. There are no immediate gaps in standards for encoding the precise positioning data and their metadata. GeodesyML in its current version has the potential to encode geodetic data and metadata. However, further expansion of GeodesyML's logical model and its alignment with other standards (e.g. TimeSeriesML and ISO 19156) to cater for current end-users within the entire GNSS data supply chain are necessary. More detailed analysis and proposals for improvement are presented in Chapter 4.

The present analysis has identified that the biggest problem is with the provision of a sufficient set of quality metadata, which would allow end-users to make confident decisions on the fitness of use of precise positioning data for their purpose. For example, for some end-user sectors there is information about accuracy expressed in specific ranges (e.g. horizontal accuracy for the agriculture sector as 2.5-30cm), whereas for other sectors only indications of the order of magnitude were obtained (e.g. m-level as one of the accuracy classes in Surveying). Similarly, inconsistency was observed in reported values for other metadata elements. For example, requirements for integrity appear differently across different sectors. In the maritime sector, the format appears as 'integrity message required'; in agriculture it appears in ranges of low, medium and high; and in the time and synchronisation sector it has an absolute requirement of $1\text{-}1\times10^{-7}$/h. Moreover, current standards do not offer a comprehensive, domain-specific (i.e. geodetic) set of elements and will require extension of the standard model. This is possible, according to the rules specified in ISO 19115-1:2014.

Table 12. End-user requirements support in current standards – Agriculture sector.

	Requirements		Supporting standards			Gaps in standards			Necessary improvement
	Element	**Value**	**Data**	**Quality**	**Metadata**	**Data**	**Quality**	**Metadata**	
Agriculture (Ag)	Accuracy	• 2.5-30cm; • sub-metre to metre level	• ISO 19133 • ISO 19148 • ISO 19156 • GeodesyML • OGC TimeSeriesML	• ISO 19157	• ISO 19115 • GeodesyML	• none	• insufficient data quality definition – missing: • quality elements • quality measures	• none	Expand ISO 19157 DQ model: • Add **Ag** DQ elements; • Specify measures for these new elements; and • Specify quality evaluation procedures for these elements. • Report metadata at end-user level – i.e. show **Ag** end-users **Ag** metadata – this requires update to the metadata catalogue interface; • Specify the data delivery format (GeodesyML, ISO 19156, TimeSeriesML, or raw data) of **Ag** data; • Include **Ag** metadata to the data delivered.
	Availability	• high • medium high							
	Integrity	• low • medium • high							
	Coverage	• national							
	Reliability	• low • medium • high							

Table 13. End-user requirements support in current standards – Road sector.

<table>
<tr><th rowspan="2"></th><th colspan="2">Requirements</th><th colspan="3">Supporting standards</th><th colspan="3">Gaps in standards</th><th rowspan="2">Necessary improvement</th></tr>
<tr><th>Element</th><th>Value</th><th>Data</th><th>Quality</th><th>Metadata</th><th>Data</th><th>Quality</th><th>Metadata</th></tr>
<tr><td rowspan="7">Road (Ro)</td><td>Accuracy</td><td>• Positional accuracy:
○ < 20cm
○ < 3m
○ < 5m
• Timing accuracy:
○ < 1ms
○ < 1s</td><td rowspan="7">• ISO 19133
• ISO 19148
• ISO 19156
• GeodesyML
• OGC TimeSeriesML</td><td rowspan="7">• ISO 19157</td><td rowspan="7">• ISO 19115
• GeodesyML</td><td rowspan="7">• none</td><td rowspan="7">• insufficient data quality definition – missing:
○ quality elements
○ quality measures</td><td rowspan="7">• none</td><td rowspan="7">Expand ISO 19157 DQ model:
• Add Ro DQ elements;
• Specify measures for these new elements; and
• Specify quality evaluation procedures for these elements.
• Report metadata at end-user level – i.e. show Ro end-users Ro metadata – this requires update to the metadata catalogue interface;
• Specify the data delivery format (GeodesyML, ISO 19156, TimeSeriesML, or raw data) of Ro data;
• Include Ro metadata to the data delivered.</td></tr>
<tr><td>Availability</td><td>• >99.5%
• >99.9%</td></tr>
<tr><td>Integrity</td><td>• Integrity message required
• Integrity message not required</td></tr>
<tr><td>Continuity</td><td>• low
• medium
• high</td></tr>
<tr><td>Reliability</td><td>• high</td></tr>
<tr><td>Authentication</td><td>• Authentication message required
• Position authentication:
○ Low (Pfa<10% & PD>68%)
○ Medium (Pfa<1% & PD>75%,)
○ High Pfa<0.2% & PD>85%</td></tr>
<tr><td>Interoperability</td><td>Measure & value not reported</td></tr>
</table>

Table 14. End-user requirements support in current standards – Rail sector.

	Requirements		Supporting standards			Gaps in standards			Necessary improvement
	Element	**Value**	**Data**	**Quality**	**Metadata**	**Data**	**Quality**	**Metadata**	
Rail (Ra)	Accuracy	• 0.01-1m • 1-10m • >10m	• ISO 19133 • ISO 19148 • ISO 19156 • GeodesyML • OGC TimeSeriesML	• ISO 19157	• ISO 19115 • GeodesyML	• none	• insufficient data quality definition – missing: ○ quality elements ○ quality measures	• none	Expand ISO 19157 DQ model: • Add **Ra** DQ elements; • Specify measures for these new elements; and • Specify quality evaluation procedures for these elements. • Report metadata at end-user level – i.e. show **Ra** end-users **Ra** metadata – this requires update to the metadata catalogue interface; • Specify the data delivery format (GeodesyML, ISO 19156, TimeSeriesML, or raw data) of **Ra** data; • Include **Ra** metadata to the data delivered.
	Availability	• low • high • 95%							
	Integrity	• low (<30s) • high(10-30s) • very high (<10s) • not applicable							
	Coverage	• national							
	Reliability	• $>2.7x10^{6}$ h • $>3.0x10^{5}$ h • $>8.0x10^{3}$h							

Table 15. End-user requirements support in current standards – Maritime sector.

	Requirements		Supporting standards			Gaps in standards			Necessary improvement
	Element	**Value**	**Data**	**Quality**	**Metadata**	**Data**	**Quality**	**Metadata**	
Maritime (Ma)	Accuracy	• Positional accuracy – ocean/coast: ○ 10m ○ 100m • Positional accuracy – inland waterway: ○ 0.1–10m	• ISO 19156 • GeodesyML • OGC TimeSeriesML	• ISO 19157	• ISO 19115 • GeodesyML	• none	• insufficient data quality definition – missing: ○ quality elements ○ quality measures	• none	Expand ISO 19157 DQ model: • Add **Ma** DQ elements; • Specify measures for these new elements; and • Specify quality evaluation procedures for these elements. • Report metadata at end-user level – i.e. show **Ma** end-users **Ma** metadata – this requires update to the metadata catalogue interface; • Specify the data delivery format (GeodesyML, ISO 19156, TimeSeriesML, or raw data) of **Ma** data; • Include **Ma** metadata to the data delivered.
	Availability	• > 99% • > 99.7% • > 99.8% • > 99.9%							
	Integrity	• Integrity message required ASAP by MSI • 10s							
	Continuity	• N/A • 99.97% over 15min							

Table 16. End-user requirements support in current standards – Aviation sector.

	Requirements		Supporting standards			Gaps in standards			Necessary improvement
	Element	**Value**	**Data**	**Quality**	**Metadata**	**Data**	**Quality**	**Metadata**	
Aviation (Av)	Accuracy	• Horizontal accuracy: ○ 16m ○ 220m ○ 0.74km ○ 3.7km • Vertical accuracy: ○ N/A ○ 4-6m ○ 8m ○ 20m	• ISO 19156 • GeodesyML • OGC TimeSeriesML	• ISO 19157	• ISO 19115 • GeodesyML	• none	• insufficient data quality definition – missing: ○ quality elements ○ quality measures	• none	Expand ISO 19157 DQ model: • Add **Av** DQ elements; • Specify measures for these new elements; and • Specify quality evaluation procedures for these elements. • Report metadata at end-user level – i.e. show **Av** end-users **Av** metadata – this requires update to the metadata catalogue interface; • Specify the data delivery format (GeodesyML, ISO 19156, TimeSeriesML, or raw data) of **Av** data; • Include **Av** metadata to the data delivered.
	Availability	• 99% - 99.99%							
	Integrity	• 1-1x10^{-7}/h • 1-2x10^{-7}/h							
	Continuity	• 1-1x10^{-4}/h to 1-1x10^{-8}/h • 1-8x10^{-6}/h per 15s							
	Time to Alert (TTA)	• 6s • 10s • 15s • 5min							

Table 17. End-user requirements support in current standards – Timing & Synchronisation sector.

	Requirements		Supporting standards			Gaps in standards			Necessary improvement
	Element	**Value**	**Data**	**Quality**	**Metadata**	**Data**	**Quality**	**Metadata**	
Timing & Synchronisation (T&S)	Accuracy	• Temporal accuracy: ○ 100-200ns ○ <10 ppb with 1.1µs phase synch and, 0.5µs for cells extend <800m ○ 1µs ○ 10µs	• ISO 19156 • GeodesyML • OGC TimeSeriesML	• ISO 19157	• ISO 19115 • GeodesyML	• none	• insufficient data quality definition – missing: ○ quality elements ○ quality measures	• none	Expand ISO 19157 DQ model: • Add **T&S** DQ elements; • Specify measures for these new elements; and • Specify quality evaluation procedures for these elements. • Report metadata at end-user level – i.e. show **T&S** end-users **T&S** metadata – this requires update to the metadata catalogue interface; • Specify the data delivery format (GeodesyML, ISO 19156, TimeSeriesML, or raw data) of **T&S** data; • Include **T&S** metadata to the data delivered.
	Authentication	• 99%-99.99%							
	Integrity	• 1-1x10^{-7}/h • 1-2x10^{-7}/h							
	Continuity	• continuous							
	Availability	• high							
	Independence	• Timing & Sync should not be dependent on GPS							
	Security	*Measure & value not reported*							
	Traceability	*Measure & value not reported*							
	Resilience	*Measure & value not reported*							
	Reliability	*Measure & value not reported*							
	Trust	*Measure & value not reported*							

Table 18. End-user requirements support in current standards – Location-Based Services sector.

	Requirements		Supporting standards			Gaps in standards			Necessary improvement
	Element	**Value**	**Data**	**Quality**	**Metadata**	**Data**	**Quality**	**Metadata**	
Location-Based Services (LBS)	Accuracy	• Horizontal accuracy: o Low: 5-10m o Medium: 1-5m o High: <1m • Vertical accuracy: o Low: 5-20m (95%) o Medium: 1-5m (enabling floor recognition) o High: <1m	• ISO 19132 • ISO 19133 • ISO 19134 • ISO 19156 • GeodesyML • OGC TimeSeriesML	• ISO 19157	• ISO 19115 • GeodesyML	• none	• insufficient data quality definition – missing: o quality elements o quality measures	• none	Expand ISO 19157 DQ model: • Add **LBS** DQ elements; • Specify measures for these new elements; and • Specify quality evaluation procedures for these elements. • Report metadata at end-user level – i.e. show **LBS** end-users **LBS** metadata – this requires update to the metadata catalogue interface; • Specify the data delivery format (GeodesyML, ISO 19156, TimeSeriesML, or raw data) of **LBS** data; • Include **LBS** metadata to the data delivered.
	Coverage	• Global • Regional • Local							
	Integrity	• TTA in seconds • Risk: o Low: <95% o Medium: 5-99% o High: 99.5%							
	Availability	• Urban canyon, canopy, indoors: o Yes/No • TTFF: o Low: >30s o Medium: 2-30s o High: <2s • Fix update type: o Continuous with given update rate o On request							

Table 19. End-user requirements support in current standards – Surveying sector.

	Requirements		Supporting standards			Gaps in standards			Necessary improvement
	Element	**Value**	**Data**	**Quality**	**Metadata**	**Data**	**Quality**	**Metadata**	
Surveying (Surv)	Accuracy	• Horizontal and Vertical Accuracy: ○ mm-level ○ cm-level ○ dm-level ○ m-level	• ISO 19156 • GeodesyML • OGC TimeSeriesML	• ISO 19157	• ISO 19115 • GeodesyML	• none	• insufficient data quality definition – missing: ○ quality elements ○ quality measures	• none	Expand ISO 19157 DQ model: • Add **Surv** DQ elements; • Specify measures for these new elements; and • Specify quality evaluation procedures for these elements. • Report metadata at end-user level – i.e. show **Surv** end-users **Surv** metadata – this requires update to the metadata catalogue interface; • Specify the data delivery format (GeodesyML, ISO 19156, TimeSeriesML, or raw data) of **Surv** data; • Include **Surv** metadata to the data delivered.
	Coverage	• Global • Regional • Local							
	Integrity & Reliability	• Low • Medium • High							
	Availability	• Urban canyon, canopy, indoors: ○ Yes/No • >95%: ○ Low ○ Medium ○ High • >99% ○ Low ○ Medium ○ High							
	TTFF	• few seconds • few minutes • >20min							
	GNSS contrib. to PT solution	• Low • Medium • High							

Table 20. End-user requirements support in current standards – Scientific Application sector.

	Requirements		Supporting standards			Gaps in standards			Necessary improvement
	Element	**Value**	**Data**	**Quality**	**Metadata**	**Data**	**Quality**	**Metadata**	
Scientific Applications (SciAp)	Accuracy	• Horizontal Accuracy: ○ 10mm + 1ppm • Vertical Accuracy: ○ 20mm + 1ppm	• ISO 19156 • GeodesyML • OGC TimeSeriesML	• ISO 19157	• ISO 19115 • GeodesyML	• none	• insufficient data quality definition – missing: ○ quality elements ○ quality measures	• none	Expand ISO 19157 DQ model: • Add **SciAp** DQ elements; • Specify measures for these new elements; and • Specify quality evaluation procedures for these elements. • Report metadata at end-user level – i.e. show **SciAp** end-users **SciAp** metadata – this requires update to the metadata catalogue interface; • Specify the data delivery format (GeodesyML, ISO 19156, TimeSeriesML, or raw data) of **SciAp** data; • Include **SciAp** metadata to the data delivered.
	Coverage	• Global • Regional • Local							
	Integrity & Reliability	High							
	Availability	High							
	Velocity of a GNSS site	• Few % of the fault slip rate • 0.1-1mm/year							

3.3. Metadata – crucial element for ensuring FAIRness

Metadata are crucial for ensuring FAIRness of digital resources (Wilkinson et al., 2016). Metadata can be *intrinsic* and *user-defined* (Mons et al., 2017). Intrinsic metadata is created automatically during data capture (e.g. time-stamps of a data record, or an automatic label of data production software) and user-defined metadata is added to provide context for understanding the creation of a digital object (e.g. through provenance information). Both types of metadata should be added to a digital resource to ensure its FAIRness.

Geospatial metadata are often stored and maintained separately from the resource itself. Ideally, for a Spatial Data Infrastructure (SDI) via its catalogue of resources, which should provide metadata records containing links to a described resource (and/or any related resources). However, SDIs provide only indirect access to a spatial resource described by the metadata stored in the catalogue. Moreover, the search for spatial resources is not a smooth process and typically happens in at least three steps (Ivánová et al., 2019):

1) Users (human or machine) access the SDI catalogue and retrieve metadata of interest
2) Users parse the metadata and compare values in crucial fields (e.g. spatial and temporal extent, time of last update, lineage etc.) with acceptable values
3) Users follow the links (not necessarily online web links) to the spatial resource

To illustrate a common search for a spatial resource, a digital resource offered through the Data and Publication portal of Geoscience Australia called 'Geodesy – Continuously Operating' is considered. This resource advertises "*Data collected from the Australian Regional Global Navigation Satellite System (GNSS) network, Auscope network and other GNSS observatories located around the world over the last 15 years.*"[44] According to the corporate metadata specification (GA, 2014), and as illustrated in Figure 4, one would expect to be provided with links, upon opening the metadata file of this product, to the resource that this metadata record describes (e.g. data and site logs from GNSS observatories).

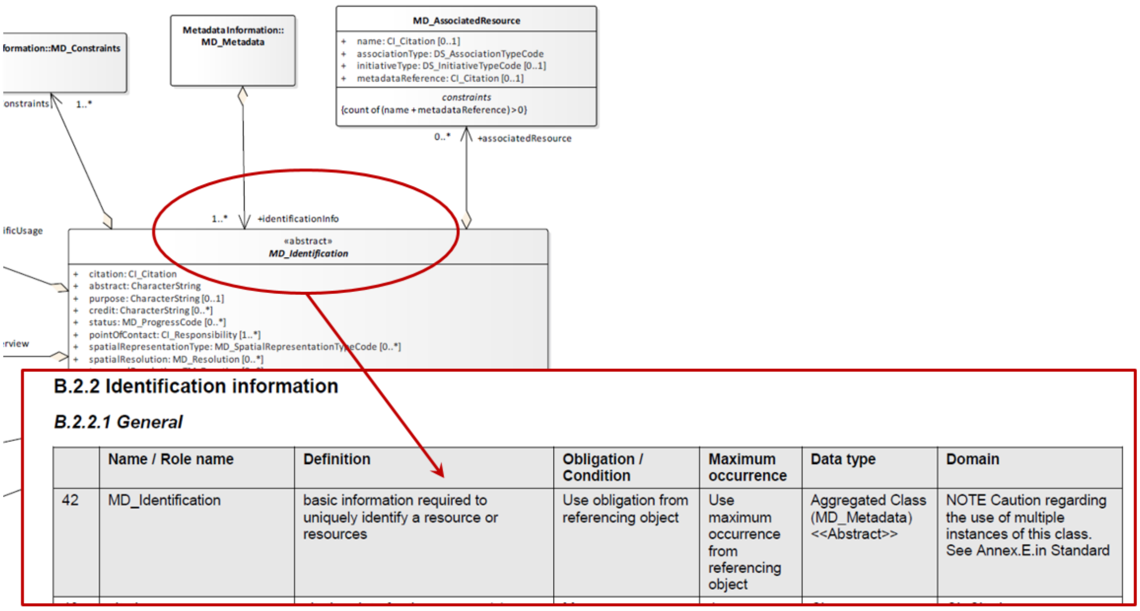

Figure 4: Resource identification information and related obligation as defined in GA (2014).

[44] http://pid.geoscience.gov.au/dataset/ga/74501

Unfortunately, as illustrated in Figure 5, this is not the case. The reference to resources related to the 'Geodesy – Continuously Operating' product is not present in its corporate standard compliant (GA, 2014) metadata.

