RESEARCH PAPER

FAIR data and metadata: GNSS precise positioning user perspective

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ABSTRACT

The FAIR principles of Wilkinson et al. [1] are finding their way from research into application domains, one of which is the precise positioning with global satellite navigation systems (GNSS). Current GNSS users demand that data and services are findable online, accessible via open protocols (by both, machines and humans), interoperable with their legacy systems and reusable in various settings. Comprehensive metadata are essential in seamless communication between GNSS data and service providers and their users, and, for decades, geodetic and geospatial standards are efficiently implemented to support this. However, GNSS user community is transforming from precise positioning by highly specialised use by geodetic professionals to every-day precise positioning by autonomous vehicles or wellness obsessed citizens. Moreover, rapid technological developments allow alternative ways of offering data and services to their users. These transforming circumstances warrant a review whether metadata defined in generic geospatial and geodetic standards in use still support FAIR use of modern GNSS data and services across its novel user spectrum. This paper reports the results of current GNSS users' requirements in various application sectors on the way data, metadata and services are provided. We engaged with GNSS stakeholders to validate our findings and to gain understanding on their perception of the FAIR principles. Our results confirm that offering FAIR GNSS data and services is fundamental, but for a confident use of these, there is a need to review the way metadata are offered to the community. Defining standard compliant GNSS community metadata profile and providing

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relevant metadata with data on-demand, the approach outlined in this paper, is a way to manage current GNSS users' expectations and the way to improve FAIR GNSS data and service delivery for both humans and the machines.

1. INTRODUCTION

The Findable, Accessible, Interoperable and Reusable (FAIR) guiding principles [1] are reflected by the key characteristics of the data and services offered via a Spatial Data Infrastructure (SDI) [2, 3]. An SDI is a collection of technologies, standards, policies, and institutional arrangements that facilitate the availability of and access to spatial data, providing a basis for spatial data and service discovery, and their subsequent evaluation by users and service providers across all levels of government for application in the commercial sector, the non-profit sector, academia, and by citizens in general [4, 5, 6]. Through use of an SDI, Global Navigation Satellite Systems (GNSS) enable existing and emerging industries to use real-time precise positioning data, allowing them to improve productivity, efficiency, and safety, while supporting a wide range of decision-making processes. In order to effectively service current and future GNSS users' demands in a robust way, geodetic data and their associated metadata, which are the main vehicle of any functional SDI, need to be FAIR [7]. And to support FAIR data reuse by both humans and machines, metadata related to GNSS data also need to be encoded in a machine-readable way [8].

The range of current GNSS data users now extend significantly beyond the 'traditional' user segments. While traditional GNSS users, typically geodesists, geophysicists and surveyors, are trained to understand the specific jargon and data encoding used by SDIs, these 'new' users come from various application domains where GNSS receivers (many of which are low-cost and widely available) are increasingly used for many data collection, monitoring and navigation applications. General requirements for the use of GNSS in various traditionally recognized application domains, such as surveying, agriculture, aerial (drone), road, rail or maritime operations are readily available in most GNSS textbooks (e.g. [9]). Moreover, specification of requirements to suit emerging user applications is becoming increasingly present in research [10, 11, 12, 13, 14]. However, to date there has not been work done to investigate how both traditional and emerging GNSS user sectors understand and perceive the FAIRness of provided precise positioning data and metadata. Understanding users' perspective on FAIR is essential for GNSS data and service providers as this will help to reveal the potential challenges users face when interacting with these resources.

Standards play a crucial role when integrating GNSS and geodetic data with data from other domains in a FAIR manner. Current standards for geographic information that are relevant in the GNSS domain, such as the ISO 19100 series developed by the International Organisation for Standardisation and its Technical Committee for geographic information (ISO/TC211)[1] or standards for geodata encoding and catalogue web services developed by the Open Geospatial Consortium (OGC)[2], support the FAIR principles reasonably

[1] https://committee.iso.org/home/tc211
[2] https://www.ogc.org/docs/is

well [7]. Although ISO and OGC standards are developed for a generic 'geographic information' many of them are relevant in the GNSS domain as well. However, to increase the FAIRness of GNSS data and services, the use of domain specific standards in addition to generic standards is essential. Moreover, ISO and OGC standards are developed with a strong producer-centric focus and do not adequately serve the needs of current and emerging GNSS users [15, 16].

This paper aims to summarise what for current precise positioning users constitutes data and metadata that comply with the FAIR principles. We also summarize the level of support for FAIR in existing international standards for geodetic data and explore whether, through standard compliant data interfaces and infrastructures current GNSS users receive what they expect. In conclusion we outline the approach towards fulfilling these requirements with improved machine-actionable precise positioning metadata model.

The remainder of this paper is structured as follows: in Section 2 we discuss the meaning of metadata in SDI, followed in section 3 with an examination of how they are currently used to deliver precise positioning data to their users across GNSS value chain. Sections 4 and 5 contain the design and results of a GNSS stakeholder engagement, in which respondents were asked about their requirements for GNSS metadata and their views on the meaning of FAIR. In Section 6 we review how well current SDIs support GNSS users' requirements, and in Section 7 we outline a potential approach in improving the current status towards delivering GNSS data and services fully compliant with the FAIR principles.

2. METADATA—A CRUCIAL ELEMENT IN A FAIR SDI

The geoscience community champions the FAIR cause by creating and contributing to data repositories, which are an online open access research repository to store research outputs and artefacts. For example, the domain specific resource dedicated to register marine and climate scientific data accessible via the Australian Ocean Data Network Portal[3], or generalist repositories like Figshare, Zenodo, Dryad or Mendeley [17]. There are also activities that upskill geoscientists in FAIR practice (e.g. via webinars on FAIR or tools for FAIRness improvement such as those offered by DataONE[4])—these are paramount to improve insufficient compliance with the FAIR principles [18]. Furthermore, 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 [19]. However, it is only recently that non-scientific communities and organisations have started producing and offering a bulk of geoscientific content (including GNSS data and services) and are subsequently starting to embrace FAIR and begin to invest resources to improve their compliance with the FAIR principles.

Metadata are crucial for ensuring FAIRness of digital resources [20], and whether intrinsic or user-defined, they are the essential information exchange vehicle between users and providers of spatial data, information and services within an SDI. Intrinsic metadata is created automatically during data capture (e.g.

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

[4] https://www.dataone.org/fair/

time-stamps of a data record, or an automatic label of data production software) and user-defined metadata is subsequently added to provide context for understanding the creation of a digital object [21].

Geospatial metadata are often stored and maintained separately from the resource itself—ideally, they should be stored in the SDI and its catalogue of resources. However, it should be noted that SDIs typically provide only indirect access to a spatial resource described by the metadata stored in the catalogue. To fully comply with the FAIR principles (especially principle F1, which requires that metadata and data are assigned globally unique and persistent identifiers [1]), the metadata need to either be embedded in the data (for example through data encoding formats, such as netCDF[5] or HDF5[6]) or linked to the data itself using unique persistent and resolvable identifiers.

2.1 What FAIR guiding principles mean for geodetic resources in an SDI

Many Australian national geodetic resources are advertised through Geoscience Australia (GA) corporate SDI metadata catalogue which is compliant with GA Community Metadata Profile of ISO 19115-1:2014 [22, 23]. In this section we review the application of FAIR principles [1] in GA Data and product catalogue (GA Catalogue[7]). We reviewed the FAIRness on an example resource called 'Geodesy—Continuously Operating'. This resource contains metadata about data collected from the Australian Regional GNSS Network, Auscope network and other GNSS observatories located around the world over the last 15 years. We used a FAIRisFAIR[8] [26] Research Data Object Assessment Service (F-UJI)[9] to derive the FAIRness score of our example resource. F-UJI is a web service which programmatically assesses research data objects (data, metadata or other documentation) based on the FAIRisFAIR Data Object Assessment Metrics [24, 25, 26] fully compliant with the FAIR principles as defined in [1]. The result of the FAIRness assessment of 'Geodesy—Continuously Operating' resource available at http://dx.doi.org/10.4225/25/552B5AAD0C34A is summarized in Figure 1.