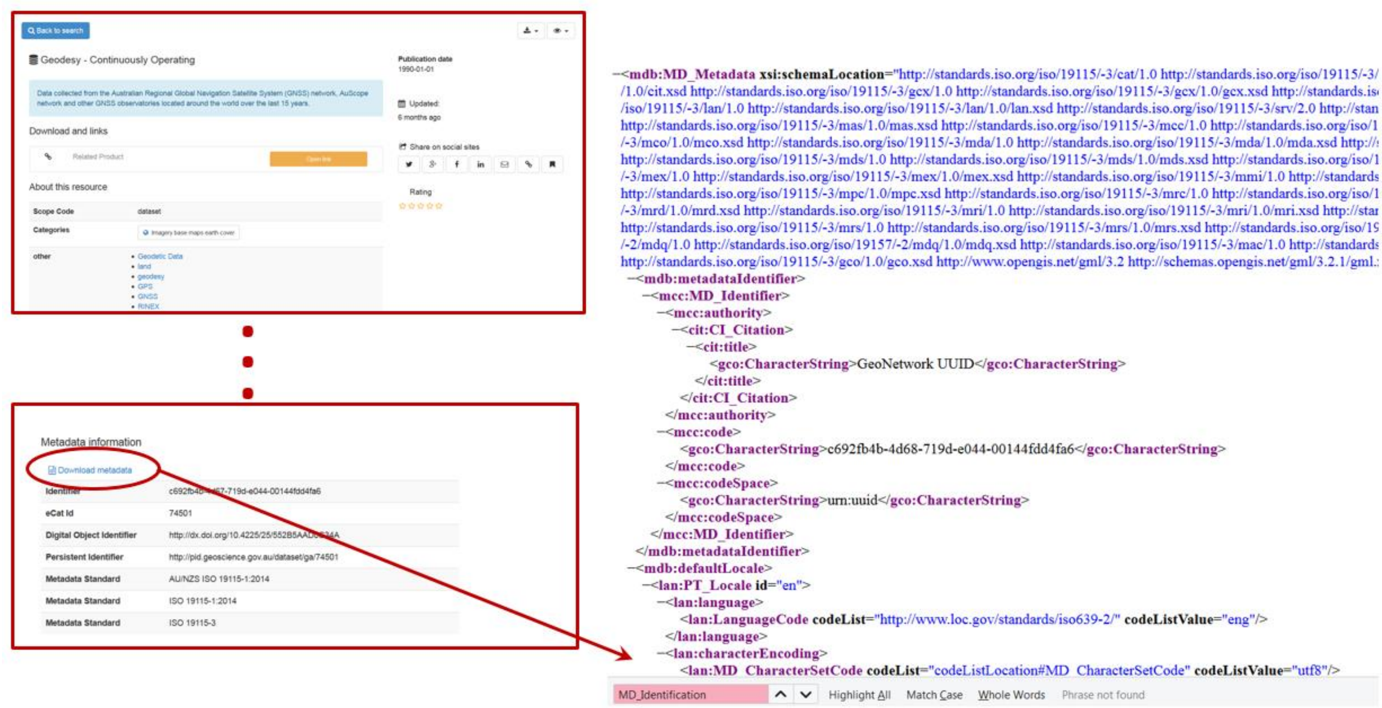

Figure 5: Missing identification of resources related to 'Geodesy – Continuously Operating' product.

On the landing information page for human access to the catalogue (Figure 6), there is a link to a location, which holds the associated resource to the product.

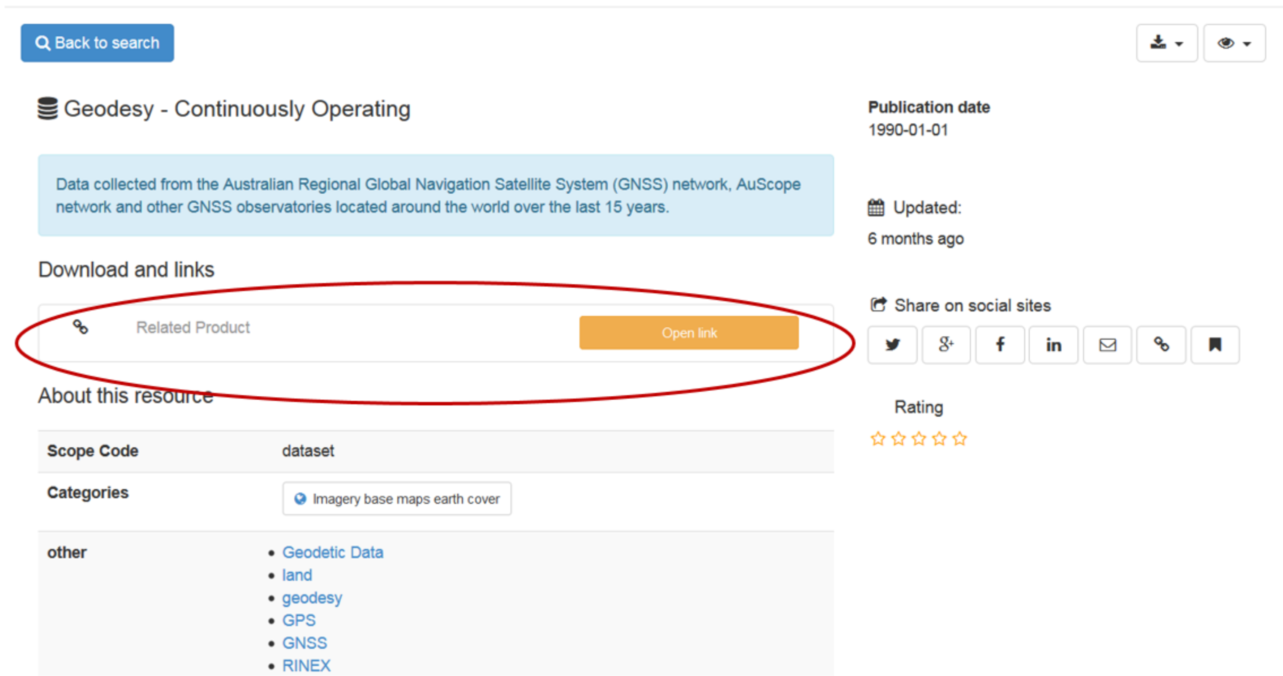

Figure 6: Landing page for human metadata consumption with link to related products.

However, this link takes several more manual clicks to get to the resource, as shown in Figure 7.

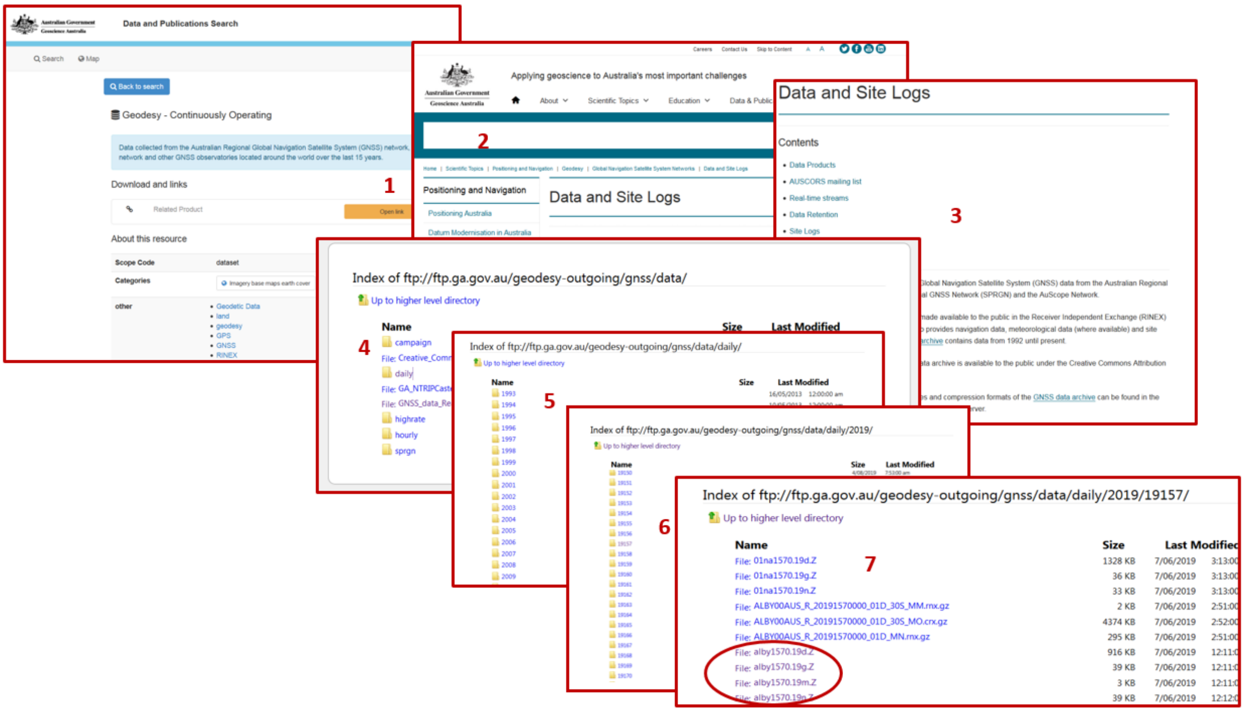

Figure 7: Navigating to the digital resource of interest advertised by the metadata.

This process may well be manageable for an educated searcher (e.g. a GNSS specialist), but a FAIR access to these resources is somewhat compromised for many current precise positioning end-users who are not GNSS specialists. They would likely have difficulty navigating through the set of pages illustrated above.

3.4. Providing the right metadata for the right user

The most important and necessary improvement in current precise positioning metadata is ensuring that providers offer the right metadata for the right user. This means that if users from the agriculture sector need access to precise positioning data and metadata, they should be able to determine its fitness for use based on metadata elements such as accuracy, availability, integrity, coverage and reliability (see Table 12). As indicated in Section 3.2 through Tables 12 – 20, this can be ensured by extending the quality of metadata, and ensuring that end-users only get exposed to metadata relevant to their interest.

3.4.1. Extending metadata in a standard compliant way

ISO/TC211 recognised that the intentional genericity of standards might create a problem in specific disciplines and offered solutions to overcome this limitation by allowing the creation of metadata extensions. A similar approach can be applied to offer required quality information for precise positioning end-users. ISO 19115 allows seven types of extensions:

1. Adding a new metadata package
2. Creating new metadata codelists to replace the domain of an existing metadata element that has 'free text' listed as its domain value
3. Creating new metadata codelist elements (expanding a codelist)
4. Adding new metadata elements
5. Adding new metadata classes

6. Imposing a more stringent obligation on an existing metadata element
7. Imposing a more restrictive domain on an existing metadata element

In the case of accommodating precise positioning user requirements, when new data quality elements are to be defined, the extensions listed in items 3, 4 and 5 above would be applicable. It is worth noting that this is also the proposed way of extending the data quality model with new, domain specific elements for the ISO 19157 on data quality, which is currently under revision at ISO/TC211.

3.4.2. Ensuring end-user sector relevant metadata exposure in data interchange

One standard compliance mechanism for ensuring access to community specific metadata is a 'community profile' (ISO, 2014). A community profile serves as a metadata extension mechanism in cases when information to be added to the standard set is extensive and specific to a discipline or application, and/or requires coordination of the proposed extension via specific user groups.

An example of a functional community profile is the GA Metadata Profile of ISO 19115-1: 2014 (GA, 2014). With this profile, a community (GA) mandates their providers to deliver more comprehensive metadata to the users of GA's data and services than the recommended minimum in (the more generic) ISO 19115.

Another example of a community profile is the ISO 19115:2003 Marine Community Profile (MCP) v2.0 Metadata[45] developed by the Australian Ocean Data Network to ensure marine end-users will receive only relevant metadata communicated through controlled vocabularies. This profile is similar to GA's metadata profile in that it is an extension to ISO 19115. In addition to a changed obligation for various metadata elements, the MCP also controls vocabulary used for expressing the value of these; e.g. MCP uses the AODN Units of Measure Vocabulary[46] for allowed entries for measures related to values provided within metadata.

The relationship between the comprehensive metadata set (currently around 400 metadata elements in ISO 19115), minimum metadata set (around four metadata elements) and a community metadata set is illustrated in Figure 8.

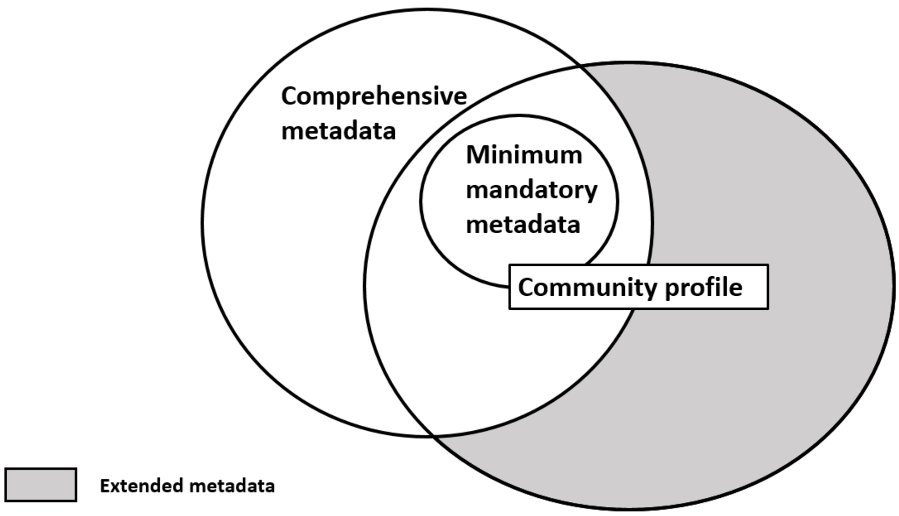

Figure 8: Relationship between comprehensive, minimum and community metadata (ISO, 2014).

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[45] https://help.aodn.org.au/contributing-data/iso-19115
[46] https://vocabs.ands.org.au/viewById/21

ISO 19115 specifies clear rules for creating metadata community profiles (ISO, 2014) and further best-practice community guidelines are available to see if such a profile is compliant with current best practices for data exchange (van den Brink et al., 2019). Decisions regarding the community scope are up to the creator of a profile. For the precise positioning community, a 'precise positioning data' community profile seems reasonable for the description of metadata relevant across high-use sectors. A challenge in this type of community profile is to ensure that only the most relevant subset of metadata of interest is exposed to the end-user sector. For human users, this can be achieved through careful design of the user interface; e.g. through the creation of user profiles that are used for restricting the display of metadata elements to only those relevant to their end-user type. For machine users, the identification of the category of end-user sector is perhaps a bit more challenging, however not impossible. Development of a 'precise positioning community profile' is underway as part of current work at Curtin University, Geoscience Australia and FrontierSI.

4. GeodesyML: a solution for FAIR geodetic data interchange

In this chapter, the rationale and purpose of the GNSS data exchange standard GeodesyML, which is used for delivering precise positioning information within the geodetic community, is reviewed and the GNSS value chain for data provision from GNSS satellites all the way to the end-user is described. Also, the use cases of the geodetic and geophysics communities are reviewed with the aim of understanding the work, resources and time required to ensure these use cases can be addressed in international standards. Use cases from the geodetic community have been provided by Geoscience Australia, and are documented in the 'eGeodesy Use Case Documentation', Version 0.1 presented by the ICSM's Permanent Committee on Geodesy (PCG) in April 2013. Unfortunately, no use cases nor related documentation have been received from the geophysics community in spite of these being requested at the initial stages of this scoping study. As an alternative, the ability of existing geodetic use cases to support requirements of the current GNSS end-user sectors identified earlier and presented in Chapter 1 was analysed. Resources used in the review for this chapter are listed in Annex A.

4.1. eGeodesy and GeodesyML – background, context and current status

eGeodesy is a logical model developed by ICSM's PCG, which aims to define a technology-independent language to model the core business processes, entities, and relationships within the geodetic domain. GeodesyML[47], an XML implementation of the eGeodesy model, is a Geography Markup Language[48] (GML) application schema for transfer of geodetic information (Donnelly et al., 2013). As such, GeodesyML is a similar GML application schema to OGC GeoSciML[49], OGC WaterML[50] or OGC CityGML[51].

The aim of examining eGeodesy use cases was to enable a description of the establishment and maintenance of the national geospatial reference system, which is fundamental to ensuring the delivery of lossless GNSS information to end-users. The basic GNSS information flow in a GNSS powered geospatial reference system is illustrated in Figure 9: raw data transmitted from the satellite is directed to the processing and correction centre, from where the corrected data is delivered to the end-user via the internet.

To increase the interoperability of geodetic data/information, ICSM's PCG together with GA promotes GeodesyML as a standard to encode geodetic data and metadata. GeodesyML, currently in Version 0.5, is still under development and is publicly available as open source at: https://github.com/GeoscienceAustralia/GeodesyML.

Encoding geodetic data and metadata in GeodesyML enhances interoperability by allowing data and metadata exchange on the internet. This way, any users, human (not only geodesist) or machine (not only specialized geodetic equipment) can request geodetic data by issuing standard web requests. GeodesyML has been designed to support event-triggered information exchange within and between organisational implementations of geodesy information systems (e.g. data centres, geodetic agencies) and users of geodetic products and services (PCG/ICSM, 2015).

As illustrated in Figure 10, the interaction between the network of IGS stations encoding their data in GeodesyML and data providers and consumers is proposed to be via a standard web service interface, such as the OGC Web Feature Service (WFS) [52] interface (Bohler et al., 2017).

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[47] http://www.geodesyml.org
[48] https://www.opengeospatial.org/standards/gml
[49] https://www.opengeospatial.org/standards/geosciml
[50] https://www.opengeospatial.org/standards/waterml
[51] https://www.opengeospatial.org/standards/citygml
[52] https://www.opengeospatial.org/standards/wfs

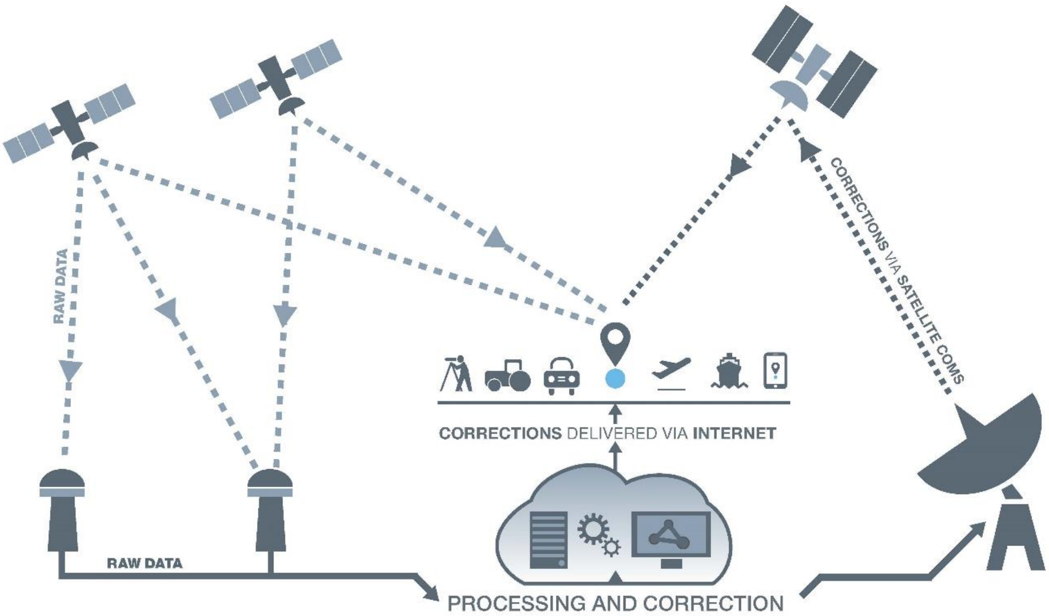

Figure 9: GNSS information flow (source: Geoscience Australia).

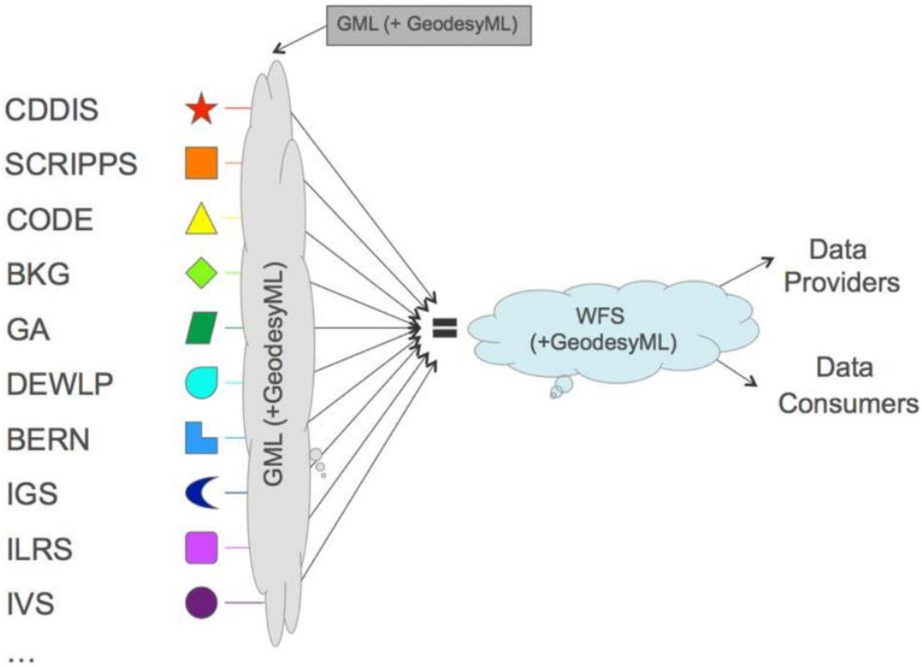

Figure 10: GNSS organisations interacting with data providers and consumers (Bohler et al., 2017).

GeodesyML provides information about GNSS (and in the future VLBI, DORIS and SLR) sites and measurements, reference frames, adjustments, quality and local ties (Bohler et al., 2017). OGC's Web Feature Service Interface (OGC WFS) enables data providers to expose this information to the web for users (human or machine) and allow requesting specific information of interest. A simple data exchange between a GNSS data provider (in our example, GA) and a user looking for an information about a site with ID 'ALBY' (this is a code of a permanent station of the continuously operating geodetic network located in Albany, Western Australia) will be used as an illustration. With site information encoded in GeodesyML and exposed to the internet through standard web service interface (e.g.) a user may simply issue the following request via OGC WFS:

https://testgeodesy-geoserver.geodesy.ga.gov.au/geoserver/wfs?request=GetFeature&typeName=geo:Site&cql_filter=gml:identifier='ALBY'

With this request, a user will receive the response illustrated in Figure 11.


```
-<wfs:FeatureCollection numberMatched="unknown" numberReturned="1"
  timeStamp="2020-01-31T02:06:26.343Z" xsi:schemaLocation="http://www.opengis.net/wfs/2.0
  http://testgeodesy-geoserver.geodesy.ga.gov.au:80/geoserver/schemas/wfs/2.0/wfs.xsd urn:xml-gov-
  au:icsm:egeodesy:0.4 http://schemas.ga.gov.au/geodesyml/0.4/geodesyML.xsd http://www.opengis.net
  /gml/3.2 http://testgeodesy-geoserver.geodesy.ga.gov.au:80/geoserver/schemas/gml/3.2.1/gml.xsd">
  -<wfs:member>
    -<geo:Site gml:id="Site.867">
        <gml:identifier codeSpace="urn:xml-gov-
        au:icsm:egeodesy:0.4:SiteIdentifier">ALBY</gml:identifier>
        <gml:name codeSpace="urn:xml-gov-au:icsm:egeodesy:0.4:SiteName">Albany</gml:name>
        <geo:type codeSpace="urn:xml-gov-au:icsm:egeodesy:0.4:SiteType">CORS</geo:type>
      </geo:Site>
    </wfs:member>
  </wfs:FeatureCollection>
```


Figure 11: Part of the response to a request for site information.

The response above provides additional information about the site; its type ('CORS') in this case. GeodesyML allows granularity in retrieved information from essential site information, such as that above, through a more detailed site log with site type or position. Note that the cumbersome construction of such requests can be avoided, for instance by using any mainstream geographic information system (e.g. QGIS[53]), thus allowing comfortable exploration of site information. To expedite adoption by software vendors, open-source GeodesyML binding libraries are being developed by GA, with bindings for Java already available at GA's developing repository[54].

GeodesyML has been designed to deal with International GNSS Service (IGS) site log information. Entities and relationships pertaining to observing system sites (e.g. GNSS CORS, SLR and VLBI), permanent survey marks, estimated positions, quality indicators, reference frames and metadata have been defined. GeodesyML handles the fundamental metadata types contained within an IGS site log, presently expressed either in text files or according to SOPAC XML schema[55] (PCG/ICSM, 2015). The current version (v 0.5) of GeodesyML contains 18 information packages for data encoding and a snippet of GeodesyML's structure (related to the 'monumentInfo' package) is illustrated in Figure 12.

---

53 https://qgis.org
54 https://github.com/GeoscienceAustralia/geodesyml-java-bindings
55 http://sopac-old.ucsd.edu/xml/XMLSchema.html

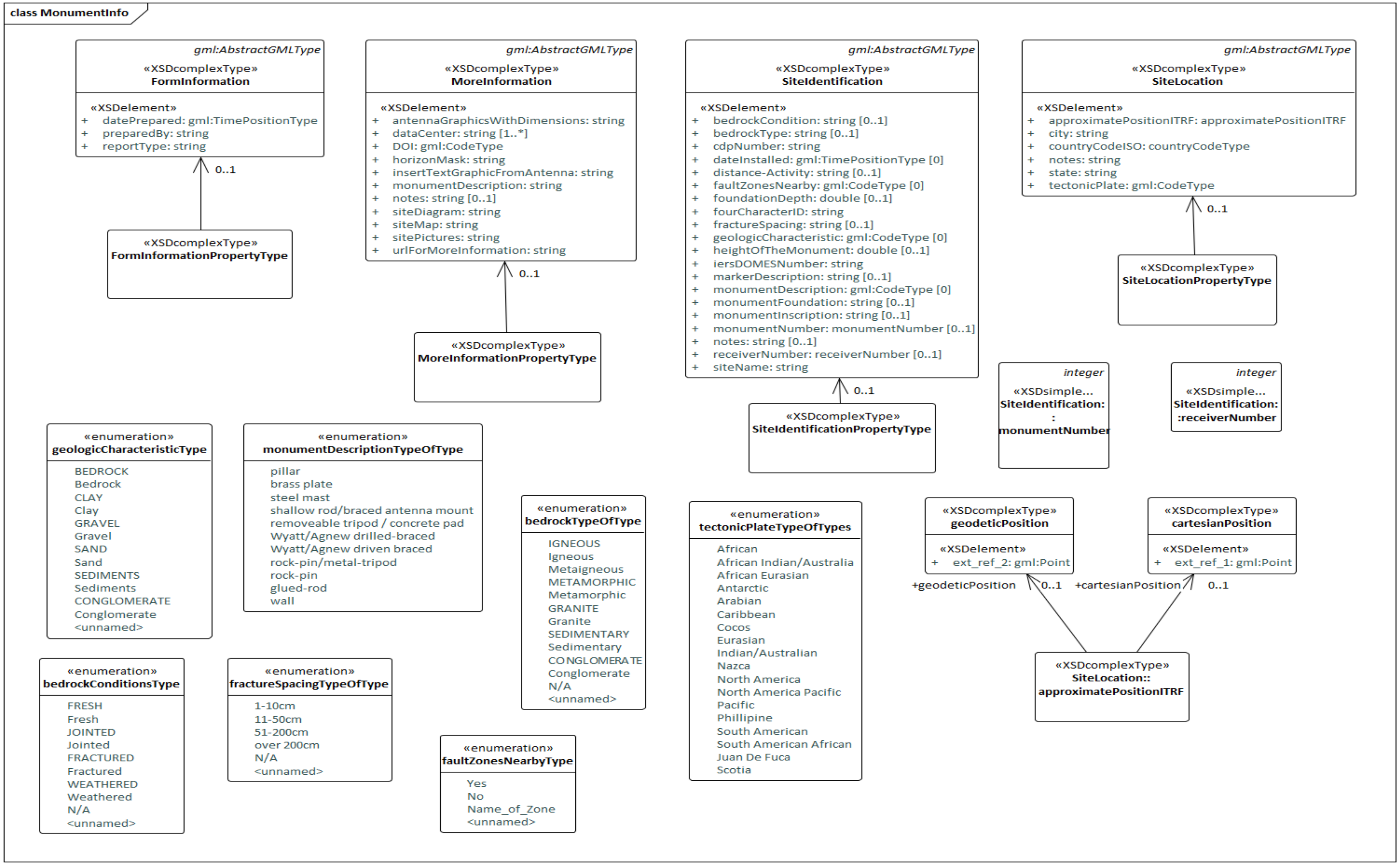

Figure 12: The 'monumentInfo' package of GeodesyML v 0.5.

GeodesyML encapsulates (parts of existing) geodetic information exchange standards allowing transfer of essential information between data produced by a variety of manufacturers (PCG/ICSM, 2015). An overview of GeodesyML's current support of existing standards is presented in (PCG, 2015) and depicted here in Figure 13.

Data and metadata	Existing Formats	GeodesyML Implementation
Raw GNSS observations	RINEX	Metadata header and pointer to RINEX file.
Terrestrial measurements	Leica GSI/DBX, Trimble, log books, etc.	Full encapsulation of data, metadata and measurement reduction source/lineage.
GNSS baselines	LGO project, various ASCII, TBC project	Full encapsulation of data, metadata and measurement reduction source/lineage.
GNSS cluster solution	SINEX	Choice of SINEX wrapper or a full GeodesyML implementation
Site/Mark metadata	IGS Site Log WKT, SOPAC XML Schema	Full encapsulation of site metadata, including full description of site type.
Site/Mark Position		Dynamic feature time series of coordinates and velocities.
Temporal separation of measurement nodes		A special data type called Node which abstracts the association between a Site and its Position for a time period.
Regulation 13 Certificates	XLSX	Site Certificate - an extension of the Node data type with an additional reference to the Site Certification definition.
Setup metadata	IGS Site Log WKT, SOPAC XML Schema	Complete abstraction of all instrument data types.
IGS Site Log	IGS Site Log WKT, SOPAC XML Schema	The choice of either the SOPAC XML Schema or a full GeodesyML implementation using GML data- types.
Coordinate Adjustment/Estimation		Full encapsulation of operands, results and reference to the adjustment process definition.
Coordinate Transformation		Full encapsulation of operands, results and reference to the transformation process definition.
Measurement reduction	LGO project, TBC project, Bernese configuration	Full encapsulation of operands, results and reference to the measurement reduction process definition.

Figure 13: Encapsulation of standards for encoding Geodetic and GNSS data (PCG, 2015).

Current implementation examples of GeodesyML demonstrate the data encoding and metadata exchange (e.g. about GNSS reference stations), and foundations are in place to support its implementation: there are example implementations, tools for translating between text-based site logs into GeodesyML and vice versa. Several test cases at GA, Royal Observatory of Belgium and at University NAVSTAR Consortium (UNAVCO) have proved successful, and the geodetic community is open to further improvements of the standard (Boler et al., 2017).

To leverage current standards and best practice of data exchange over the web (W3C, 2017), a standard for encoding GNSS data should not only support encoding of GNSS metadata, but also encoding of the data, ideally in the same record. This would allow data discovery and an automated decision regarding its fitness for intended use. Essentially, GeodesyML is designed in such a manner, as shown by the example depicted in Figure 14.

```xml
<geo:surveyedLocalTie>
    <geo:SurveyedLocalTie gml:id="SLT_1">
        <geo:tiedMarkerName>Melbourne South PM 520</geo:tiedMarkerName>
        <geo:tiedMarkerUsage>Local Height Control,</geo:tiedMarkerUsage>
        <geo:tiedMarkerCDPNumber/>
        <geo:tiedMarkerDOMESNumber/>
        <geo:differentialComponentsGNSSMarkerToTiedMonumentITRS>
            <geo:dx>31.8727</geo:dx>
            <geo:dy>15.4048</geo:dy>
            <geo:dz>-7.1087</geo:dz>
        </geo:differentialComponentsGNSSMarkerToTiedMonumentITRS>
        <geo:localSiteTiesAccuracy>1</geo:localSiteTiesAccuracy>
        <geo:surveyMethod>Total Station</geo:surveyMethod>
        <geo:dateMeasured>2012-06-07</geo:dateMeasured>
        <geo:notes>Deep driven copper clad rod - 2.8m long</geo:notes>
    </geo:SurveyedLocalTie>
    <geo:dateInserted>2012-06-07</geo:dateInserted>
</geo:surveyedLocalTie>
<geo:surveyedLocalTie>
```

Figure 14: Example of site tie accuracy encoding with GeodesyML v 0.5.

4.2. GNSS value chain to deliver data from satellite to end-user

GNSS consists of three segments: the space segment (satellites), the control segment (monitoring stations) and the user segment (the GNSS receivers in application sectors). From the perspective of the GNSS signal direction, GNSS can be viewed as a combination of upstream (station to satellite and back) and downstream (station to user) components. The GNSS **upstream** component is comprised of the space and control segments that provide a signal to users. The GNSS **downstream** component utilizes the infrastructure and signal provided by the GNSS upstream component within applications and services that encompass the entire value chain of GNSS-specific components, such as GNSS receivers, GNSS-enabled systems, GNSS-enabled software and value-added services (GSA, 2020). The downstream industry can be classified into three main types of providers (GSA, 2020):

1. **Component manufacturers** including manufacturers of GNSS-specific components (e.g. GNSS chipsets and antennae), small GNSS receivers and integration-ready GNSS receivers
2. **System integrators** adding GNSS capability into larger systems such as vehicles
3. **Value-added service providers** whose services improve access and use of GNSS (e.g. maps, location based services, telecoms)

GNSS end-users are an inseparable part of the value chain. The interaction between GNSS downstream components with example providers is illustrated in Figure 15 (GSA, 2019):

Component and receiver manufacturers		System Integrators		System providers		Users
Avago (Broadcom)	US	Apple	US	Alphabet inc. (Google)	US	Users of consumer, transport and professional GNSS-based solutions
Garmin	US	Bosch	DE	Denso	JP	
Hexagon	SE	China First	CN	ESRI	US	
Honeywell	US	Ford	US	Garmin	US	
Mediatek	CN	General Motors	US	Here International	NL	
Qualcomm	US	Honda	JP	Hexagon AB	SE	
Rockwell Collins	US	Nissan	JP	Microsoft	US	
Tomtom	NL	Samsung Electronics	KR	Pioneer	JP	
Trimble Navigation	US	Toyota	JP	Radius Payment Solutions	GB	
U-Blox	CH	Volkswagen	DE	Trimble Navigation	US	

Figure 15: Downstream GNSS value chain (GSA, 2019).

It is essential to ensure that end-users receive what they are expecting in the format they are expecting. According to earlier analysis, in order to have confidence in GNSS data, end-users need to understand the associated metadata. In other words, access to additional information about the data they are receiving is expected, including indicators of accuracy, availability, integrity and similar quality characteristics of the chosen GNSS product. For example, there are several components comprising a GNSS powered farm machinery guidance system (illustrated in Figure 16), and these need to ensure that the data together with metadata are transmitted to the vehicle. In a manual lightbar guidance system, the symbiosis of the GNSS receiver and antenna, computer for cross-track error computation ('Controller' in Figure 16) and the interface need to ensure that the driver receives consistently reliable indications on the guidance display that their vehicle is on track.

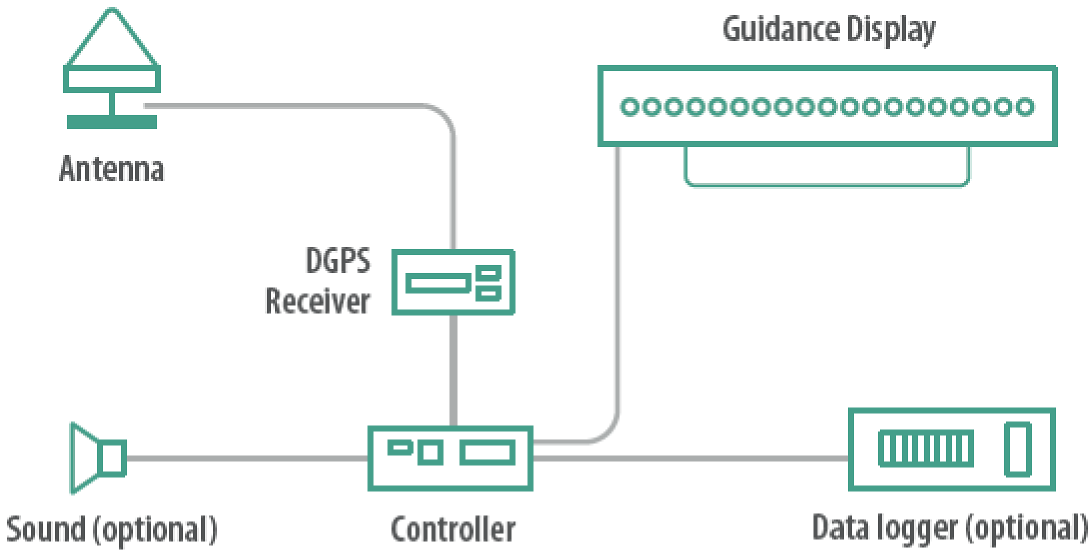

Figure 16: GNSS powered farm machinery guidance system (GSA, 2018).