According to the results illustrated in Figure 1 the overall FAIRness score of our example resource is 45% indicating an initial level of FAIRness maturity, with breakdown on each component as follows: F—86%, A—33%, I—25%, R—30%.[10] F-UJI scores each component based on metrics, fully compliant with the FAIR principles [1].[11]

Resources 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 [1, 27].

[5] https://www.unidata.ucar.edu/software/netcdf/
[6] https://www.hdfgroup.org/solutions/hdf5/
[7] https://ecat.ga.gov.au/geonetwork/srv/eng/catalog.search#/home
[8] https://www.fairsfair.eu
[9] https://www.f-uji.net
[10] Full report with partial results included is available here: https://www.f-uji.net/view/154
[11] Full explanation of metrics and tests applied by F-UJI is available here: https://www.f-uji.net/index.php?action=methods

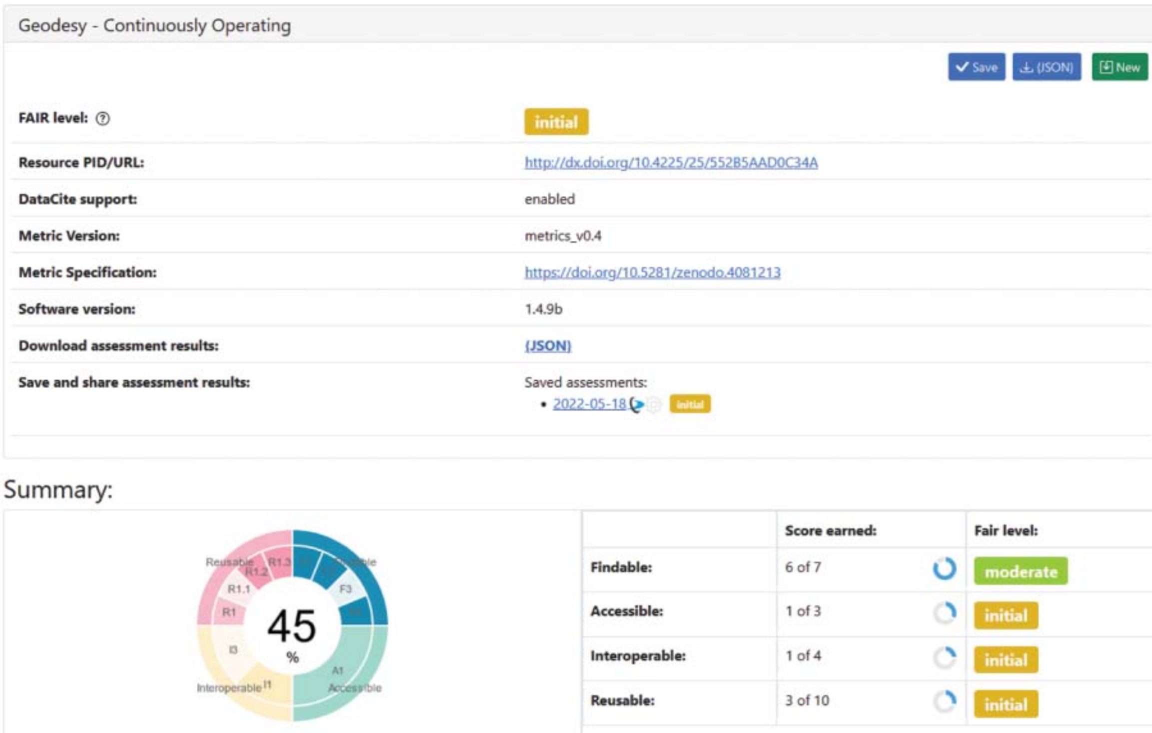


Figure 1. FAIRness score of 'Geodesy—Continuously Operating' GNSS resource available in GA Catalogue as scored by F-UJI assessment tool [24].

Our example GNSS resource called 'Geodesy—Continuously Operating', which is registered in and advertised through GA Catalogue, can be considered findable for number of reasons, namely:

- The metadata are assigned a globally unique and persistent identifier.[12]
- The resource is described with rich human- and machine-readable metadata.[13]
- The metadata clearly and explicitly include the identifier of the resource it describes.
- The metadata are registered or indexed in searchable resource (GA Catalogue is a web-based metadata catalogue).

As such, the 'Geodesy—Continuously Operating' resource complies with the F1, F2 and F4 principles described in [1], but according to the results from F-UJI, not with F3 (see 'findability' score being only 86%). This is because, although the metadata point to a website[14] with various downloadable content, the pointers are not resolving to a data object itself.

[12] http://dx.doi.org/10.4225/25/552B5AAD0C34A and http://pid.geoscience.gov.au/dataset/ga/74501
[13] https://ecat.ga.gov.au/geonetwork/srv/api/records/c692fb4b-4d67-719d-e044-00144fdd4fa6/formatters/xml?approved=true
[14] https://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/gnss-networks/data-and-site-logs

Digital resources are **accessible**, when anyone (human or machine) with access to the Internet understands exactly how to access the digital resource and what are the conditions on its reuse [1, 27]. A 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 that there is both clarity and transparency on the conditions of access, use, and reuse of these objects [21]. For example, those resources registered in GA Catalogue that have a Digital Object Identifier (DOI) can be considered accessible because their metadata are retrievable by their identifier using a standardized free, open and universally implementable communication protocol, which allows for an authentication and authorisation procedure (such as HTTPS), and the associated metadata are accessible, even when the data are no longer available. ‘Geodesy—Continuously Operating’ resource from the GA Catalogue scored 33% on ‘accessibility’ having metadata accessible through open protocol. The missing components are information on how and through which protocol to access the data themselves (A1.1 and A1.2 as in [1]).

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” [27, p.9]. According to [1], to be interoperable, metadata and data have to use vocabularies that are FAIR, e.g. in a format compatible with semantic web [21, 28]. Even if not fully compliant with the FAIR principles defined in [1], use of a well-defined community profile (e.g. [22]) and providing metadata in a machine-readable format (e.g. XML) definitely increases interoperability of a resource. Some resources, including the example resource assessed in this section, registered in GA Catalogue are described by metadata in compliance with the GA Profile of the ISO 19115-1:2014 standard[⑧], which is a formal, accessible, shared, and broadly applicable language for metadata [7, 23]. Moreover, (meta)data include qualified references to other metadata (ISO 19115-1:2014 metadata standard inherently refers to ISO 19157 [29], which is the standard for data quality metadata). However, the vocabulary of this profile is not machine-accessible at a persistent identifier accessible via the Web, which is required by I2 as in [1]. Also, cross-references between data and related entities which would enrich the data resource’s context (I3 as in [1]) are missing as well. This explains the low (25%) ‘interoperability’ score for our example resource.

License information and the description of the provenance are the two crucial factors determining the **reuse** of a digital resource [27]. In addition, both humans and machines should be able to reuse the digital resources [21], which requires that the description of the license and provenance information need to be provided in a suitable format (e.g. XML or RDF). ‘Geodesy—Continuously Operating’ resource in GA Catalogue is described with metadata that are released with a clear and accessible data usage license (CC BY 4.0). However, this description is only human-readable and not machine-readable as demanded by R 1.1 as defined in [1]. Metadata of our example resources are associated with data provenance (lineage attribute in GA profile of ISO 19115-1:2014 is a mandatory element), but this information, again, is not

[⑧] http://dx.doi.org/10.11636/Record.2018.026

machine-readable, as the format of 'lineage' as in GA profile of ISO 19115-1:2014 is free text [22, 23]. And because our example resource meets the domain relevant community standards (ISO 19115-1:2014 is a community standard for describing geographic information), the resulting 'reusability' score is 30%.

These results confirm that current way of providing generic metadata resource in GA Catalogue still needs improvement to comply with the FAIR principles, despite GA's profile of the ISO 19115-1:2014 being much stricter in that it mandates producers to report than its source (ISO 19115-1:2014) [22]. It is noteworthy that GA's profile of the ISO 19115-1:2014 is still a generic profile for geographic information metadata which does not ensure a full compliance with FAIRness requirements as in [1]—for example, there is a need to increase performance on 'reusability' by mandating machine-readable record of provenance. Moreover, to address R1.3 in particular [1], the metadata profile needs to include domain specific metadata attributes—in Section 7.1 we outline a potential approach of addressing this issue.