The requirements for a GNSS powered farm machinery guidance system are indicated in Figure 17.

Agriculture Application Categories	Application	Accuracy	Survey method and its relevance per app	Availability		Robust-ness	Authen-tication	Integrity and reli-ability	Size, weight, autonomy		Fixing and convergence time
		(Horizontal)		Canopy					Relevance	Autonomy	
		mm-level cm-level sub-metre m-level	Relevance per App √ √ √ √ √ √	Yes/No	Low Medium High	Low Medium High	Low Medium High	Low Medium High	Yes/No	>1h >5h >8h >24h	a few seconds a few min >20min
	Farm Machinery Guidance	10 - 30 cm (pass-to-pass)	SBAS √ √ √ DGNSS √ √ RTK/N-RTK √ PPP/PPP-RTK √	No	High	Low	Low	High	N.A.	N.A.	a few min

Figure 17: Requirements for GNSS powered farm guidance system (GSA, 2018).

The challenge with interpreting Figure 17 is to understand who needs to receive what information from the table. The driver would probably need only to see in the guidance display to ensure the vehicle is on track. However, they also need to trust the display, meaning that the track calculation and display output need to be based on reliable inputs. This raises the question of whose job it is to ensure the input is reliable? This needs to be part of the Controller's capability (see Figure 16), which in turn means that the quality metadata (accuracy, availability, robustness, integrity and convergence information) needs to accompany the raw data in the format required by the Controller.

4.3. eGeodesy – What works well and areas in need of improvement

Current eGeodesy use cases cater for all business processes involved in establishment and maintenance of the Australian Geospatial Reference System (AGRS). The AGRS is comprised of an integrated network of CORS stations, survey control marks, systems for management and dissemination of survey control mark information, and various related policies, standards and guidelines (PCG/ICSM, 2013). The following business cases supporting solutions at campaign, jurisdiction and national level are currently well-documented in the eGeodesy logical model:

- Processing GNSS data from the CORS network
- Import, retrieval and validation of measurements in a variety of supported formats, including the interoperable, vendor independent formats (such as the GeodesyML, RINEX and SINEX); and in some commonly used proprietary formats (such as Leica or Trimble formats); but also for any other formats, provided that the data is accompanied by the required metadata
- Asia-Pacific Reference Frame solution processing
- Management and validation of constrained and unconstrained adjustments
- Notification of agents involved in the network management (e.g. jurisdiction adjuster)
- Archive update

Current eGeodesy use cases are well described and cover the necessary functionality between the CORS and GNSS experts processing the data at the GNSS data processing centre. As illustrated in Figure 18, eGeodesy use cases reflect the part of the GNSS value chain highlighted by the red ellipse.

Figure 18: Current eGeodesy support (highlighted) in the GNSS value chain (GSA, 2019).

More use cases (for GNSS end-user sectors identified in Chapter 1) are needed to complete the GNSS value chain. These include descriptions of interaction between component manufacturers and system integrators, and between system integrators and value-added service providers.

Moreover, eGeodesy currently **lacks the description of use cases that cover GNSS data provision from GNSS experts all the way to the end-users within high-end GNSS use sectors** (as identified in Chapter 1). These additional use cases should be accompanied with descriptions of both the way end-users interact with the GNSS data and how the data is manipulated during the process. Key variables include what type of equipment is used by the end-user, which interfaces, protocols and data formats are used, and exactly what type of information is transferred (e.g. Only location? Or metadata first and then location? Or vice versa?).

4.4. GeodesyML and its compatibility with current standards

GeodesyML is a GML application schema for transfer of geodetic information encoded in XML, an accepted language-independent standard of the lossless information exchange over the internet and the 'golden standard' for the geoweb since early 2000. XML documents (such as GNSS site log data encoded in GeodesyML), which are both machine and human-readable, can be requested, parsed for values stored in variables of the structured file, and have specific values retrieved. For example, through OGC's Web Feature Service interface (the same interface through which users can access GNSS site log data encoded in GeodesyML), a user (human or machine) can request GNSS data of interest at feature or feature property level (i.e. finer detail than is the whole dataset). Data is requested through standard OGC WFS URL requests, e.g. DescribeFeature or GetFeature (see example in Section 4.1).

OGC API – Features[56] is the next evolution of the interface for accessing spatial data over the web. Rather than the complete dataset, as in the case of any other API, OGC API – Features provides access to data of interest at feature or feature property level. This evolution of the WFS standard reflects a general trend in the evolution of the web, in which data and metadata are exchanged as data (as JSON[57] or RDF[58]) rather than as documents (e.g. in HTML, or XML). Via OGC API - Features, users should be able to browse (e.g. in their web browsers) features in the collection and request data through standard HTTP requests (i.e. navigate to the webpage of interest). To allow this, the standard recommends to data providers that they should offer:

1. Support for browsing the dataset and its features with a web browser as well as enabling search engines to crawl and index the dataset
2. Implementations supporting GeoJSON[59] as an encoding for features and feature collections.

Although XML is still an allowed option, the preferred option for data encoding is JSON (more specifically, the GeoJSON). This evolution is not only consistent with wider trends to move data (including spatial data) to the Web (W3C, 2017; van der Brink et al., 2019), but also provides numerous advantages in the way spatial data

[56] https://www.opengeospatial.org/standards/ogcapi-features
[57] JavaScript Object Notation – data encoding format (https://www.json.org)
[58] Resource Description Framework – framework for describing resources on the Web (https://www.w3.org/RDF)
[59] geospatial data interchange format based on JSON (https://tools.ietf.org/html/rfc7946)

(including GNSS data) is exposed to the user via the web. As one example, JSON is shorter, quicker to read and write data, and hence is faster to transmit and process data (Nurseitov et al., 2009).

In contrast with XML, JSON is language dependent (it is written in JavaScript) as it is designed purely to exchange data (and not metadata). It might therefore come as a surprise that it is the preferred standard for modern spatial data web interchange. JSON gained its popularity with the rise of public APIs based on REST APIs web architecture (over traditional SOAP/WSDL models on which traditional OGC web services depend) due to it being text-based, light-weight and requiring no additional code for parsing, all of which contribute to the faster data interchange over the web[60].

Current developments in one of the GNSS end-user sectors, the automotive sector, justify the need for GeodesyML's improvement in the direction specified above:

Automotive and Transportation data goes to the Web

Advances in sensors, communications, cloud and data analytics infrastructure, geophysical mapping, machine learning, mobile devices, user interfaces and related areas have created a rich foundation that can offer tremendous opportunity for improving experience and creating value for passengers by offering them enhanced information, entertainment, efficiency, maintenance, safety and convenience[61]. To enable utilization of current technology to improve road transportation, there is a need to both increase automotive and transportation information interoperability and prepare standards and recommendation for automotive and transportation data interchange[62]. Immediate work in progress comprises of two specifications: Vehicle Information Service[63] and Vehicle Information API[64] with the core request: expose data and metadata as JSON via API.

And although the example developments above only deal with the data and information of the vehicle itself, these efforts send a clear signal that it is probably only a question of time until vehicles will mandate JSON and web APIs as the preferred communication platform for information interchange. Such interchange could include information on the closest refuelling station, a typical piece of information powered by GNSS precise positioning data.

For eGeodesy, this means the need to reconsider the way GNSS data encoded in GeodesyML is provided to the user. Current implementation (which served for eGeodesy pilot demonstration purpose mostly and as yet have not expanded beyond that) offers site log data via OGC WFS. Site log information is one of the smallest and probably most static data package that can be requested by the GNSS user. When it comes to other GNSS precise positioning data and metadata, more flexible and responsive web interfaces will be necessary.

OGC API – Features is one candidate to test for efficiency, with OGC API guidelines for implementation available online[65]. More OGC API standards are underway[66], and all of these build on the simple access to content in OGC API – Features, suggesting an easy extension of the spatial API built on OGC API into a robust self-explaining system (a system described with proper metadata) for provision of spatial data on the web. For future improvement in eGeodesy, two examples will be interesting to follow: OGC API – Records (for metadata)[67], and OGC API – Processes[68].

60 https://www.json.org/xml.html
61 https://www.w3.org/auto
62 https://www.w3.org/auto/wg
63 http://rawgit.com/w3c/automotive/gh-pages/vehicle_data/vehicle_information_service.html
64 https://w3c.github.io/automotive/vehicle_information_api/vehicle_information_api_specification.html
65 https://github.com/opengeospatial/OGC-Web-API-Guidelines
66 http://www.ogcapi.org
67 https://github.com/opengeospatial/ogcapi-records
68 https://github.com/opengeospatial/wps-rest-binding

Furthermore, the following questions will need to be answered in order to improve GeodesyML:

- Is GeodesyML capable of encoding and transmitting data or metadata?
- If data, which data? Persistent data (i.e. data offered via agency portals, or data/metadata in the catalogue?) or raw data (transmitted to and from the equipment)?
- Assuming GeodesyML is intended for transmitting raw data, which data (and metadata) needs to be transmitted, what else needs to be put in place (e.g. automated processes for fitness for use decision), and where do these extra components need to be placed? (i.e. At the end-users' or providers' end?)
- What about automated conversion from raw data to GeodesyML? Is this expected?
- If automated conversion is desired: who does this and how?

A significant amount of work remains to be done to develop and integrate GeodesyML as a means of delivering precise positioning data and metadata for a wide range of end-user application areas. However, GeodesyML, which can be implemented in accordance with the FAIR principles, provides a clearly beneficial alternative to current methods of transmitting and archiving geodetic data.

5. Summary and way forward

This report has presented the findings of a scoping study into the standards for geodetic data exchange, dissemination and archiving, and their support for FAIR principles. The method used in this report was desk-based, utilising the scientific literature as well as various online tools to examine current geodetic resources from Geoscience Australia.

It was found that current geodetic standards and practices do not have sufficient support for FAIR, as in the past they were aimed at specialist human users only. This situation is changing rapidly as new positioning markets emerge and more non-specialist human and machine users will need access to positioning and geodetic data. As such, it is vital for the geodetic community to adopt FAIR standards and practices as early as possible.

The preferred way to do so would be to adopt GeodesyML as the standard of choice going forward, as it has support for many FAIR principles for GNSS as well as for geodetic data, such as terrestrial observations, reference frames and adjustments. In the future, this could be extended to cover other space observation techniques including SLR, VLBI and DORIS. GeodesyML has been trialled by a number of geodetic agencies around the world including Geoscience Australia, Royal Observatory of Belgium, UNAVCO and BKG, and while it has shown great potential, significant work needs to be carried out to progress from pilot projects into production, and to gather world-wide industry support for the standard.

Follow up work is currently underway by Curtin University, Geoscience Australia and FrontierSI under the Positioning Australia program to continue the work initiated by this scoping study, and to further increase the adoption of FAIR into standardised geodetic practices.

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ACIL Allen Consulting Pty Ltd. (2013d). *Precise positioning in the construction sector: An estimate of the economic and social benefits of the use of augmented GNSS services in the construction sector.* http://www.ignss.org/LinkClick.aspx?fileticket=ntyClJz4fh8%3d&tabid=56.

ACIL Allen Consulting Pty Ltd. (2013e). *Precise positioning in the maritime sector: An estimate of the economic and social benefits of the use of augmented GNSS services in the maritime sector.* http://www.ignss.org/LinkClick.aspx?fileticket=b%2f3x6KEaFS4%3d&tabid=56.

ACIL Allen Consulting Pty Ltd. (2013f). *Precise positioning in the mining sector: An estimate of the economic and social benefits of the use of augmented GNSS services in the mining sector.* http://www.ignss.org/LinkClick.aspx?fileticket=X3x6ARJjTcI%3d&tabid=56.

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Annex A List of additional resources used in the review

Organisational websites:

- ANZLIC ICSM's Permanent Committee on Geodesy: https://www.icsm.gov.au/what-we-do/permanent-committee-geodesy
- Geoscience Australia's Positioning and Navigation domain: https://www.ga.gov.au/scientific-topics/positioning-navigation
- European GNSS Agency: https://www.gsa.europa.eu
- Eurogeographics Positioning Knowledge Exchange Network: https://eurogeographics.org/knowledge-exchange/posken
- International GNSS Society: http://www.ignss.org
- International GNSS Service: http://www.igs.org
- US government's official resource on GPS and related topics: https://www.gps.gov
- FrontierSI SBAS testbed: https://frontiersi.com.au/project/satellite-based-augmentation-system-test-bed

eGeodesy & GeodesyML resources:

- GeodesyML's GitHub repository: https://github.com/GeoscienceAustralia/GeodesyML
- GeodesyML's discussion forum: http://geodesyml.org/forum
- Material published by the Permanent Committee on Geodesy (PCG) of the Australian and New Zealand Intergovernmental Committee on Surveying and Mapping (ICSM) at: https://www.icsm.gov.au
- Various UNAVCO repositories available at: https://www.unavco.org
- Various related standards such as:
    - OGC GeoSciML: http://www.geosciml.org and https://www.opengeospatial.org/standards/geosciml, and
    - OGC Geography Markup Language: https://www.opengeospatial.org/standards/gml
    - Scripps Orbit and Permanent Array Center (SOPAC)'s XML: http://sopac-old.ucsd.edu/xmlGeodesy.shtml

Annex B Detailed reports on metadata requirements and potential GNSS applications

Table A.1 End User Requirements in the Agriculture sector.

GNSS Handbook	**Metadata Elements**	• Accuracy • Availability • TTFF
EGNOS User Needs and Requirements Reports	**Metadata Elements**	• Accuracy (horizontal, pass-to-pass, year-to- year/long-term/GNSS drift) • Survey Method (SBAS, DGNSS, RTK/N-RTK, PPP/PPP-RTK) • Availability • Robustness • Authentication • Integrity and Reliability • Fixing and Convergence Time • Continuity • Data Compatibility across Devices: DGPS receiver, Controller, Data Logger and set of agricultural sensors (e.g. Variable Rate Drive, Moisture Sensor, Mass Flow Sensor) • Size, Weight and Autonomy
	Applications	• Emerging multi-frequency and multi-constellation solutions • Galileo High Accuracy Service novelties • RTK remains the preferred option with PPP being an interesting alternative due to the minimal equipment needs and global accessibility • Integrated Farm Management Solutions: combining GNSS with complementary technologies to allow real-time data collection and modelling (uptake in EU expected to rise from 10% in 2016 to 40% in 2018): 　o Remote Sensing via satellites (Sentinel, SAR): used in conjunction with GNSS 　o RPAS (UAV): GNSS a key enabling technology both in terms of continuously available signals and, of course, high accuracy of operations 　o Robotics/fully autonomous field machines enabled by automatic steering technologies and high-precision GNSS positioning 　o Big Data Analytics, IoT, Future ICT (i.e. 'Smart Farming") powered by GNSS
ACIL ALLEN GNSS Economic Benefit Reports	**Metadata Elements**	• Coverage • Accuracy • Identifying applications for livestock (fitness for use, or 'usage' as in ISO 19115-1) • Reliability (direct relationship btw reliable GNSS and $$ yield)
	Applications	• Low-cost livestock tagging and tracking (with RPAS - GNSS device in livestock is paired with the one on the RPAS) • Precision agriculture esp. in grain, cotton and viticulture management • Yield monitoring • Reduction of soil tracking in 'tram tracking' • Horticulture: 　o Use of RPAS to monitor canopy health 　o Use of self-driving vehicles with sensors to monitor fruit ripeness

Table A.2 End User Requirements in the Rail sector.

GNSS Handbook	**Metadata Elements**	• Accuracy • Integrity • Authentication • Availability • Continuity • Time To Alert (TTA) • Alert limit
EGNOS User Needs and Requirements Reports	**Metadata Elements**	• Accuracy of location - (5m + 5%s; s = distance travelled from last calibration of the odometric device) • Age of location measurement (time stamp? - less than 1s before sending the position report) • Accuracy of speed (±2km/h for speed < 30km/h increasing linearly up to ±12km/h at 500km/h) • Availability (not less than 99.973%) • Safe clock drift: 0.1% • Integrity • Safety integrity Level (SIL; SIL4) • TTA • Reliability measured in Mean Time Between Failures (MTBF) ranging from 8.0x103 hrs (for minor failures) up to 2.7x106 hrs (for major failures)
	Applications	• Automatic train locator with GNSS • GNSS Odometry Subsystem to provide **accurate position and speed** • Absolute positioning - to provide **confidence interval** on position independently of the travelled distance • Cold movement detection • Train integrity (belief of train being complete with no wagons left behind) and train length monitoring (with positioning systems at the front and at the back) • Track identification - using GNSS with other track infrastructure to identify the current track on which the train is running • Odometer calibration with GNSS • Level crossing protection - GNSS subsystem with a digital map to determine allowed speed levels. • Trackside personnel protection - GNSS on personnel, rail assets and the trains; e.g. issue warnings to trains to slow down or stop depending on the location of the working team, and/or warnings to the team to abandon the area when the train is approaching. • Rail Emergency Management with GNSS • Train warning systems to passengers when train is approaching at speed larger than expected - requires details of train location, speed and other infrastructure data = result automatic station announcement via public service broadcast. • To introduce virtual balises for EU Rail Traffic Management System. • Door Control Supervision - GNSS to locate train within a specific station and a specific platform. • Fixed asset management - survey with GNSS for signal sighting, asset data collection, site surveys, design verification, route familiarisation, rapid response, gauging surveys, location of GSM-R reports, virtual inspection • Cargo and hazardous cargo monitoring • Location-based energy monitoring.

		• Infrastructure charging - GNSS for location/speed/time service used within the infrastructure use charging process to determine accurate infrastructure usage and generate accurate billing information, and to provide evidence for charges for train delays
		• Passenger information:
		  ○ On-train ticketing, retail and authentication
		  ○ On-train reservation, catering and services
		  ○ On-board train crew, passenger and customer information services
		  ○ Personal journey assistant, LBS and POI service
		  ○ Passenger broadband (internet access caching)
		GNSS Limitations for its use in Rail (very safety-sensitive environment):
		• Obscuration in tunnels, deep cuttings and in the shades of high hills/mountains and out-of-coverage areas
		• Accuracy on parallel tracks or in train stations (Horizontal Protection Level (HPL) < 3m required)
		• TTA is a critical parameter

ACIL ALLEN GNSS Economic Benefit Reports	**Metadata Elements**	• Accuracy • Reliability • Integrity • Coverage • Robustness (interference with environment and surrounding, e.g. electrical network)

	Applications	• Automated train management system:
		  ○ asset location and monitoring
		  ○ efficiency of train loading by monitoring the path of forklift trucks
		  ○ monitoring the progress of trains within track segments
		  ○ recording of journey progress for customer tracking
		  ○ recording the location of incidents that cause delays or where potential maintenance is required
		  ○ triggering of the important events, such as shift changes, required on-train activities or procedures
		  ○ providing information btw train and the control centre using telecommunication network
		  ○ time stamping of train location
		• Surveying and managing rail infrastructure
		• Locating trains
		• Problem with GNSS use in tunnels and areas of sparse coverage
		• High-accuracy GNSS as used for automated stevedoring at ports might be deployed at rail terminals for train loaders
		• Replace trackside with in-cab signalling
		• fuel economy software to reduce the need for acceleration braking

Table A.3 End User Requirements in the Road sector.

GNSS Handbook	**Metadata Elements**	• Accuracy • Integrity • Authentication • Availability • Continuity • TTA • Alert limit
EGNOS User Needs and Requirements Reports	**Metadata Elements**	• Availability (SCA, PCA, RCA, SM) • Accuracy (SCA, PCA, RCA) • GNSS Time accuracy (SCA, PCA) • Integrity message (SCA) • TTFF (SM) • Robustness to interference: jamming, spoofing, multipath (SCA, RCA) • Authenticity (PCA, RCA), ensuring users that the signal comes from a valid source • Detection of GNSS interferences • GNSS sensitivity (SCA) • Continuity (SM) • Position fix rate • Latency • Indoor penetration • Power consumption indication
	Applications	**Current use of GNSS in road segment** • Safety critical applications (SCA): ○ Red light violation warning ○ Curve speed warning ○ 360° all around view blind spot lane change warning, oversize vehicle warning ○ Obstacles on the road, work zone warning, weather based hazards, queue warning ○ Emergency brake assist, collision avoidance ○ Wrong way driving ○ Emergency electronic break light ○ Automatic speed limitation ○ Automated driving ○ Autonomous car ○ Precise time synchronisation • Payment critical applications (PCA): ○ Road use charging ○ Pay-per-use insurance ○ Pay-as-you-drive insurance ○ Taxi meter ○ Parking fee calculation • Regulatory critical applications (RCA): ○ Digital tachograph ○ eCall (sending position and time provided by GNSS, to public safety answering points) ○ Hazardous material tracking ○ Livestock tracking ○ Geofencing (GNSS triggers and alert when vehicle enters or exit geographically defined boundaries)

		• Smart mobility (SM): ○ Freight, fleet, cargo asset management ○ Vehicle access/clearance control ○ Origin destination survey ○ Emergency vehicle priority ○ Bus and tram priority at traffic lights ○ Road navigation with lane level positioning ○ Speed limitation information ○ Electronic horizon ○ Reduce speed warning ○ Green light optimal speed advisory ○ Automated parking ○ Tailgating advisory ○ Lane departure warning ○ Traffic jam ahead and snowplough in operation ○ Connected eco driving ○ Dynamic ride sharing ○ Stolen vehicle recovery ○ Electro mobility (optimizing the usage of electric vehicles) ○ Mobility services for users of drive-services (e.g. public transport vehicle location) • Cooperative Intelligent Transport System (C-ITS): ○ Traffic warnings ○ Safety warnings ○ Automated interventions ○ Driving automation **Prospective use of GNSS in road segment - 3 main areas** • Advanced Driver Assistance System • Vehicle to Vehicle/Infrastructure communication • Autonomous vehicle **GNSS limitations for its use in the Road Segment:** • Receiver vs in-vehicle system user requirements • Definition of the reference test scenarios
ACIL ALLEN GNSS Economic Benefit Reports	**Metadata Elements**	Reliability Integrity Accuracy Interoperability Continuity Availability Timeliness
	Applications	• Fleet and logistics management - route selection, driver fatigue, fuel efficiency • Container management • Road maintenance - road geometry, condition and asset management • Intelligent transport systems: ○ In-vehicle navigation ○ Stolen vehicle recovery ○ Automatic crash notification and may-day services ○ Fleet management ○ Logistics/supply chain management ○ Hazardous goods management ○ Electronic toll collection • Direct heavy vehicle charging for road usage

Table A.4 End User Requirements in the Maritime sector.

GNSS Handbook	**Metadata Elements**	• Accuracy • Integrity • Authentication • Availability • Continuity • TTA • Alert limit
EGNOS User Needs and Requirements Reports	**Metadata Elements**	• Accuracy; max error • Availability • Continuity • Integrity: Warning, Risk, Alert limit, TTA • Coverage • Horizontal alert limit • Fix Interval (=TTFF) • Update rate of the computed position data • Support for International Association of Lighthouse Authorities (IALA) DGNSS service and the Automatic Identification System (AIS) **From International Maritime Organisation (IMO) regulations - requirements on GNSS:** • The GNSS must be able to be used by an **unlimited number of multimodal users**, being also reliable and of **low user cost**. • Integration of GNSS and terrestrial systems using **compatible geodetic and time reference systems** • Inform users of **system performance degradations through integrity messages** • GNSS **controlled by international civil organisation** (= metadata on system owner and maintainer)

	Applications	• Traffic management and surveillance:
		  ○ Ship-to-ship coordination
		  ○ Ship-to-shore reporting and shore-to-ship monitoring
		  ○ Shore-to-ship management
		• Search and rescue activities with near real-time alert localisation and message detection
		• Fisheries monitoring:
		  ○ Fishing vessel control
		  ○ Positioning during fishing
		  ○ Location of fishing ground
		• Port operations
		• Hydrography and Oceanography: mapping
		• Marine engineering: surveying
		• Offshore exploration and exploitation:
		  ○ Exploration, e.g. seismic survey
		  ○ Appraisal drilling
		  ○ Field development
		  ○ Support to production and post-production
		• Ocean navigation

		• Coastal navigation • Recreational navigation • Port approach and restricted water phase, port phase • Inland waterways • Tugs and pushers: require relative positioning btw tug and the other vessel • Icebreakers: keeping the ship on a pre-planned track using position, heading and speed info • Automatic collision avoidance
ACIL ALLEN GNSS Economic Benefit Reports	**Metadata Elements**	• Accuracy • Integrity: ○ Alert limit (in metres) ○ Integrity risk ○ TTA • Availability • Control • System life expectancy • Reliability • Coverage • TTFF
	Applications	• Navigation (and e-navigation) and maritime traffic control • Electronic chart display information system • Ship-to-ship & ship-to-shore data exchange system • Portable pilot units with integrated GNSS • Under keel clearance • Monitoring and control (e.g. barrier reefs) • Vehicle traffic service • Automatic ship reporting • Oil and gas operations • Dynamic positioning of marine vessels • Hydrographic surveys • Geotechnical surveys • Mobile drilling rigs

Table A.5 End User Requirements in the Aviation sector.

GNSS Handbook	**Metadata Elements**	• Accuracy • Integrity • Continuity • Availability • TTA • Compliance with safety requirements & standards
EGNOS User Needs and Requirements Reports	**Metadata Elements**	• Accuracy • Horizontal/Vertical Alert Limit • Velocity accuracy • Time accuracy • System Design Assurance • Position integrity • Integrity • TTA • Continuity • Availability
	Applications	• Localized Performance with Vertical guidance (LPV) • Surveillance • GNSS combined with Enhanced and Synthetic Vision Guidance Systems • GNSS satellite selection and de-selection without additional workload to the flight crew • Performance-based navigation with the support of Dual-Frequency Multi-Constellation GNSS • Use of GNSS on drones/RPAS/UAVs
ACIL ALLEN GNSS Economic Benefit Reports	**Metadata Elements**	• Accuracy • Integrity
	Applications	• Surveillance • User-preferred routing • Barometric height measurement • Instrument landing system

Table A.6 End User Requirements in the Time & Synchronisation sector.

GNSS Handbook	**Metadata Elements**	• Temporal Accuracy • Authentication
EGNOS User Needs and Requirements Reports	**Metadata Elements**	• Accuracy: positional, temporal • Resilience and reliability • Authentication • Availability • Traceability • Trustability • Security • Integrity • Independence of GNSS Timing & Synchronisation System • Certification • Protocols: Network time Protocol (NTP) and Precision Time Protocol (PTP), IRIG-B, SyncE, SONET/SDH
	Applications	• Telecom • Electricity transmission • Finance: banks & stock exchange • Transportation systems • Water and wastewater systems • Scientific applications: astronomy, particle physics, geophysics, metrology • Digital TV broadcast • LTE small cells networks • Internet of Things applications
ACIL ALLEN GNSS Economic Benefit Reports	**Metadata Elements**	*Report unavailable*
	Applications	*Report unavailable*

Table A.7 End User Requirements in the LBS sector.

GNSS Handbook	**Metadata Elements**	• Accuracy • Integrity • Availability • TTFF • Authentication • Resistance to Multipath • Lone worker protection
EGNOS User Needs and Requirements Reports	**Metadata Elements**	• Accuracy • Authentication • Resilience - susceptibility to interference, jamming, spoofing, environmental conditions • Availability • Position, navigation, timing in urban canyons, under canopy and indoors • TTFF • Fix update type • Power consumption alert • Integrity messages: risk, TTA • Service area/Coverage
	Applications	• Turn-by-turn pedestrian navigation: **GNSS combined with Assisted-GNSS (A-GNSS), network positioning and inertial/motion sensors** • Real-time public transport • Eco-driving and carbon emission footprint • Smart parking • Geomarketing and advertising, fraud management, location- based billing • Safety and emergency • Enterprise applications: mobile workforce management • Sports: fitness and performance monitoring • Augmented reality • Health tracking: guidance of visually impaired, vulnerable people tracking, fall detection • Tracking: children locator, parolee monitoring, pets locators, tracking of goods • Social networking: friends locator, dating, chat and instant messaging services • Infotainment: POIs. Photos and videos geotagging, geolocated news • Mobile mapping and GIS **Prospective innovations in GNSS for LBS:** • Multi-constellation processing • Multi-frequency processing • Sensor fusion/hybridisation (with Wi-Fi, Bluetooth, Cellular network positioning, MEMS) • **Availability of raw measurements**, incl. raw pseudoranges, dopplers and carrier phase measurements, through compliant APIs. • Chip-based indoor location techniques • Innovative algorithms – **SLAM, satellite shadow matching, multipath mitigation, interference rejection**; **PPP in smartphones** • Miniaturisation • Cloud processing • Open Mobile Alliance (OMA) and 3GPP protocols for GNSS, A-GNSS and the smartphone
ACIL ALLEN GNSS Economic Benefit Reports	**Metadata Elements**	*Report unavailable*
	Applications	*Report unavailable*

Table A.8 End User Requirements in the Surveying sector.

GNSS Handbook	**Metadata Elements**	• Accuracy • Availability • TTFF
EGNOS User Needs and Requirements Reports	**Metadata Elements**	• Accuracy • Service area/coverage • Availability • Integrity • Robustness • Relevance of the surveying method • TTF Accurate(A)F • Size, weight and autonomy/Power consumption • Interoperability and software flexibility • Real-time and post- processed capability • Multi-functionality and compatibility with other sensors (e.g. bar code readers) • Continuity • Antenna ruggedness, performance and phase-centrum stability • Time-to-Convergence (TTC) • Reliability
	Applications	• Cadastral surveying and Geodesy: o National/international reference frame survey o Geodetic survey o High-order/Low-order control surveys o DGNSS or RTK reference station positioning o High-order/Low-order detail surveys and positioning o Cadastral surveys o Land seismic, dimensional control and source positioning o Land survey, real-time topographic detailing and profiling o Temporary DGNSS reference for monitor station positioning • Construction surveying: o Setting-out/staking, alignment, trajectory, machine control o Vehicle tracking and asset management o Asset positioning at 3m level o High-order/Low-order control survey o Temporary DGNSS reference for monitor station positioning • Mapping/GIS: - Photogrammetry/remote sensing high-order ground control - Photogrammetry: camera positioning, control points - High-order topographical profiles - Automated mapping/facilities management - Spatial database update, digital mapping - GIS, assets positioning and attribute collection - Topographic mapping • Mining: - Slope, stability, volumetric surveys - Machine control - Vehicle tracking and asset management • Marine cadastre

		• Marine survey: ○ Real-time tidal monitoring ○ Vessel positioning ○ Hydrographic survey and vessel navigation ○ Off-shore exploration **Prospective use of GNSS in surveying:** • Multi-frequency and multi-constellation solutions • High-accuracy services to support Precise Point Positioning (PPP) • Increased uptake of PPP in contrast to decreasing use of RTK • Integrated solutions with complimentary techniques: 3D laser scanning, total stations, LiDAR and photogrammetric cameras, RPAS, Augmented Reality, SLAM
ACIL ALLEN GNSS Economic Benefit Reports	**Metadata Elements**	• Accuracy • Reliability
	Applications	• Engineering surveys • Monitoring sea level rise • Infrastructure surveys • Land management and subdivisions • Geophysical surveying • Augmented reality • Photogrammetry survey control

Annex C Standards in Action

C.1. Example 1: Finding and accessing spatial data on the internet

USER SCENARIO

The user wants to find and obtain access to the required inputs to assemble national coastal dataset from spatial data curated within various jurisdictions in Australia.

THE PROBLEM

Traditionally finding an obtaining spatial data was a complicated and cumbersome endeavour involving several significant hurdles, and requiring great efforts from users. In their quest, users needed to know precisely which spatial data they needed to solve their problem (*data from cadastral dataset or topographic dataset?*), which producers in which jurisdictions produced this data, and where these producers are based (*which organization and in which state?)*. After that, users needed to contact providers by specified means (*telephone*, *mail*, *visit*) at given hour (*varied opening hours*) to finally obtain the data on a given medium (*paper map, floppy disk, CD-ROM*). The process of traditional approach to spatial data discovery and access is illustrated in Figure 19, in which we are following an example of a user looking to assemble national coastal dataset:

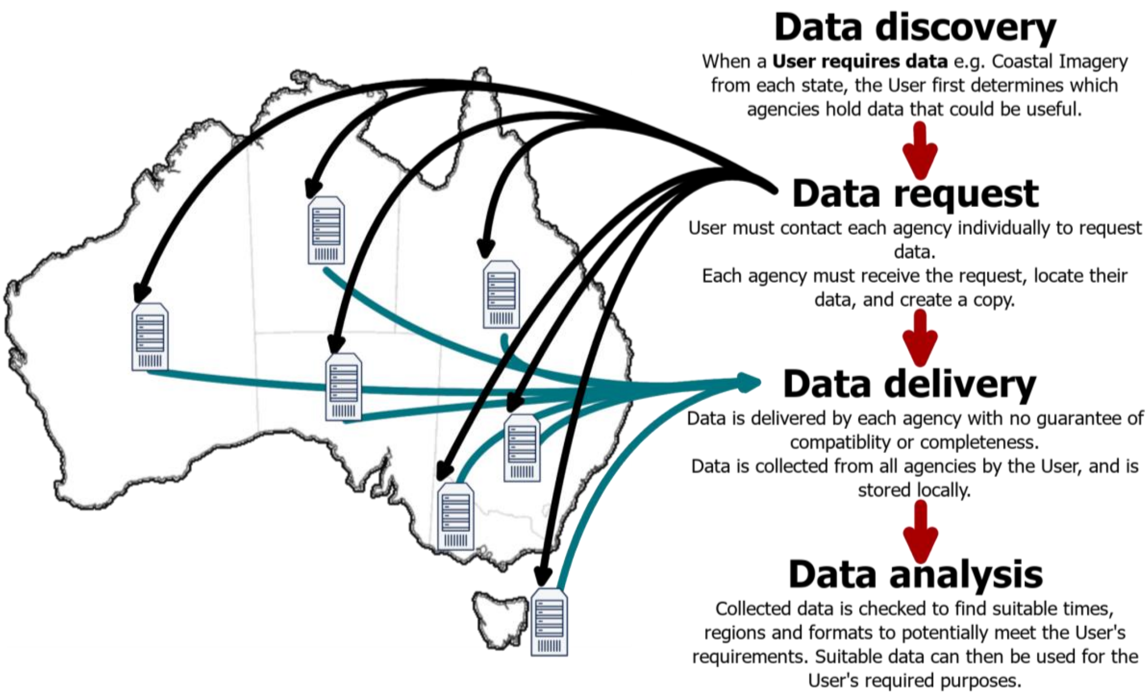

Figure 19: Quest for spatial data without standards.

SOLUTION

With the invention of the internet and spatial data infrastructures, the quest for spatial data is now quite different. Spatial data providers use the internet to advertise their data through dedicated data portals to spatial data infrastructures, allowing users to search for and explore spatial data, find those that fit their application needs and, ultimately, obtain these data. Each of these steps can be performed from the comfort of their office. This is possible because of existing standards for discovery and access to spatial data. The process of finding and accessing of spatial data today is illustrated in Figure 20, we are following the same example as before of a user looking to assemble national coastal dataset.