2.2 Current Precise Positioning Data and Metadata Delivery in an SDI

Standards are one of the three pillars of any SDI, alongside organisational and technical rules, which collectively serve users from the current high-end precise positioning sectors. Internationally, several groups are working on defining standards for geospatial and geophysical metadata, and the enhancement of their interoperability. ISO/TC211 and the OGC are the two main organisations involved with defining standards for geographic information and its exchange. In the geodetic community, the International GNSS Service (IGS) is the main organisation developing standards for GNSS message interchange. Several well-defined standards are already in use in the precise positioning domain, such as independent exchange format standards for the GNSS receiver data (Receiver-Independent Exchange Format—RINEX[16]), ionosphere maps (Ionosphere Map Exchange Format—IONEX[17]) and processing solutions (Solution independent Exchange Format—SINEX[18]). These standards for GNSS message encoding and exchange are well known to many geodesists and surveyors. Interestingly, all the above standardisation organisations deal with spatial information interchange, and yet there remains a surprising divide between the users of ISO and OGC standards, and users of IGS standards. Leveraging ISO and OGC standards in the GNSS domain has the potential to enable cross-domain integration of geodetic datasets with other spatial datasets and thus serve the current GNSS users in more efficient way. Although there is currently no international strategy to ensure FAIR geodetic data, several efforts, such as the formation of the EarthScope Consortium[19] to provide joint access to geodetic and seismological data and services to the community, or the UN-GGIM's Global Geodetic Center of Excellence[20] to maintain and improve the Global Geodetic Reference Frame, indicate the GNSS community's awareness and contribution FAIR to geodetic data and services. Furthermore, various initiatives towards controlled and FAIR cross-domain vocabularies are ongoing via several (geo)scientific

[16] https://www.igs.org/wg/rinex/

[17] https://files.igs.org/pub/data/format/ionex1.pdf

[18] https://www.iers.org/IERS/EN/Organization/AnalysisCoordinator/SinexFormat/sinex.html

[19] https://www.earthscope.org

[20] https://ggim.un.org/UNGGIM-wg1

platforms (e.g. ESIP[21], RDA[22] or CODATA[23]) with one recent example on increasing interoperability of FAIR vocabularies in Earth Sciences organized under the auspices of CODATA in 2021[24].

In the past few years FAIR has become increasingly common in most organisations defining standards and best practice for geodata (such as at ISO/TC211, OGC and IGS) and at most important geospatial events (e.g. GEO Week 2019, AGU 2019 Fall meeting, ESIP 2019 Summer and Winter meetings). There have been some attempts to 'encode' FAIR principles into geodata standards and best practice. The most recent, and one of the first very specific mentions of FAIR is contained in the recently released version 4.0 of the Receiver Independent Exchange Format (RINEX)[25], a GNSS data encoding standard, released in December 2021 [30]. If GNSS receiver data is encoded using this version of the standard, observational data files now may include information such as the Digital Object Identifier (DOI) defined for the file, data usage license, and an explicit link to the associated metadata about the GNSS station the data file refers to. With this information encoded, the geodetic data files support the 'Findable' and 'Reusable' from the FAIR principles [1]. Although this is a step forward, a lot more is needed to make geodetic files in RINEX 4.0 format fully compliant with the FAIR principles.

Although this emerging trend of attention to FAIR continues to gain traction, implementing the full list of 15 FAIR principles [1] is not yet common practice within the geospatial and geodetic community. There are numerous standards available for defining and sharing geospatial data (for example, at the time of writing, there are 90 published standards in the ISO 19100 series for geographic information alone) as well as several community profiles and best practices. However, in most cases these standards fall short of ensuring the FAIR distribution of geospatial resources. However, the geospatial community' recognises the need for FAIR digital resources. For example, at the end of 2019, the OGC changed its mission from being an organisation producing standards for a human- and machine-actionable geospatial web into being an organisation driven to make geospatial (location) information and services for humans and machines FAIR, i.e. Findable, Accessible, Interoperable, and Reusable[26]. 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 each available.

Ivánová et al. [7] have investigated current international standards, mostly from the ISO 19100 series and best practice for geodetic data and metadata and their support for FAIR. The ISO 19100 series was chosen due to its comprehensiveness in defining various aspects of geospatial metadata and several are relevant to the provision of information about geodetic resources. Results of standards FAIRness evaluation showed that current geodetic standards (i.e. standards from the ISO 19100 series directly relevant for the

[21] https://www.esipfed.org/
[22] https://www.rd-alliance.org/
[23] https://codata.org/
[24] https://codata.org/initiatives/decadal-programme2/dagstuhl-workshops/dagstuhl-workshops-2021/interoperability-for-cross-domain-research-fair-vocabularies/
[25] https://igs.org/formats-and-standards/
[26] https://www.ogc.org/about

geodetic domain) do provide support for FAIR inherently as a suite is designed to encompass all aspects of the data lifecycle and is developed with the view to support SDI principles [7, 31]. Due to the wide-reaching scope of the ISO 19100 series, the standards do not need to be implemented as a full collection and it is up to providers to select the appropriate collection of metadata and make sure a FAIR description of their resources is provided. It is noteworthy that ISO 19100 series provides generic metadata and, however strict (as in GA's profile of the ISO 19115-1:2014), these ensure compliance with some of the FAIR principles. In case of those FAIR principles that require domain standards (e.g. I and R) these need to be ensured by standards defined by the specific domain community—for geodetic community these standards should be developed under the auspices or with strong participation of the International Association of Geodesy of the International Union of Geodesy and Geophysics (IAG/IUGG)[27].

A snippet of the earlier evaluation of existing standards' FAIRness [7] is illustrated in Figure 2—for example ISO 19115 suite of standards for metadata of geographic information fully support 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		✓	✓	

Figure 2. FAIRness of current 'geo' standards: subset of the standard collection with standards on geographic information metadata highlighted in red rectangle. Full list of standards relevant for precises positioning data together with their FAIRness evaluation is available in [7].

However, even if standards for ensuring FAIRness of digital resources are available, like in the example highlighted in Figure 2, the selection of an appropriate set of standards and the provision of information beyond the mandated minimum (e.g. including metadata as required by the user) remains a decision for the digital resource producer.

[27] http://www.iugg.org/associations/

As can be observed from the results in Figure 1 and Figure 2, standards for geographic information are moving towards better compliance with FAIR principles. The deficiencies causing low FAIR score are similar to those indicated by [32] and [21], current data and metadata records miss elements of interoperability and reusability, which include machine-readable records of the provenance, machine-readable license information, and links to well-defined and established domain vocabularies of a resource. Although there is an evolution in ISO/TC211 towards more machine-actionable focus of the ISO 19100 series (see for example procedures on URI assignment for ISO 19100 concepts[⑧]), as stated earlier, this series is dedicated for providing a generic metadata constructs, which ensure partial compliance with the FAIR principles as defined in [1]. The reusability aspect of FAIR will only be ensured with community participation—for example, through a community profile for metadata as proposed in Section 7.1 and Section 7.2, or a community standard for domain specific encoding of data with embedded metadata such as next version of RINEX standard or some new data encoding standard, such as GeodesyML as outlined in Section 7.3). 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. UNDERSTANDING THE CHANGING FACE OF GNSS COMMUNITY

Thanks to the increased availability of GNSS technology and access to low-cost GNSS receivers, the user landscape has changed in recent years and new, previously undefined (or unnoticed) sub-sectors of users have emerged [7, 33]. If, in the past, users of precise positioning data were mostly surveyors, geodesists or geophysicists [9], the current composition is richer and more expansive, including GNSS users from unexpected members of society, such as pensioners who use GNSS technology to assure their own health and safety (e.g. emergency caller localisation, senior mobility monitoring), or transport passengers, who use GNSS technology to stay updated in real-time during their journey via their smartphones [34].