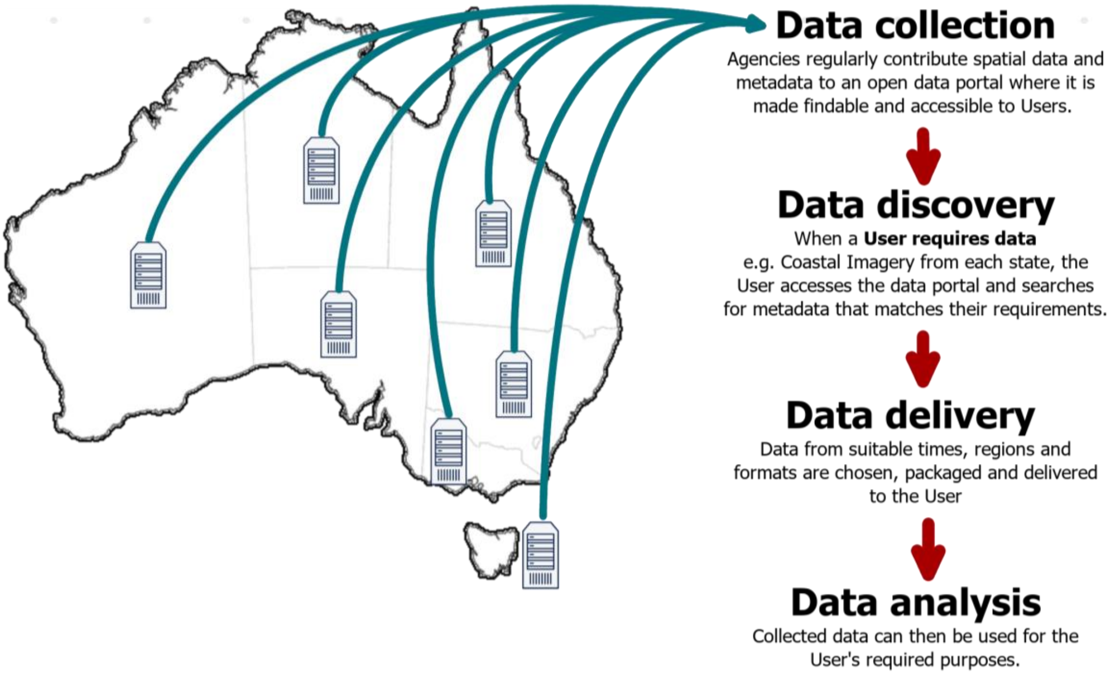

Figure 20: Search for spatial data of interest with standards in place.

WHY DOES IT WORK?

Standards for spatial data, internet and the web greatly simplify the quest for spatial data (Figure 21).

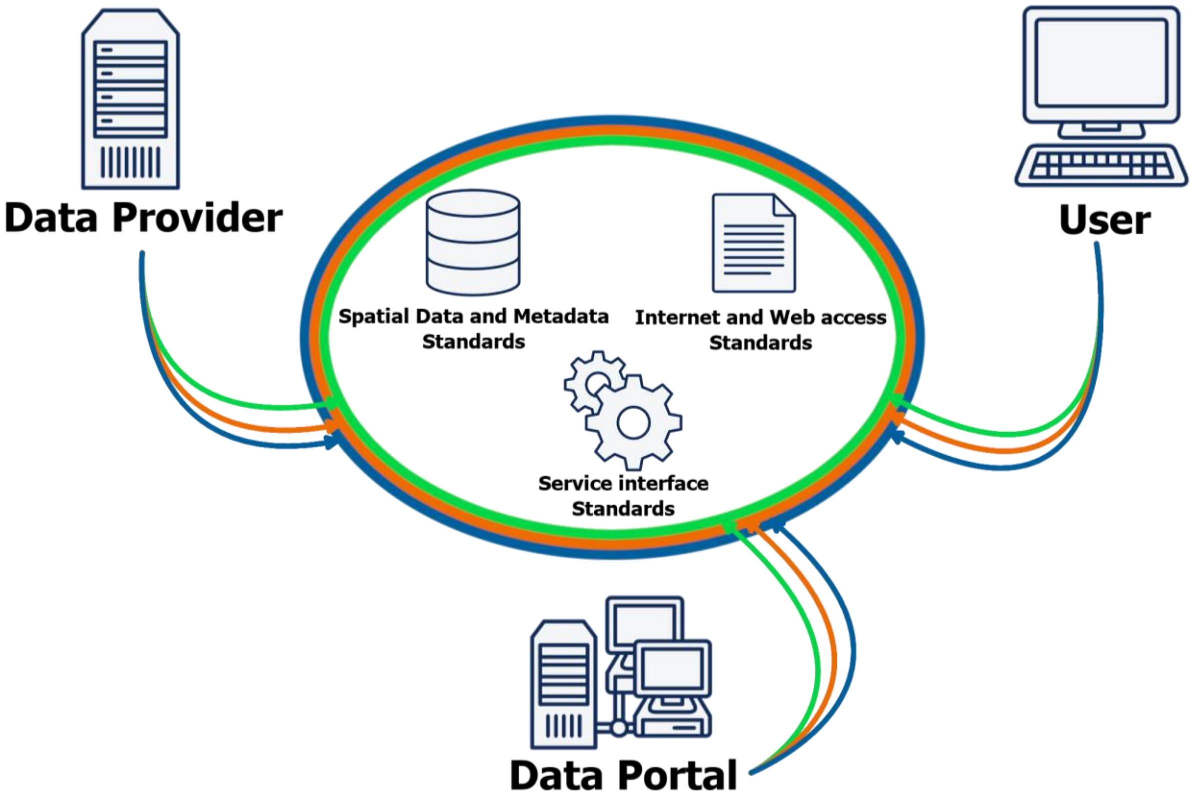

Figure 21. Efficient spatial data discovery and access.

How it works

Figure 22 illustrates how standards help with efficient data search and discovery over the web.

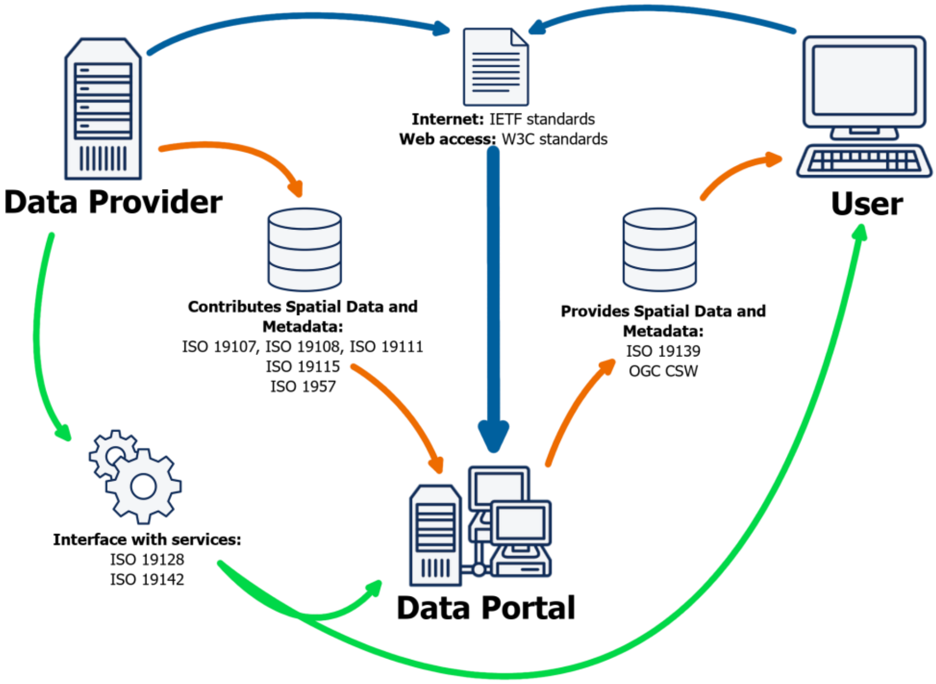

Figure 22: Standards in action for efficient spatial data discovery and access.

Standards in action

Following are the standards enabling efficient access to spatial data:

- IETF standard suite for enabling the existence and operation of internet (e.g. TCP/IP)
- W3C standard suite for enabling the web (e.g. HTTP, XML)
- ISO 19100 series of standards for geographic information, such as:
  - Data standards for defining the spatial and temporal schema (ISO 19107 & ISO 19108), and data referencing with coordinates (ISO 19111);
  - Metadata standards for encoding descriptive information about data (ISO 19115 and ISO 19157);
  - Standards for enabling web interface to data (ISO 19128 and ISO 19142) and metadata (ISO 19139 and OGC CSW)

C.2. Example 2: Providing addresses for Australian business and governments

User Scenario

The user wants to use authoritative dataset to find an address for their applications covering Australian spatial extent.

The problem

In the past, addresses have been used almost exclusively in relation to the properties, e.g. to identify the end-point for sending utility bills. Today, the usage of addresses has broadened, for example, we need a unique and authoritative address to identify Automatic Teller Machines (ATM) or natural reserves. In addition to an official address recorded by an authoritative agency, community recognizes unofficial, in-use addresses and validation and harmonization of these is often challenging. Problems with addresses are not only frustrating, but can cause significant losses for businesses. Another challenge is that addresses are typically not geocoded and a small typo can cause problems (e.g. just imagine shipping sensitive content to the wrong recipient).

In Australia there is no federal legislation for national addressing. It is the responsibility of the state and territory agencies to collate and keep a concise record of all addresses, but only within their jurisdiction. As there is no one primary custodian of addressing in Australia, validation and authorisation of an address when needed can be a complex exercise.

Solution

Geocoded National Address File (G-NAF), created by PSMA Australia, is the one-point of contact for an authoritative address. G-NAF contains at least one entry for every one of the approximately 14.5 million street addresses in Australia, as well as address aliases and relations (units within lots; addresses within localities), and data including the state, suburb, street, number and coordinate reference (or "geocode" for each street address in Australia). G-NAF has a variety of contributors, including state and territory land agencies. An automated mechanism is set up to independently examine, validate and match source data and create linkages to other datasets including data from Australian Bureau of Statistics. Additionally, complex analysis such as address verification in a utility service dispute are possible via standard service interfaces to G-NAF. Prospective use of G-NAF is that of a framework that provides a consistent way to seamlessly integrate data on people, business, and the environment.

Why does it work?

G-NAF custodian implements national and international standards for addressing and structuring address spatial data, and exposes these for automated use via internet and the web allow access to the single authoritative address data source. Figure 23 illustrates the symbiosis between state and territory custodians of address databases and G-NAF.

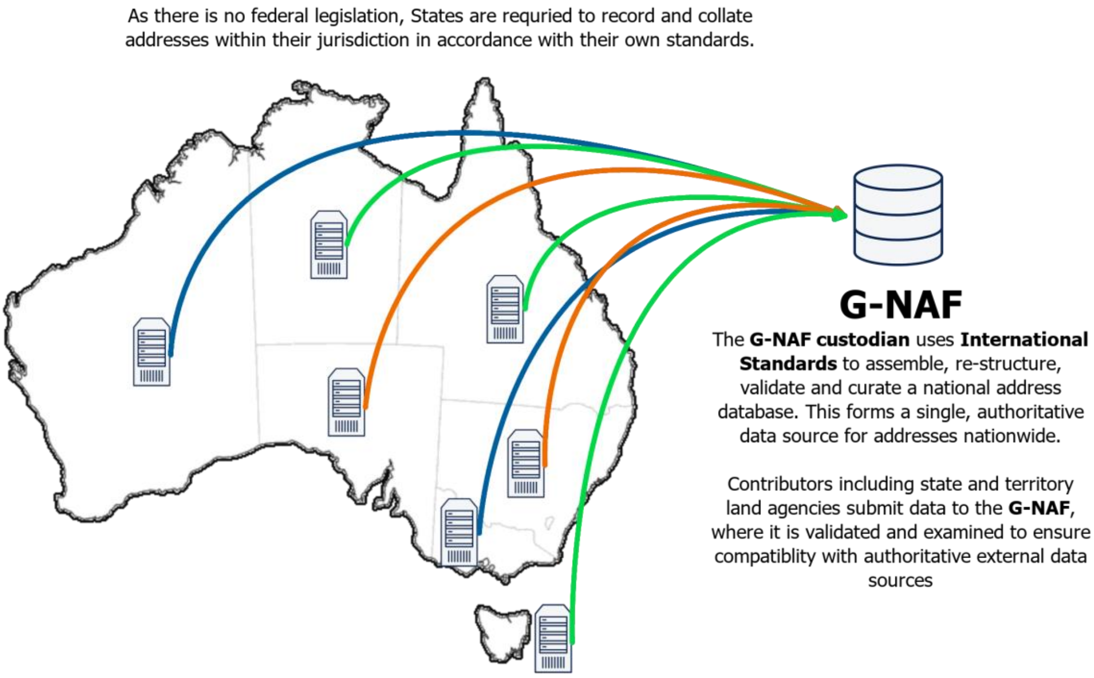

Figure 23: Taking care of state and national addresses.

HOW IT WORKS

Figure 24 illustrates standards helping in access to harmonised geocoded national address dataset.

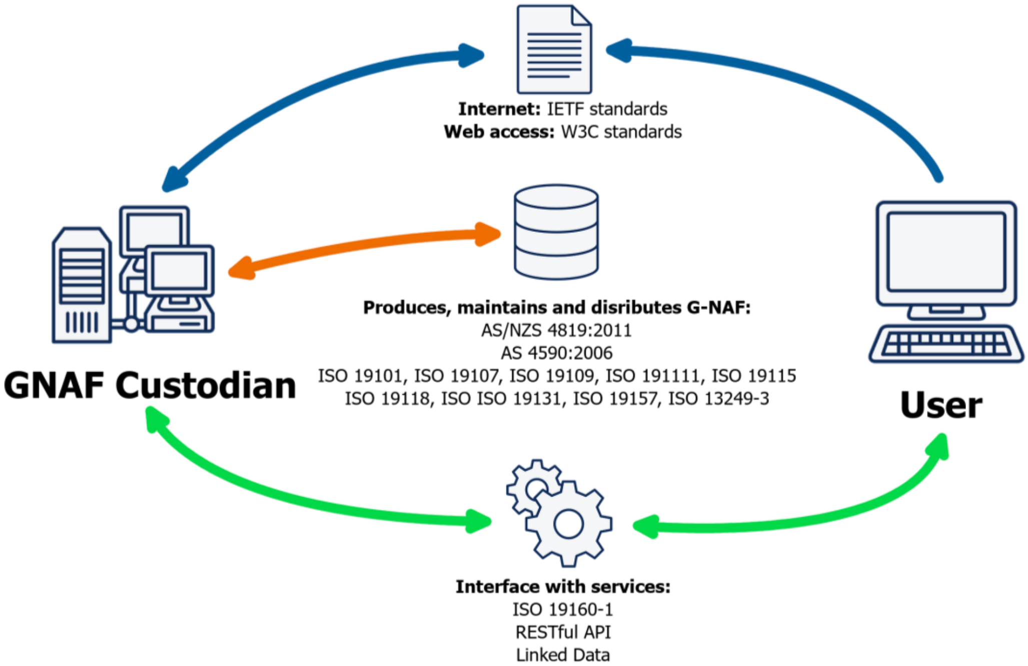

Figure 24: Standards in action for access to authoritative address data.

STANDARDS IN ACTION

Following are the standards enabling efficient access to spatial data:

- Internet Engineering Task Force (IETF) standard suite for enabling the existence and operation of internet (e.g. TCP/IP)
- World Wide Web Consortium (W3C) standard suite for enabling the web (e.g. HTTP, XML)
- ISO standards for geographic information, such as:
  - Standard to describe G-NAF as a product (ISO 19131);
  - Data standards for defining the structure of address data (AS/NZS 4819, AS 4590, ISO 19101, ISO 19107, ISO 19109, ISO 19111, ISO 19118 and ISO 13249-3);
  - Metadata standards for encoding descriptive information about data (ISO 19115 and ISO 19157);
  - Standards for enabling semantic web interface to data (ISO 19160-1, Linked Data) via RESTful API (the application programming interface to resources exposed via the Representational state transfer web software architecture);

This example has been developed mainly with resources from PSMA Australia and Location Index (locationindex.org), namely:

- G-NAF Data product specification, https://psma.com.au/wp-content/uploads/2020/02/G-NAF-Product-Description.pdf, and
- G-NAF FAQ, https://psma.com.au/support/
- http://locationindex.org/

C.3. Example 3: Representing geometry for lossless data exchange

User Scenario

The user needs to transfer their spatial data together from one database to another with the definition of the coordinate reference system (CRS), and without losing or modifying data and thereby compromising dataset's quality.

The problem

Dozens of different systems exist for storing and processing of spatial data, and all of these systems use their own way of structuring and encoding. When it comes to data exchange between different systems, it often happens that the internal standards of applications sharing these data are incompatible. This leads to compromising dataset's quality and incorrect representation of data at receiving end. Figure 25 illustrates a situation where different representations of the same locality (Perth, 115.87 Longitude, -31.95 Latitude) from the source application (on the left) resulted in different representations in the destination application (on the right).

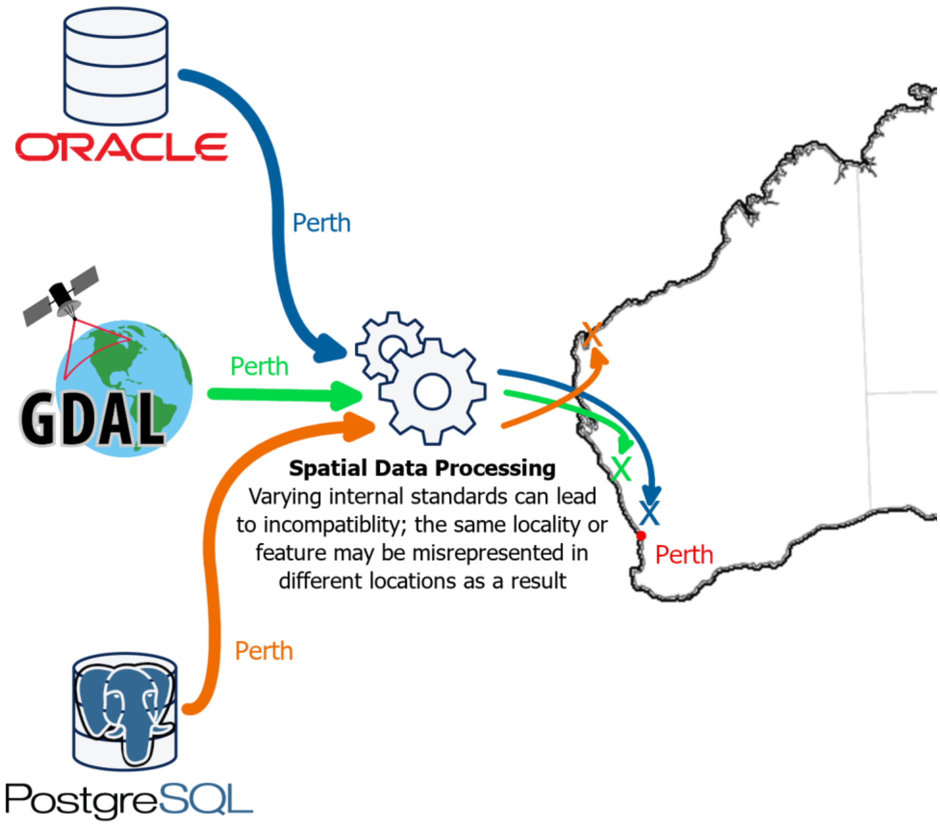

Figure 25: Many formats resulting to many different representations.

Solution

To overcome the unwanted scenario illustrated above, all parties involved in spatial interchange use Well-Known Text (WKT) representation for geometry and coordinate reference system encoding. This helps ensure an accurate data exchange and unique description of data structure and definition of coordinate reference system. This WKT standard defines an unambiguous structure for spatial data and reference system encoding and this is clearly interpreted into one and only one representation of a spatial object (Figure 26).

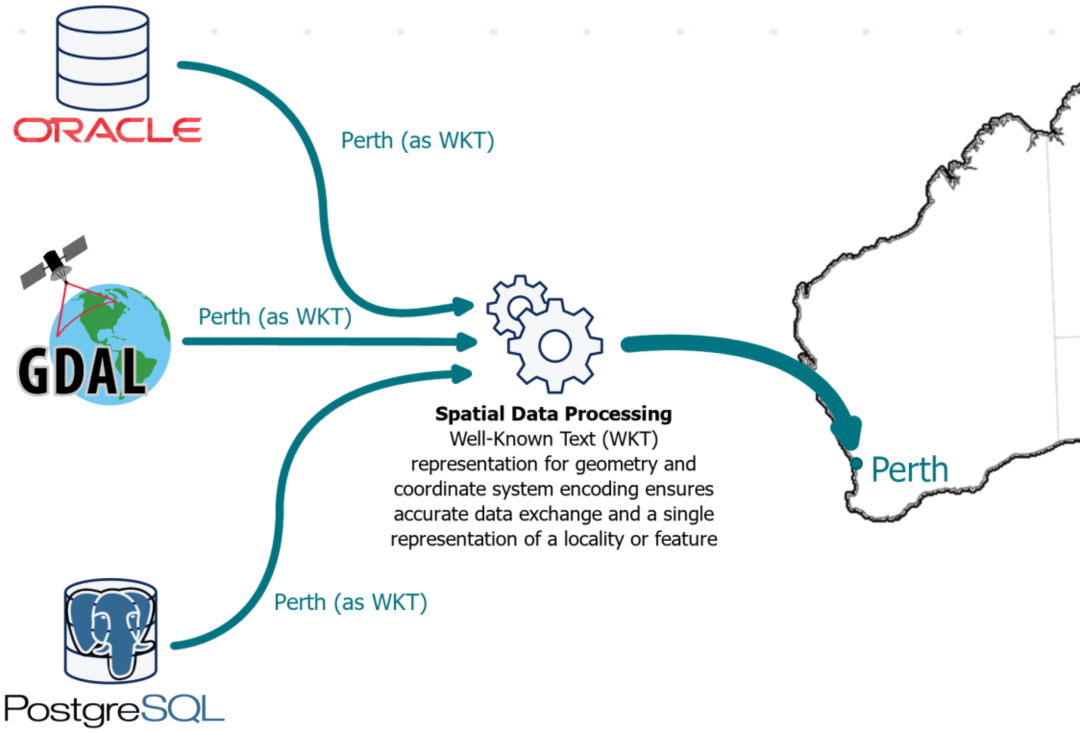

Figure 26: WKT representation of geometry results in an accurate representation of the object.

WHY DOES IT WORK?

Exchanging spatial data without modifying its quality works thanks to the support WKT data format on both ends of spatial data exchange: spatial data producers *translate* their data format from native format into WKT and users of spatial data process these with an application supporting WKT format (Figure 27).

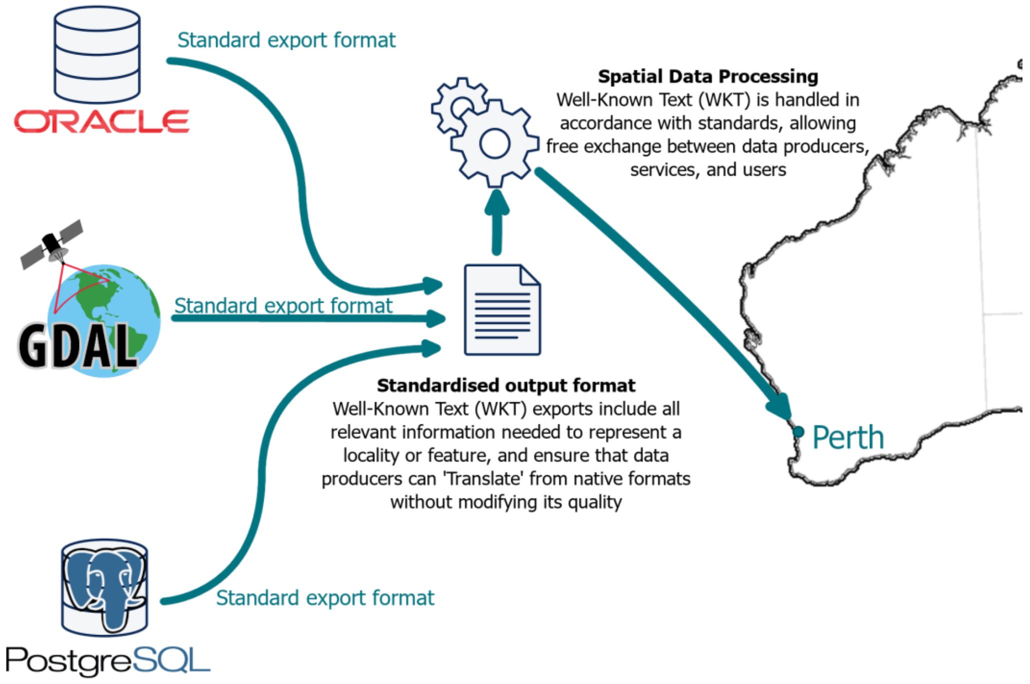

Figure 27: Taking care of state and national addresses.

How it works

Figure 28 illustrates how standards are helping in ensuring spatial data is exchanged without losing any content or modifying the quality of exchanged spatial data.

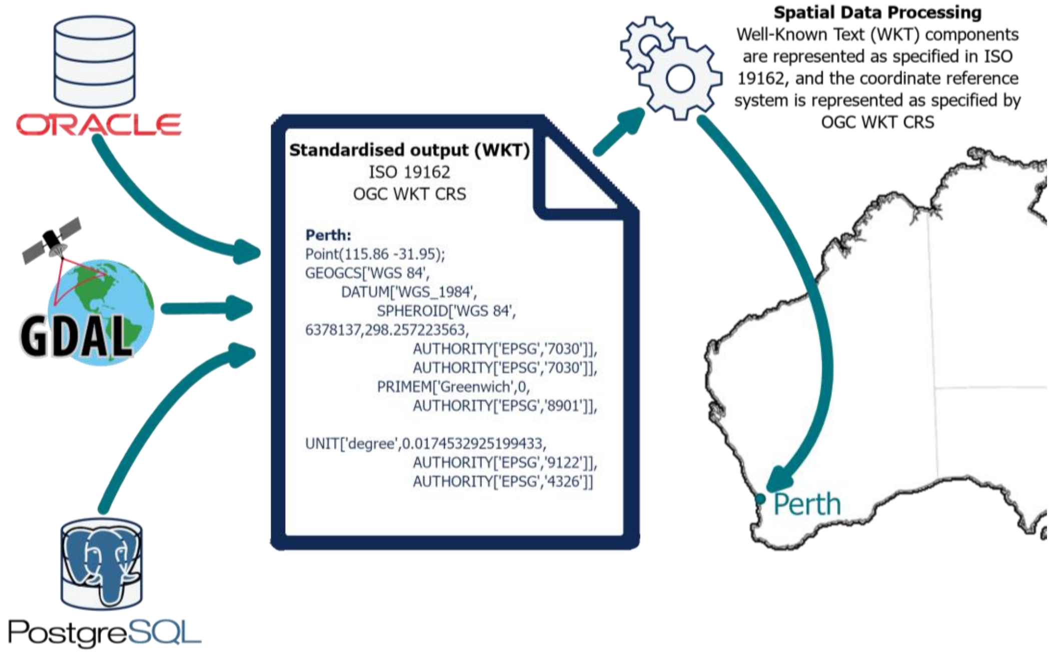

Figure 28: Standards in action for access to authoritative address data.

Standards in action

Following are the standards enabling efficient spatial data exchange:

- ISO 19162 for representing spatial data as well-known text
- OGC WKT CRS for representing the coordinate reference system in which spatial data is embedded

C.4. Example 4: Extracting spatial data to fit user's area and topic of interest

User Scenario

The user wants to obtain spatial data representing properties in a specific local government area in a city.

The problem

Spatial data with myriad of information at different resolutions is increasingly available from data providers. These datasets are typically much larger than what users need for their applications, and it can therefore be difficult to find just the information they need, for example, property information in the Wantirna suburb of Melbourne, Australia. This is because the motivation of data producers when acquiring and processing their data is different to what users' application of interest require. This means that when users need spatial data they have to obtain the entire dataset offered by the producer instead of purchasing just a subset of it. Clearly, this leads to unwanted expense and low user satisfaction. Figure 29 illustrates creation of a map of interest in three steps.

Figure 29: Obtaining all existing data from the provider.

Solution

Web Feature Service (WFS) interface offers data providers a possibility to expose their spatial data over the web, and provides users with direct, fine-grained access to data at feature level. This means that users can access and request just the portion of the spatial data they need. For example instead of the whole dataset as created by the producer (e.g. properties dataset in Victoria, Australia), users can request just few objects precisely matching their interest (e.g. properties of Wantirna suburb of Melbourne in Victoria, Australia). Figure 30 illustrates the process of obtaining data of interest in just one step.

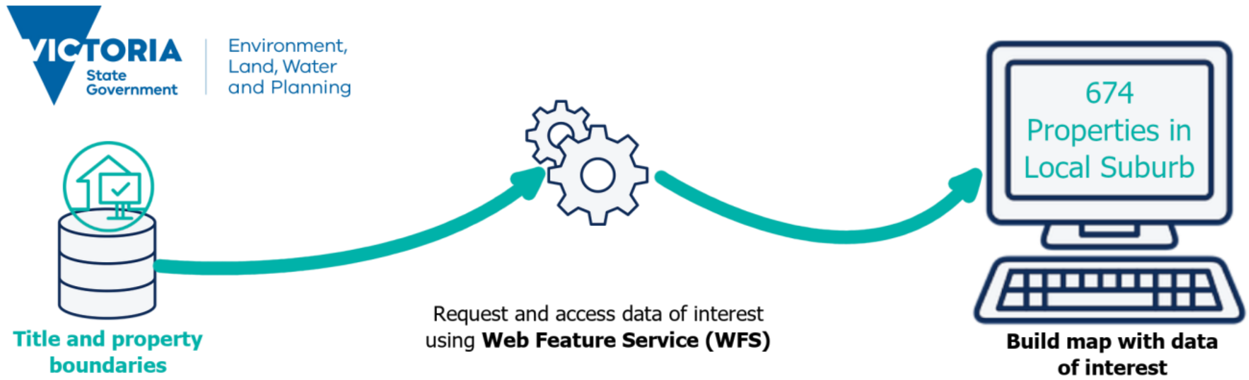

Figure 30: Obtaining the data of interest from the provider.

Why does it work?

Extracting the exact portion of spatial data of interest works because there is a support for standards on both ends of spatial data exchange. More precisely, spatial data producer publishes their spatial dataset to the web and exposes these via WFS, and users use an application for accessing and extracting spatial data that supports WFS.

Extracting the exact portion of spatial data of interest works because there is a support for standards on both ends of spatial data exchange. More precisely, spatial data producer publishes their spatial dataset to the web and exposes these via WFS, and users use an application for accessing and extracting spatial data that supports WFS (Figure 31).

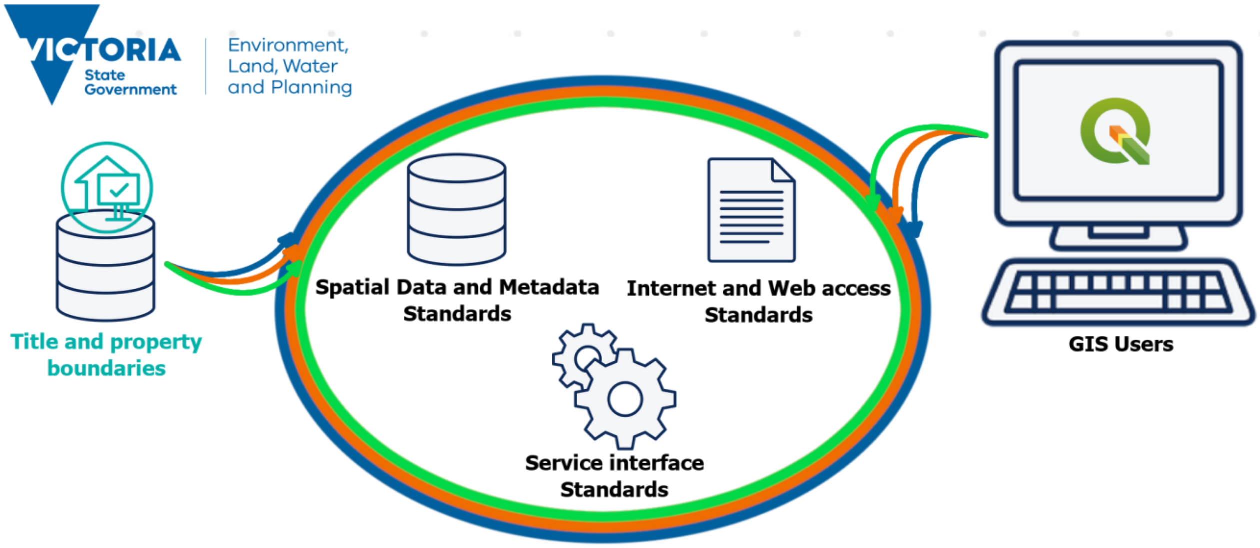

Figure 31: Reason for simplified process.

How it works

Figure 32 illustrates standards helping accessing and requesting spatial data of interest.

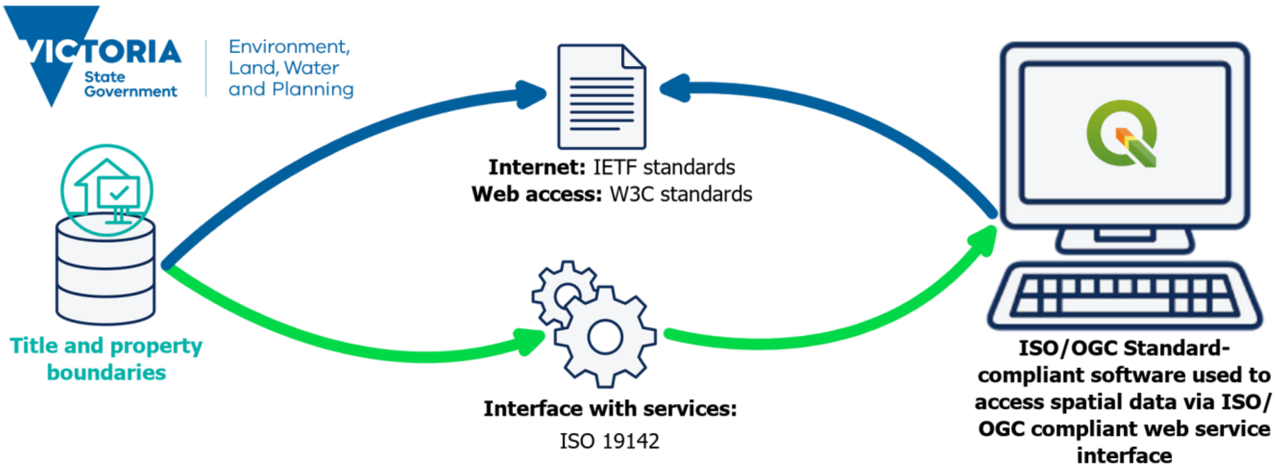

Figure 32: Standards in action.

Standards in action

Following are the standards enabling efficient access to spatial data:

- Internet Engineering Task Force (IETF) standard suite for enabling the existence and operation of internet (e.g. TCP/IP)
- World Wide Web Consortium (W3C) standard suite for enabling the web (e.g. HTTP, XML)
- Standard for enabling web service interface to spatial data (ISO 19142);

C.5. Example 5: Accurate and reliable delivery of GPS data

User Scenario

The user wants to receive accurate and reliable GPS position from the satellite in real-time.

The problem

Data flow between various archiving and processing components of the GPS correction system exist in wide variety of formats and thus requires several format-specific readers and writers (written in specific application language, e.g. Java, Python, C++) required by each application system. The resulting GPS message from the various platforms might not be consistent and requires careful human interpretation to assure its applicability. Figure 33 illustrates a simplified GPS information flow in 'just' seven steps starting with user requestion a GPS position, going through different stages of data archival and processing, until the user receives the requested position. This process involves translation from several data formats compliant with a standard in each data center.

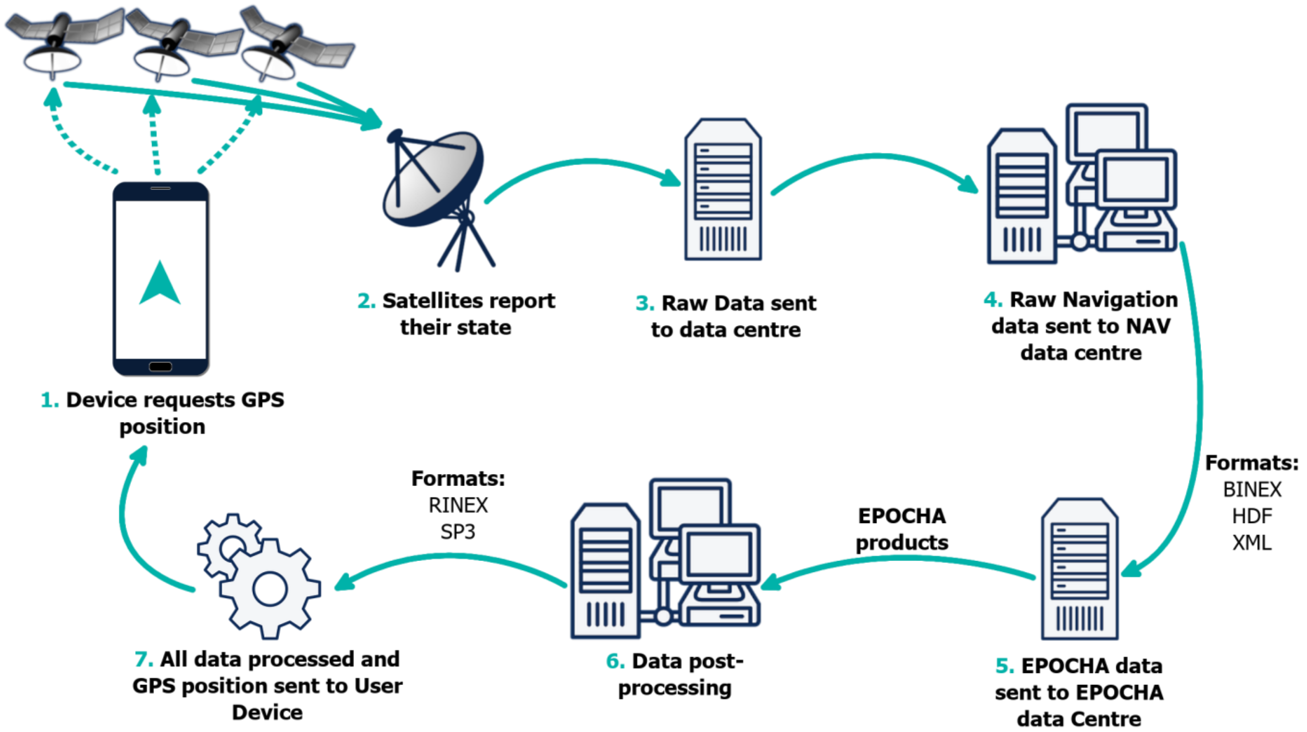

Figure 33: GPS message exchange - many standards, many formats.