3.1 GNSS Value Chain

GNSS consists of three fundamental segments: the space segment (GNSS satellites), the control segment (satellite monitoring stations) and the user segment (the GNSS receivers in application sectors). From the perspective of the GNSS signal workflow, we can view GNSS as a combination of upstream (monitoring station to satellite) and downstream (monitoring station to user) components (see Figure 3). The GNSS **upstream** component is comprised of space and control segment that provide a signal to users. The GNSS **downstream** component utilizes within their applications and services the infrastructure and signal provided by the GNSS upstream component. These applications and services encompass the entire value chain of GNSS-specific components, GNSS receivers, GNSS-enabled systems, GNSS-enabled software and added-value services. The downstream industry can be classified into the following four categories [34]:

⑧ https://committee.iso.org/sites/tc211/home/resolutions/isotc-211-good-practices/--structure-of-uris-in-isotc-211.html

1. **Component manufacturers**, including manufacturers of GNSS-specific components (e.g. GNSS chipsets and antennae), small GNSS receivers and integration-ready GNSS receivers (i.e. supplied to system integrators).
2. **System integrators**, integrating GNSS capability into larger systems such as vehicles.
3. **Value-added service providers**, whose services improve access and use of GNSS, these include services provided by the International Association of Geodesy (IAG) and other organisations contributing to enhancement of the GNSS data service (bundled into the Innovation User category in Figure 3).
4. **End Users**: arguably, the most important segment of the GNSS value chain, who consume GNSS data and services to collect input for their applications (e.g. the operator of the GNSS unit in control traffic farming, or autonomous vehicle using GNSS unit for high-accuracy navigation in urban area).

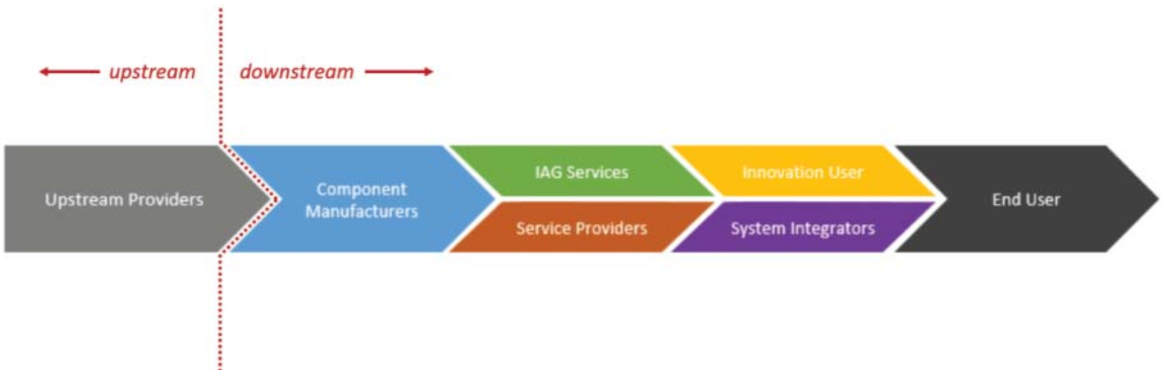


Figure 3. GNSS value chain.

3.2 GNSS Users

Today's GNSS user sector (humans and machines) are well-conversant in the GNSS domain and expect active participation in selection of the best positioning information to suit their needs [34]. Along with location information, users request information about the quality of their precise positioning and other relevant metadata [7, 33]. Accuracy, availability and integrity of the GNSS data, last data/service update and provenance of the GNSS site, are a few examples of such GNSS quality metadata [7, 35]. Depending on the sector, the relevance of metadata information vary. For example, 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, positioning accuracy is paramount, whereas in sectors that have inherent safety components to them such as rail, road and aviation (including safety-of-life services), information authentication and integrity are significantly more important [7, 9, 33].

4. GNSS USER REQUIREMENTS ELICITATION: METHOD

The primary objective of the GNSS user requirements elicitation conducted by GA in 2021 was to identify precisely what users expect to receive with the data and services they subscribe to. In other words, which are the metadata that ensure users are able to find, access and use geodetic data and services. The GNSS user requirements elicitation consisted of two parts, Desk-based research, and Stakeholder consultation.

4.1 Desk-Based Research Design

The first phase of user requirement elicitation consisted of a thorough review of existing scientific literature as well as the grey literature (organizational technical reports, white papers, analyses, websites and discussion fora) on the topic. Reports and literature used are included are detailed in [7], and organizations and societies consulted during the desk-based research in addition to the existing literature are listed below:

ANZLIC ICSM's Permanent Committee on Geodesy[29]
Geoscience Australia's Positioning and Navigation domain[30]
European GNSS Agency[31]
Eurogeographics' Positioning Knowledge Exchange Network[32]
International GNSS Society[33]
International GNSS Service[34]
US government's official resource on GPS and related topics[35]
FrontierSI SBAS testbed[36]

The objective was to identify which metadata are essential in recognized emerging GNSS user communities (e.g. agriculture, rail or road sector). Results of the GNSS user requirements identified through the desk-based research are summarized in Section 5.1.

4.2 Stakeholder Consultation Design

It is worth noting that most documents and reports consulted in the desk-based GNSS user requirements elicitation focus on the 'End User' part of the GNSS value chain defined in Section 3.1. The objective of our stakeholder consultation was not only presenting end users with the result of the desk-based research, but also to ensure their appropriate representation within the GNSS value chain (Figure 3).

[29] https://www.icsm.gov.au/what-we-do/permanent-committee-geodesy
[30] https://www.ga.gov.au/scientific-topics/positioning-navigation
[31] https://www.gsa.europa.eu
[32] https://eurogeographics.org/knowledge-exchange/posken
[33] http://www.ignss.org
[34] http://www.igs.org
[35] https://www.gps.gov
[36] https://frontiersi.com.au/project/satellite-based-augmentation-system-test-bed

Identification of participants in the stakeholder consultation was non-probabilistic, having been identified and selected through a combination of a haphazard, purposive and snowball sampling [36].

The following methods were used to engage with industry, in order to obtain survey participants and to reach the broadest spectrum of users:

- Targeted and direct engagement with known users of GNSS technology using Geoscience Australia's existing subscriber mailing list and AusCORS[37] user lists.
- Targeted, but indirect engagement via publicly available contact details of large-scale entities who are known to be users of precise positioning found via publicly listed company data.
- Non-targeted engagement via social media platforms, calls for respondents via both the Geoscience Australia and FrontierSI social media pages (LinkedIn, Twitter and Facebook).
- Promotional events managed by Geoscience Australia and FrontierSI were also used to cross promote the survey.

The survey was sent to entities in each section of the GNSS value chain, and a diverse sector of industries were represented (see Figure 3). 952 direct requests were sent to enable participation in the survey with active social media campaign on platforms with over 5000 followers. We received 106 responses by the end of the campaign.

All respondents who elected to receive the results of the survey were sent a summary of the results, contributing to an improved awareness of FAIR data, the GNSS value stream and the role of metadata across the GNSS value stream.

The stakeholder consultation was conducted in accordance with Geoscience Australia's Privacy Policy[38], including the completion of a Privacy Impact Assessment[39]. This process ensured that any possible impacts on the privacy of individual's personal information were identified and mitigated. Each response was anonymised, removing all identifiable information about the respondent, retaining only the segment of the GNSS value chain and the answers to each question, before being compiled for subsequent review and analysis by the project team. Each anonymous response was then reviewed to clarify any ambiguity, note any unexpected findings, and to gauge the relevant frequency of common responses. At the end of the stakeholder consultation process each respondent was contacted and individually provided a high-level summary of the findings to which they contributed.

The survey used in the stakeholder engagement has been conducted in two sessions and included following sections:

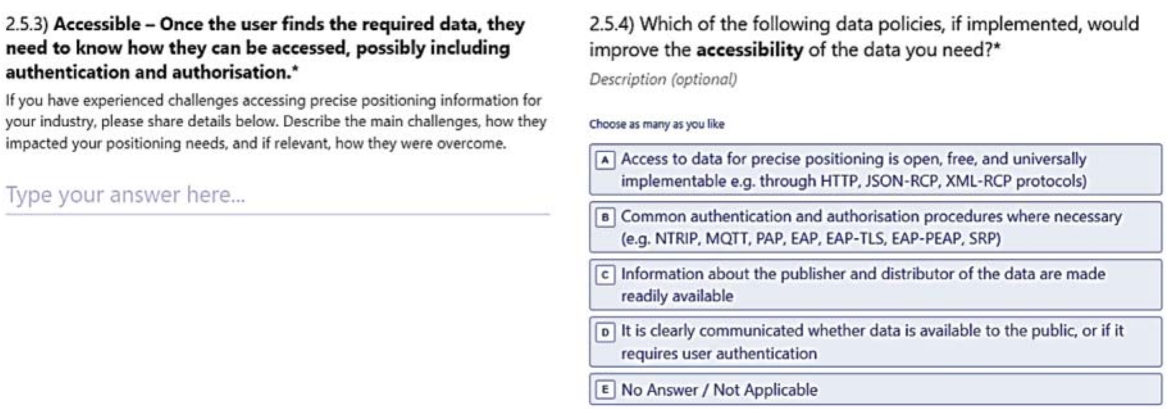
[37] https://www.auscors.ga.gov.au/

[38] https://www.ga.gov.au/privacy

[39] https://www.ga.gov.au/__data/assets/pdf_file/0018/104508/Privacy-Impact-Assessment-Industry-Engagement-on-the-Adoption-of-Precise-Positioning-Information-Endorsed.pdf

1. Definition of the GNSS user sector—requesting details about the participants and their organisation, and which of the GNSS sectors, as well as which role from the GNSS value chain identified during desk-based research they represent.
2. Insight to the use of Precise Positioning Information—asking about how they use precise positioning, including: where they access data, what technology and software they use to access the information, and which are the standards and protocols involved in this activity.
3. Validation of identified metadata elements, their values and units—asking for participants' feedback on relevance, importance and correctness of identified metadata for a chosen application or a range of these in their industry sector.
4. Elicitation of participants' view and perception of FAIR—asking for which of the FAIR principles defined by [1] do GNSS users find essential for information to be findable, accessible, interoperable and reusable.
5. Identification of current and emerging technology, standards and protocols for the use of GNSS data and services—asking participants to identify which technology, standards and protocols they currently use and, which are of their interest as potentially more efficient.

Questions were exposed as a combination of multiple choice, multiple answer and short answer responses. An example of two questions are illustrated in Figure 4. As illustrated in Figure 4, we first asked participants to report in free-text any issues they might have had with accessing data (question 2.5.3 in Figure 4), and then we requested them to identify from the list of FAIR principles on resources' accessiblity [1] what they consider as the essential conditions for accessibility of GNSS data.


2.5.3) **Accessible – Once the user finds the required data, they need to know how they can be accessed, possibly including authentication and authorisation.***

If you have experienced challenges accessing precise positioning information for your industry, please share details below. Describe the main challenges, how they impacted your positioning needs, and if relevant, how they were overcome.

Type your answer here...

2.5.4) Which of the following data policies, if implemented, would improve the **accessibility** of the data you need?*

Description (optional)

Choose as many as you like

A Access to data for precise positioning is open, free, and universally implementable e.g. through HTTP, JSON-RCP, XML-RCP protocols)

B Common authentication and authorisation procedures where necessary (e.g. NTRIP, MQTT, PAP, EAP, EAP-TLS, EAP-PEAP, SRP)

C Information about the publisher and distributor of the data are made readily available

D It is clearly communicated whether data is available to the public, or if it requires user authentication

E No Answer / Not Applicable

Figure 4. Example from the questionnaire used during the Stakeholder consultation with a question on 'A' from the FAIR principles.

Figure 4 shows an example of a question on FAIR with examples tailored to the GNSS users. For example, the answer B in the multiple-choice list in Figure 4 refers to principle A1.1 as described by [1]—with example including protocols typically used in GNSS data and service transmission.

The table in Figure 5 contains metadata and their potential values (magnitudes) of associated with a GNSS application as expected in a GNSS user sector. For example, in the Agriculture GNSS user sector, for an application 'Farm Machinery Guidance' 10–30cm accuracy is sufficient, whereas for an 'Automatic Steering' application, the accuracy needs to be within 2.5cm. Some values are provided in the spectrum of 'low-medium-high'—to clarify these to our stakeholders, we showed our respondents an explanation as in Figure 6. During stakeholder engagement, participants with expertise in particular industry sectors were asked to examine these values and identify any values for any application and metadata elements that did not match their requirements and suggest alternative values for each.

AGRICULTURE (1 = Controlled Traffic Farming (CTF) | 2 = Precision Livestock Tracking (PLT))						
	METADATA Requirements					
PAg Application	Accuracy	Availability	Integrity and Reliability	Robustness	Authentication	TTFF
Farm Machinery Guidance	10-30cm	High	High	Low	Low	a few min
Automatic Steering	2.5cm	High	High	Medium	Low	a few min
Spraying, Spreading, Harvesting, Bulk Crops (VRA*-Low)	10-30cm	High	High	Low	Low	a few min
Seeding, Planting (VRA*-High)	2.5-10cm	High	High	Low	Low	a few min
Harvest/Yield Monitoring	sub-metre	Medium	Medium	Low	Low	a few seconds
Biomass Monitoring	sub-metre	Medium	Medium	Low	Low	a few seconds
Soil Sampling	m-level/sub-metre	Medium	Low	Low	Low	a few min
Precision Viticulture	sub-metre	Medium	Medium	Low	Low	a few seconds
Precision Forestry	sub-metre	Medium	Low	Low	Low	a few seconds
Livestock tracking and Virtual Fencing	m-level	High	Medium	Low	Low	a few seconds

Figure 5. Part of the stakeholder engagement soliciting feedback on identified metadata elements, their values for a chosen GNSS sector and application(s)—example is from the Agriculture sector and Precision Livestock Tracking application (or sub-applications therein).

Further details on the results of the stakeholder engagement are reported in Section 5.2.

5. GNSS USER REQUIREMENTS ELICITATION: RESULTS

In this section we summarize the results of both, desk-based research and the stakeholder consultation. In Section 5.1 we review the GNSS user requirements as reported in the literature and in Section 5.2 we report views, observations and comments of GNSS users in Australia and New Zealand when confronted with the requirements gathered from the literature.

5.1 Desk-Based Research: Results

Desk-based research was part of an earlier work reported in detail in [7]. Here we refer to the summary informing out stakeholder engagement design. Table 1 contains the summary of metadata requirements per user sector as identified during the desk-based research.

METADATA ELEMENT	DESCRIPTION OF THE MEASURE	UNITS	HIGH	MEDIUM	LOW
Accuracy	the degree of conformance of an estimated or measured position to a reference value	metres	< 0.1 m	0.1 - 0.5 m	> 0.5 m
Authentication	a technique to verify the receiving signal or navigation message expressed as a probability of false alarm, and probability of detection	%	False alarm at < 0.2% and Detection at > 85%	False alarm at < 1% and Detection at > 75%	False alarm at < 10% and Detection at > 68%
Availability	the percentage of time that a specified level of accuracy, integrity, and continuity is available and useable within a specified area (in scenarios -- U = urban; C = canopy; I = indoors)	%	95% >	50 - 95%	< 50%
Continuity	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	% / hours	95% > / <10 hr	50 - 95% / 5 - 10 hr	< 50% / < 1 hr
Coverage	a geographic area serviced by the navigation satellite system (global or regional) or positioning service	qualitative	Global	Regional	Local
Fix Update Type	the type of update operation of the TTFF message (continuous, change of fix state, or on request)	state	Continuous	On Fix state change	On request
GNSS Sensitivity	the minimum signal strength at the antenna, as detectable by the receiver	dBm or dBW	< -148 dBm	-148 to -160 dBm	> -160 dBm
Integrity	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 to provide timely warning to the user about when the specified accuracy should not be trusted	metres / %	> 2.5 m / 10^{-6}	< 25 m / 10^{-4}	> 25 m / 10^{-4}
Latency	the correction latency (time taken for corrections signals to be received from a positioning provider), or receiver latency (difference between the time the receiver estimates the position and the presentation of the position solution to the end user)	seconds	< 1 s	1 - 5 s	> 5 s
Position Fix Rate	the rate at which the position terminal outputs PVT (position, velocity and time) data	Hz	> 20 Hz	1 - 20 Hz	< 1 Hz
Power Consumption	the amount of power a device uses to provide a position	mA	< 2 mA	2-10 mA	> 10 mA
Reliability	the ability of the system to detect blunders in the measurements and to estimate the effects of undetected blunders on the position solution	failures / hours	> 2.6 x 10^{-6}	2.6 x 10^{-6} - 8 x 10^{-3}	> 8 x 10^{-3}
Robustness	the ability of the GNSS system to withstand signal interference (e.g. jamming and spoofing)	qualitative	Appears unaffected by disruptors	Frequently impacted by disruptors	Significantly impacted by disruptors
Safety Integrity Level (SIL)	indicator derived from the different tolerable hazard rates, taking into consideration the specified environment. For Hazard Rates of <10^{-9} failures/hour, a 'SIL 4' process will be applicable.	level	4 (> 99.99% availability and <10^{-4} probability of failure)	2 - 3 (99 - 99.99% availability and >10^{-4} - <10^{-4} probability of failure)	1 (90-99% availability and <10^{-2} probability of failure)
Time to Alert (TTA)	a maximum time allowed when a system that was previously declared safe for use can no longer assure that it meets all its integrity requirements for a given operation	seconds	< 1 s	2 - 10 s	> 10 s
Time to First Fix (TTFF)	a receiver's performance covering the time between activation and output of a position within the required accuracy bounds	seconds	< 10 s	10 - 120 s	> 120 s
	PA1008 Industry Engagement on the Adoption of Precise Positioning Information				