Solution

Adopting a standard for message encoding and connecting the whole GPS ecosystem, i.e. satellites, reference stations, processing centres and end-users' receivers, facilitates GPS information exchange. Example in Figure 34 demonstrates how 'GPS Web Services' network reduces the request and delivery of GPS position to the user into just two steps.

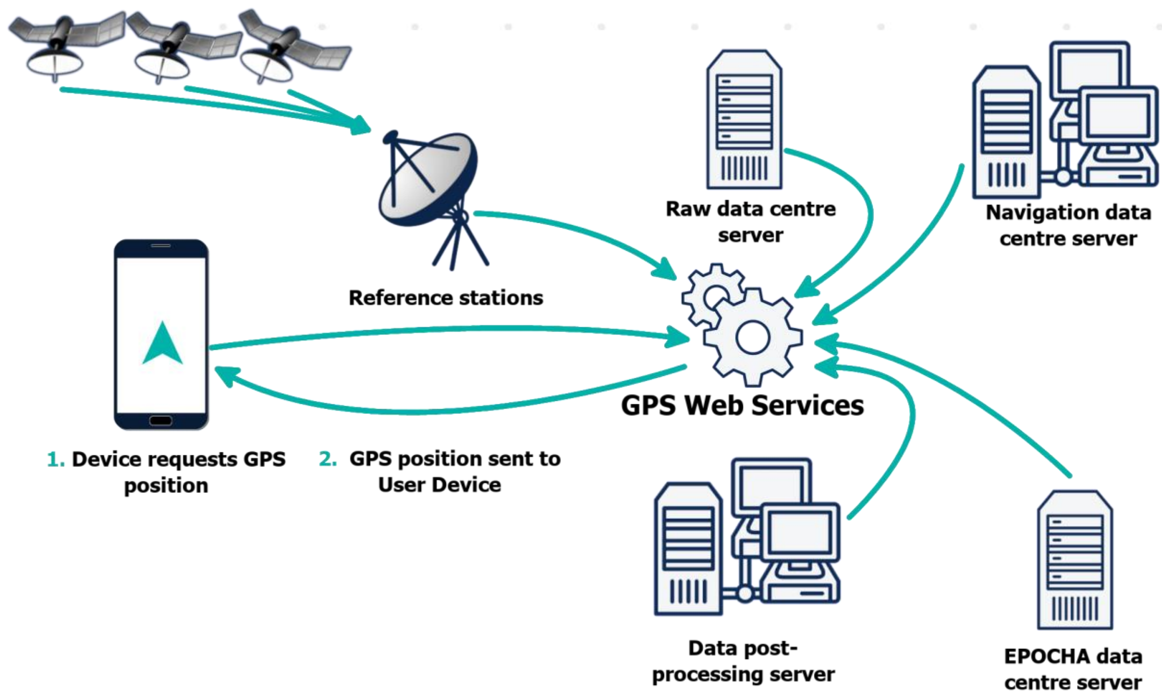

Figure 34: Components of standard-compliant GPS message exchange framework.

WHY IT WORKS

GPS information is flow and consistent due to the support for standards in all components of the GPS information exchange network (Figure 35).

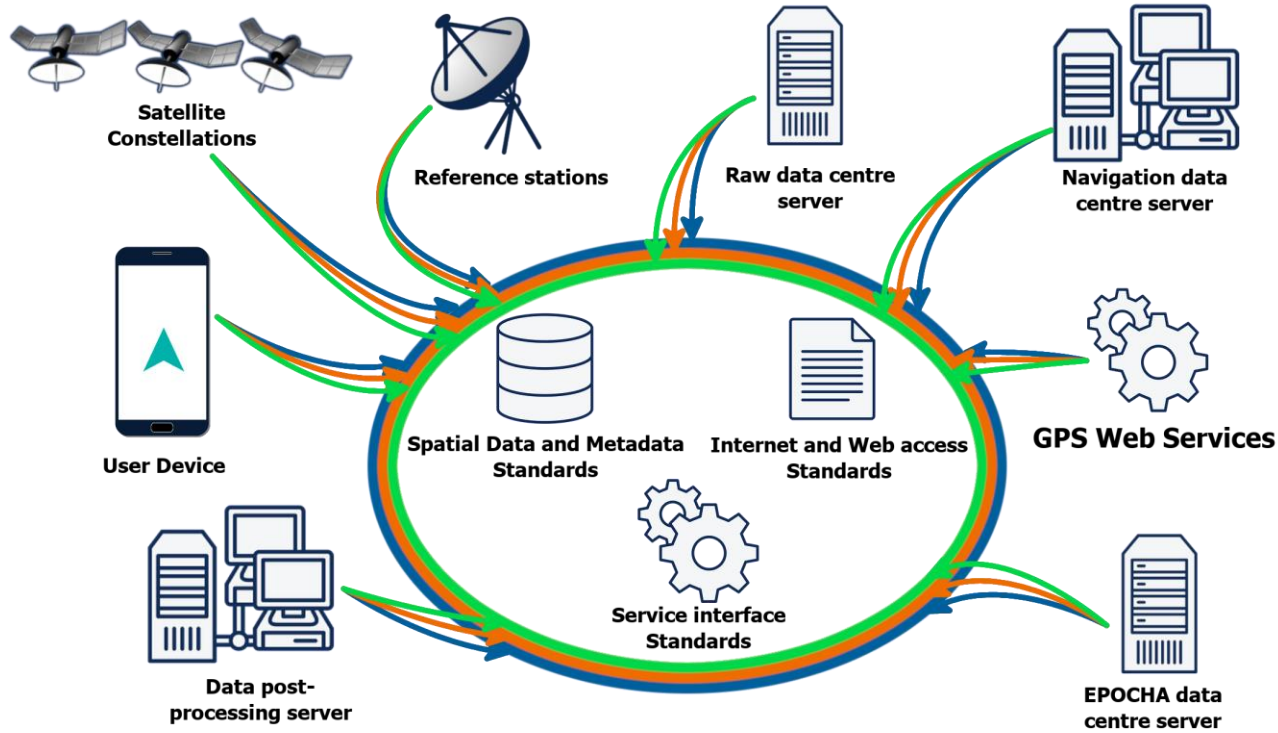

Figure 35: Standards enable simpler GNSS information exchange.

How it works

Realization of 'GPS Web Services' is possible using various standards - Figure 36 illustrates one example selection of standards helping in efficient requesting and obtaining GPS data.

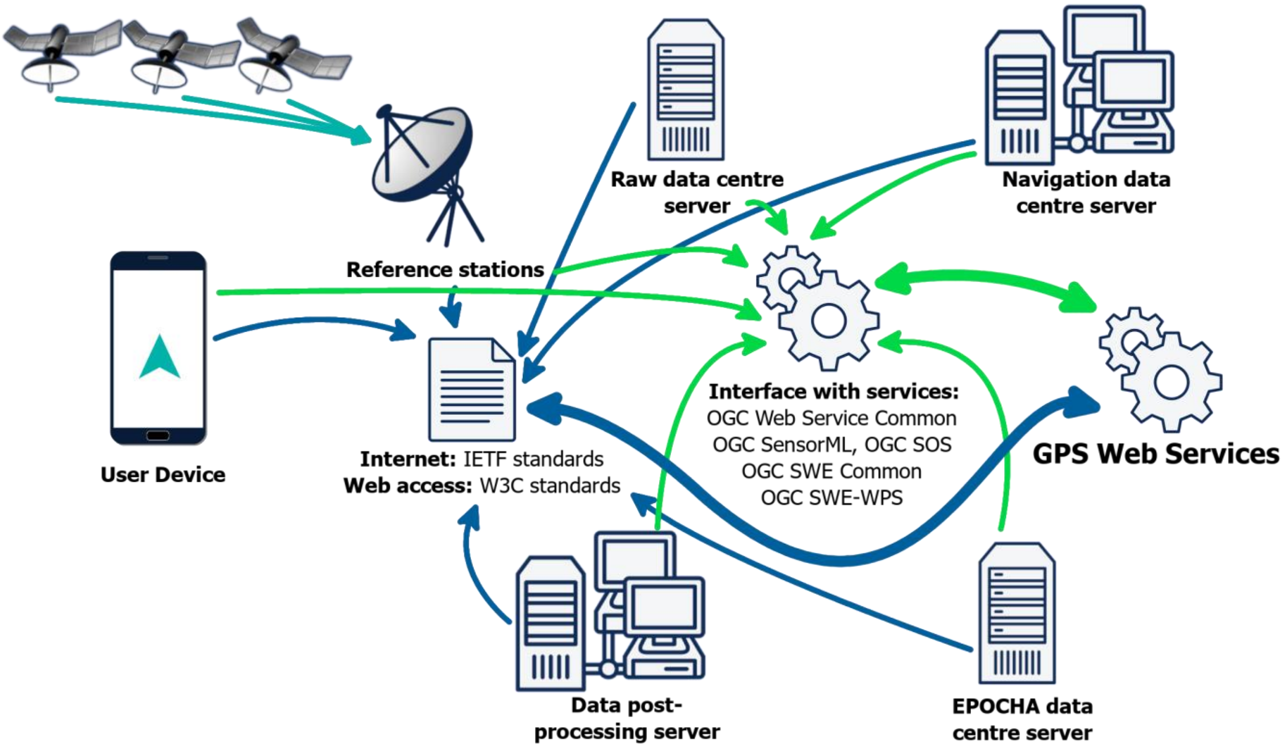

Figure 36: Standards in action.

Standards in action:

Following are the standards enabling efficient access to spatial data:

- Internet Engineering Task Force (IETF) standard suite for enabling the existence and operation of internet (e.g. TCP/IP);
- World Wide Web Consortium (W3C) standard suite for enabling the web (e.g. HTTP, XML);
- Standard for enabling web service interface to GPS data (OGC© Web Service Commons, OGC© SWE Common Data Model Encoding Standard, OGC© Sensor Modeling Language (SensorML), OGC© Sensor Observation Service, OGC© Web Processing Service);

Annex D FAIRness evaluation of GA's metadata record with MetaDIG

Table below represents the result of FAIRness evaluation results for an example metadata of GA's data repository ('Geodesy – Continuously Operating') with MetaDIG engine.

check namee	category	message	status
dataset.abstract.length.1	Findable	"The abstract word count of '27' is less that the recommended minimum of '100'"	FAILURE
dataset.keywords.controlled.1	Findable	"1 groups of controlled keywords (from a vocabulary) found (out of 9 keyword groups.)"	SUCCESS
dataset.keywordType.present.1	Findable	"The following keywords do not have a type specified: 'Geodetic Data	land, geodesy, GPS, GNSS, RINEX
dataset.publicationDate.timeframe.1	Findable	FAILURE	
metadata.identifier.present.1	Findable	"The metadata identifier 'GeoNetwork UUID	SUCCESS
dataset.naturalLanguageKeywords.present.1	Findable	"8 groups of natural language keywords found (out of 9 keyword groups.)"	SUCCESS
dataset.creator.present.1	Findable	"A dataset author/originator is not present"	FAILURE
dataset.creatorIdentifier.present.1	Findable	"A dataset creator identifier was not found."	FAILURE
dataset.revisionDate.present.1	Findable	"A dataset creation or revision date is not present"	FAILURE
entity.identifier.present.1	Findable	"The entity identifier 'http://pid.geoscience.gov.au/dataset/ga/74501' was found (first of 2 identifiers)"	SUCCESS
entity.identifierType.present.1	Findable	"The entity identifier type 'Geoscience Australia Persistent Identifier' was found"	SUCCESS
dataset.publicationDate.present.1	Findable	"A entity publication date is not present"	FAILURE
dataset.title.length.1	Findable	"The number of words in the dataset's title is 5. The minimum recommended word count is 7."	FAILURE
dataset.spatialExtent.present.1	Findable	"A spatial extent is present"	SUCCESS
geographic.description.present.2	Findable		FAILURE
dataset.taxonomicExtent.present.1	Findable	"A taxonomic extent is not present"	FAILURE
dataset.temporalExtent.present.1	Findable	"A temporal extent is not present"	FAILURE
dataset.accessControlRules.specified.1	Accessible	"The access control rules 'license' were found"	SUCCESS
dataset.landingPage.present.1	Accessible	"A dataset landing page url was not found."	FAILURE
distribution.contact.present.1	Accessible	"A distribution contact was not found."	FAILURE
distribution.contactIdentifier.present.1	Accessible	"A distribution contact identifier was not found."	FAILURE
dataset.distribution.present.1	Accessible	"A dataset distribution URL was not found."	FAILURE
dataset.publisher.present.1	Accessible	"A dataset publisher is not present"	FAILURE
dataset.publisherIdentifier.present.1	Accessible	"A dataset publisher identifier was not found."	FAILURE
dataset.serviceLocation.present.1	Accessible	"A service location is not present"	FAILURE
dataset.serviceProvider.present.1	Accessible	"A service provider was not found."	FAILURE
entity.access.public.1	Accessible	"Access rule for 'public' user found in DataONE system metadata. Data are publicly available"	SUCCESS
entity.attributeName.differs.1	Interoperable	"No entity definitions found	SKIP
entity.attributeNames.unique.1	Interoperable	"No entities found	SKIP
entity.attributeDefinition.present.1	Interoperable	"No attributes are present	SKIP
entity.attributeDefinition.sufficient.1	Interoperable	"No attributes are present	SKIP
entity.attributeStorageType.present.1	Interoperable	"No attributes are present	SKIP
entity.checksum.present.1	Interoperable	"An entity checksum is not present."	FAILURE
coverage.contentType.present.1	Interoperable	"A coverage content type was not found."	FAILURE
entity.attributeEnumeratedDomains.present.1	Interoperable		SUCCESS
entity.format.present.1	Interoperable	"A entity format was not found."	FAILURE
entity.name.present.1	Interoperable	"No entities are present so cannot check their name	SKIP
entity.type.present.1	Interoperable	"An entity type was found"	SUCCESS
dataset.serviceType.present.1	Interoperable	"A service type is not present"	FAILURE
entity.format.nonproprietary.1	Reusable	"An entity format was not found."	FAILURE
entity.attributeDomain.present.1	Reusable	"No attributes present so measurement domain cannot be	SKIP
entity.attributeUnits.present.1	Reusable	"No attributes present that require units	SKIP
entity.attributeMeasurementScale.present.1	Reusable	"No attributes present	SKIP
entity.attributePrecision.present.1	Reusable	"No attributes present that require measurement precision	SKIP
entity.description.present.1	Reusable	"No entities are present so cannot check their descriptions	SKIP
entity.qualityDescription.present.1	Reusable	"A data quality description was not found."	FAILURE
dataset.methods.present.1	Reusable	"A detailed methods section was found."	SUCCESS
metadata.license.present.1	Reusable	"A metadata license was not found."	FAILURE
provenance.processStepCode.present.1	Reusable	found."	FAILURE
provenance.sourceEntity.present.1	Reusable	"A lineage source is present"	SUCCESS
provenance.trace.present.1	Reusable	"Provenance trace information was not found."	FAILURE
dataset.entityLicense.present.1	Reusable	licenses)"	SUCCESS

Green = pass; Red = fail; Yellow = check skipped

Annex E Overview of available Geographic Information Metadata standards

Standard	Description
ISO 19110: 2016 Geographic information – Methodology for feature cataloguing	Defines methodology for developing a catalogue containing definitions of features and their properties in a domain of interest
ISO 19111: 2019 Geographic information – Referencing by coordinates	Defines metadata of the coordinate reference system
ISO 19115-1: 2014 Geographic information – Metadata – Part 1: Fundamentals ISO 19115-1: 2014/AMD 1:2018 Geographic information – Metadata – Part 1: Fundamentals, Amendment 1 ISO 19115-2:2019 Geographic information – Metadata – Part 2: Extension for acquisition and processing ISO 19115-3: 2016 Geographic information – Metadata – Part 3: XML schema implementation for fundamental concepts ISO 19139-2: 2012 Geographic information – Metadata XML schema implementation – Part 2: Extension for imagery and gridded data	Provides a framework and defines concepts for metadata of spatial datasets and services
ISO 19119: 2016 Geographic information – Services	Provides a framework and defines concepts for spatial services' metadata
ISO 19130-1: 2018 Geographic information – Imagery sensor models for geopositioning – Part 1: Fundamentals ISO 19130-2: 2014 Geographic information – Imagery sensor models for geopositioning – Part 2: SAR, InSAR, lidar and sonar ISO 19130-3 (under development) Geographic information – Imagery sensor models for geopositioning – Implementation Schema	Specifies a sensor model and provides metadata to be distributed with a sensor product
ISO 19139-1: 2019 Geographic information – XML schema implementation – Part 1: Encoding rules	Provides XML encoding rules for UML conceptual schemas commonly used in ISO/TC211 standards
ISO 19157: 2013 Geographic information – Data Quality ISO 19157: 2013/AMD 1:2018 Geographic information – Describing data quality using coverages ISO 19157-2:2016 Geographic information – Data Quality – Part 2: XML schema implementation	Defines metadata about the quality of a dataset.
ISO 19165-1: 2018 Geographic information – Preservation of digital data and metadata – Part 1: fundamentals ISO 19165-2 (under development) Geographic information – Preservation of digital data and metadata – Part 2: Content specification for earth observation data and derived digital products	Extends ISO 19115-1 with metadata required for the long-term preservation of digital geospatial data