Figure 6. Explanation of metadata elements, units and potential values included in metadata tables (as in Figure 5) used for interaction during the stakeholder engagement.

Table 1. Summary of GNSS end user metadata requirements as identified during the desk-based research per each GNSS sector (from [7]).

	Agriculture	Rail	Road	Maritime	Aviation	Consumer	Surveying & Spatial
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 Availability

As reported in Table 1, emerging GNSS users in all identified 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 consumer, demand information about service 'authentication', which is not so relevant to the agriculture sector where coverage and reliability take precedence. This is confirmed with the expected 'low' authentication value across various applications in the Agriculture GNSS sector as illustrated in Figure 5. Findings in Table 1 indicate that there is a need for customized metadata within each sector, which is not yet part of current metadata practice in GNSS community. Metadata requirements as presented in Table 1 further illustrate that current GNSS users are interested to understand the quality of the precise positioning data they are receiving. Not all of this information is currently present with data encoded in current standard formats, such as NMEA[40] and RINEX, or in the associated metadata file which is transmitted to the users. The information about GNSS data quality, such as accuracy, integrity, coverage can however be encoded in additional metadata (e.g. using standards such as the ISO 19100 series or extending other geodetic standards, such as those defined by the IGS). Metadata requirements gathered during the desk-based research have been incorporated into the questionnaire used during the stakeholder consultation, and the results of this process are presented in the following section.

5.2 Stakeholder Consultation: Results

The survey used during the stakeholder consultation was available for four months and as a result, we received 106 responses from participants all along the GNSS value chain, including component manufacturers, service providers, innovators, integrators and end users. Summary of key findings are provided in line of the survey design principles explained in Section 4.2.

5.2.1 Definition of the GNSS User Sector

Precise positioning data and services are accessed primarily by GNSS receiver manufacturers, custom GNSS solution integrators, GNSS services value added resellers, and end users with strong background in surveying and/or geodesy. This is unsurprising as the above are traditional GNSS users historically. The breakdown from each role in the GNSS Value Chain (see Figure 3) was as follows: End-Users—38.3%, Service Providers—16%, System Integrators—13.6%, Innovation users—12%, Component Manufacturers—7.4%, IAG/IGC Service providers—3.7%, and only 0.02% (2 out of 106 respondents) identified as GNSS upstream providers. This imbalanced breakdown across the GNSS value chain can be attributed to the sampling method used in the stakeholder consultation design (see explained in Section 4.2). A targeted direct engagement is planned as a follow-up to these first results to compensate for the missing representation of roles across GNSS value chain. However, results also confirm a changing GNSS end user community by our respondents indicating they are using GNSS in applications such as recreational aviation with general public operating a GNSS equipped drones, smart farming with GNSS devices being used for automated tractor navigation, or personnel tracking (e.g. offenders on parole, lone workers in remote areas or lost pensioners).

5.2.2 Insights to the Use of Precise Positioning Information

The majority of respondents confirmed the usage of precise positioning data and services through current, traditional GNSS protocols, such as NTRIP[41], commonly using RTCM[42] and NMEA[43] standard formats. Some

[40] https://www.nmea.org/content/STANDARDS/NMEA_2000

[41] https://kb.unavco.org/kb/article/what-is-ntrip-291.html

[42] https://www.rtcm.org/

[43] https://www.nmea.org/

participants in the resources, rail, road and government sectors have implemented MQTT[44] or JSON-RPC[45] based solutions, which confirm the community's trend towards adoption of novel approaches to precise positioning data and service transmission.

There was higher than expected response from users of satellite-delivered corrections rather than users of traditional, radio-based systems. This can be attributed to increasing familiarity of GNSS users with Satellite-Based Augmentation System (SBAS) recently tested in the Australia/New Zealand region delivering precise positioning data through satellites [37].

Respondents reported wide variety of software (desktop or mobile) in use, with many GNSS users still relying on offline processing rather than live use of GNSS data and services.

As reported during the consultation, international standards, such as those published by ISO and OGC, as well as regional and national standards (mostly adopted from ISO and OGC) are well-known within the user community. However, respondents felt that current data standards were not fit for purpose. The primary reasons given were scalability issues, lack of provided metadata including missing details on quality assurance and control related to provided data.

When asked about limitations to achieving the required performance for demanding positioning applications, responses featured mostly technical limitation with common issues including maintaining connectivity inside and outside of mobile coverage, coverage and quality of GNSS observations in environments with poor sky-view (such as forest canopy), or high subscription costs to GNSS data and services.

5.2.3 Validation of Identified Metadata Elements, Their Values and Units

We exposed our participants' metadata as identified for a chosen application per industry sector during the desk-based research. Participants were asked for feedback on relevance, importance and correctness of values and format used to express these metadata. There was overwhelming agreement with identified metadata, their format and values with few participants requiring more metadata (e.g. information related to expected power consumption when using GNSS or information about quality evaluation procedure used to determine values for quality metadata). Participants from few sectors identified additional requirements on metadata elements—an example of a detailed response on missing metadata from Spatial and Surveying sector is illustrated in Figure 7.

During our engagement we discovered that many participants subscribe to the GNSS services in real-time. This means that they need to be receiving identified metadata elements together with the data, which, as explained in [14] is currently not the case.

[44] https://mqtt.org/
[45] https://www.jsonrpc.org/

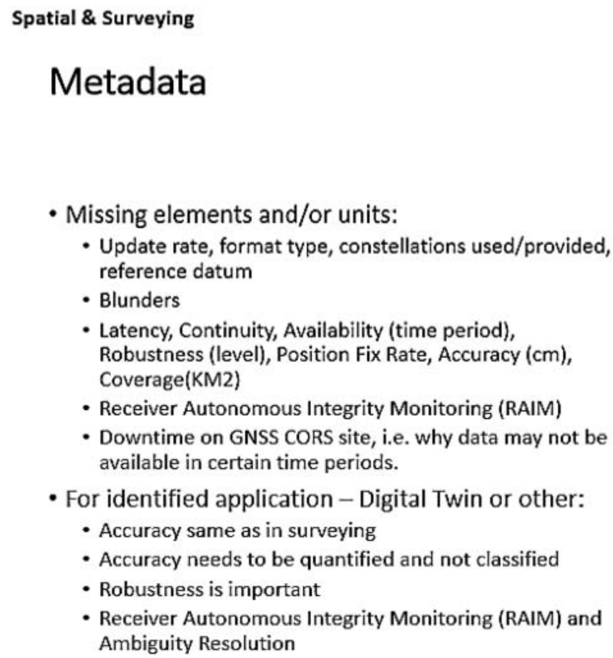


Figure 7. Snipped from the stakeholder engagement summary report—example illustrates missing metadata as identified by the GNSS users from the Spatial and Surveying sector.

5.2.4 Elicitation of Participants' View and Perception of FAIR

Respondents from different stages of the GNSS value chain had different understandings of what FAIR meant for their organisation, but results across sectors and roles within the GNSS value chain demonstrated similar agreement with the importance of individual FAIR principles as selected from the multiple-choice list in the questionnaire (see Figure 4). Example of GNSS users' response on 'findability' of precise positioning data and services is illustrated in Figure 8. In this example, it might be a little surprising to see that GNSS users were not interested in finding their resources on the web using search engines (with only 34.6% respondents indicating this was important). This is because rather than searching for data and services on the web using search engines, GNSS users typically visit a known data portal (e.g. GA Catalogue) or subscribe to a known service provider and receive data to their GNSS receivers directly.

Another interesting observation is that in average around 20% respondents did not provide an answer on their understanding of FAIR principles—this might indicate the need for continuous education on what these principles mean or simply a choice to ignore this part of the survey as irrelevant for them. However, that fact that the FAIR principles as defined by [1] are not as relevant in the GNSS end-user community, does not mean that GNSS data and services provision will not benefit from the being compliant with these. This was also confirmed by the widespread agreement among our respondents that being a beginner to precise positioning is difficult, and that all aspects of FAIR, if improved in provided data and metadata, are essential to ensure proper use of data and services, and to avoid their misuse. Several participants require

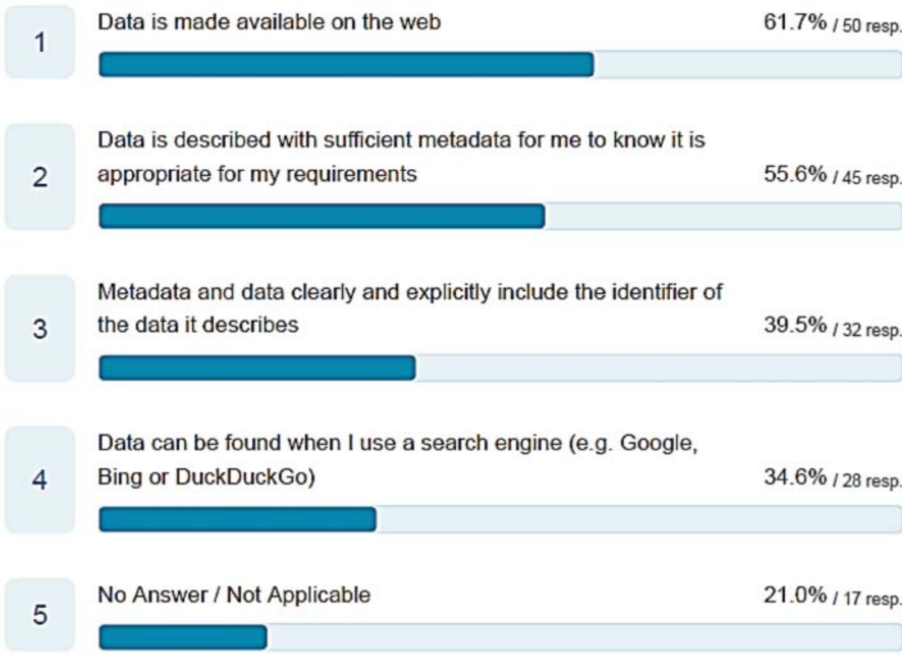


Figure 8. Requirements for findability of GNSS data and services as identified during stakeholder consultation.

access to more metadata quality information, including the most recent updates and downtime of CORS, and they reported (again, in widespread agreement) the importance of data quality and useful metadata as fundamental to ensure FAIRness (especially of 'R' in FAIR as defined by [1]) of GNSS data and services.

5.2.5 Identification of Current and Emerging Technology, Standards and Protocols for the Use of Gnss Data and Service

On the topic of upcoming trends or key technology, the most common responses indicated expectations from the improved regional precise positioning framework and technology (i.e., SBAS), increased adoption of Free and Open-Source Software, and modern transmission protocols (such as Message Queue Telemetry Transport[46]) which allow subscription to the user-defined portion of data instead of receiving anything available.

Figure 9 contains an example of compiled response of positioned assets, used communication technology, standards and protocols—example in Figure 8 illustrates responses by participants from the 'Spatial & Surveying' sector across GNSS value chain. As can be noted in Figure 9, some compartments (Upstream Providers and IAG Services in the figure) are empty—this is because we did not receive responses from these roles in the sector. Follow-up interviews are planned in the future to complete the requirements analysis in these roles.

[46] https://mqtt.org/

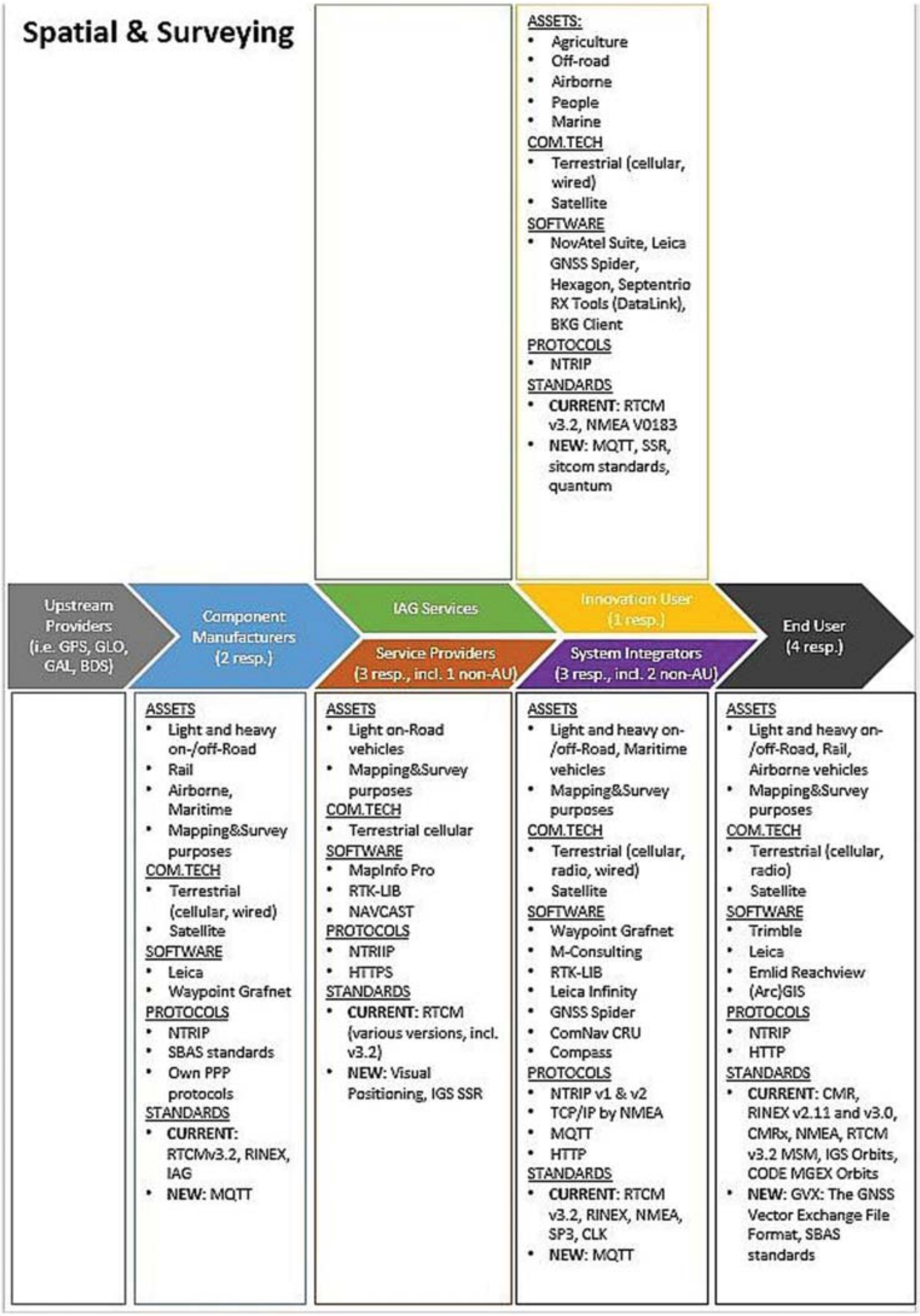


Figure 9. Example from stakeholder engagement summary in a GNSS user sector: example from the Spatial & Surveying GNSS user sector. Requirements were derived from identified positioned assets and communication technology, software, and standards and protocols in use.

6. ARE GNSS USERS GETTING DATA AND METADATA THEY EXPECT?

As discussed in Section 2.2, an SDI via its catalogue of resources, provides metadata of geospatial resources, including those related to GNSS positioning. However, the search for spatial resources is not always a smooth process and typically happens in at least three steps [6, 14]:

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.

A crucial part of the data and metadata search process explained above is step 2, when the user is deciding on data resources fitness for use in their application. This decision is expected to be made using metadata, more specifically, the values as specified in expected metadata elements. We illustrate a common problem with this step in most SDIs and over most resources [39, 40].

According to the findings presented in Section 4 and Section 5, current GNSS user expect to be provided with metadata describing this product in terms of elements such as those defined in Table 1. Unfortunately, as illustrated in Figure 10, this is not the case. None of the metadata elements are currently present in its metadata.

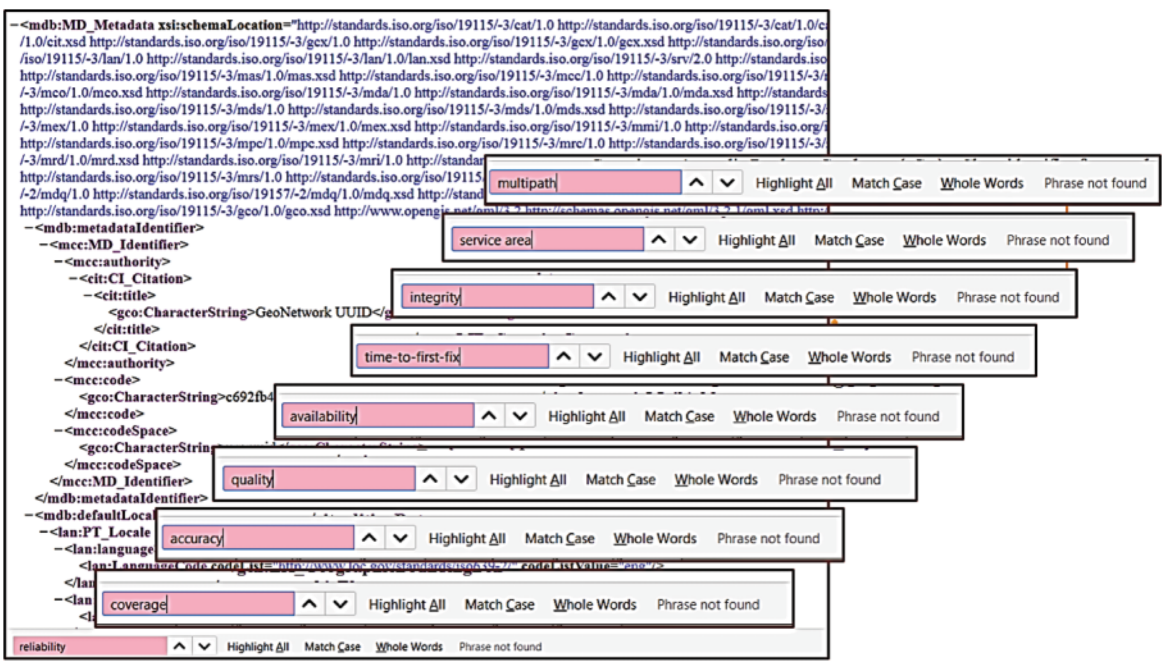


Figure 10. Missing identification of resources related to 'Geodesy—Continuously Operating' product.

The reason for this is simply that according to the current standard used for metadata provision in this example catalogue does not mandate provision of metadata containing information about quality as expected within a specific domain of use. The absence of required metadata limits the use of the example GNSS resource to specialists with detailed knowledge of the product and its lineage (i.e. how it was produced).

Data discovery and access is still a very challenging, and at times close to an impossible exercise even if comprehensive metadata are provided in a standard-complaint way. From our stakeholder engagement, the main reason for this appears to be that understanding of even most comprehensive standard metadata (e.g. compliant with ISO 19115-1:2014) can be problematic for users from non-geodesy domains (e.g. agriculture, maritime or defence). As confirmed during our stakeholder engagement, users find the language too technical with a lack of explanation regarding how the reported quality of positioning data will affect their use for a particular application.

Although from a different scientific domain, GNSS users' perception of FAIR is similar as reported by Alharbi et al. [38], in which participants confirm FAIR data and metadata contribute to efficient and confident data reuse. Data and metadata FAIRification needs to commence at the source [41]—for GNSS data, services and metadata this means, that most improvements need to happen to the way metadata is provided with the data and services. In the next section we outline our approach to this.

7. MANAGING USER EXPECTATIONS WITH FAIR GNSS DATA AND SERVICES

During our engagement with GNSS user sectors who operated across the GNSS value chain, we worked to understand user requirements and ensure that GNSS data and services that are compliant with the FAIR principles [1] could be delivered to each sector. We propose the following improvements to current data and metadata delivery: extending the metadata model currently in use, defining a specific metadata profile for GNSS community, and ensure metadata related to data instances are delivered with data.

7.1 Extending Metadata in a Standard Compliant Way

ISO 19115-1:2014, the standard currently used for providing metadata in the geospatial domain is intentionally generic [23, 31]. This might create a problem when implemented in specific disciplines. For instance, as our research presented in this paper confirms, current metadata standard does not deliver the necessary information to the GNSS community: there are missing metadata elements (see Section 5). To overcome this limitation, ISO/TC211 allowed the creation of metadata extensions, and these are the permitted types of extensions in the current metadata standard [23]:

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 GNSS user requirements as identified during requirement elicitation, when new data quality elements are to be defined, the extensions listed in items 3, 4 and 5 above would be applicable. The work on extended metadata applicable to GNSS products us currently underway as part of the implementation of our survey's results.

7.2 Ensuring User Sector Relevant Metadata Exposure in Data Interchange

Other standard compliant mechanism for ensuring access to community specific metadata is a 'community profile' [23]. 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 [22] mentioned in Section 2. 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 19115-1:2014 [23].

ISO/TC211 also specifies clear rules for creating metadata community profile in ISO 19115-1:2014 [23], where it specifies allowed extensions, and in ISO 19106:2004 [39], where it defines types of community profiles and rules for their development. Further best-practice community guidelines are available to ensure such profile is compliant with current best practices for data exchange [28]. For GNSS user 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 follow-up work to the stakeholder engagement presented in this paper. The profile will be developed as ISO 19115-1 compliant metadata profile including metadata about quality, as identified during the stakeholder engagement. This profile will then be adapted to extend the GA ISO 19115-1 compliant profile, and, in a prototype implementation, the current metadata template of GA Catalogue will be extended, and the result will be tested with GNSS users participating in the stakeholder engagement. The GNSS metadata profile will be proposed for a wider review within geodetic community and under auspices of the IAG/IUGG.

7.3 Ensuring GNSS Users Subscribing to Data and Services Receive Required Metadata with the Data

To increase the interoperability of geodetic data/information, Australian and New Zealand's Intergovernmental Commission on Surveying and Mapping (ICSM) promotes GeodesyML[47] as a standard to encode geodetic data and metadata [43]. GeodesyML is an application schema of OGC's Geography Mark-up Language[48] and serves for transfer of geodetic information currently encoded in XML, which is both machine and human-readable and allows custom requests (i.e. parts of the whole dataset—something, which is increasingly popular among the subscribers to GNSS data and services). Current version of GeodesyML allows encoding of the GNSS permanent station information, which is requested by GNSS users to process their own measurements. The snippet of the site encoding is illustrated in Figure 11.

```
<?xml version="1.0" encoding="UTF-8"?>
<geo:GeodesyML gml:id="GEO_1" xmlns:gml="http://www.opengis.net/gml/3.2"
    xmlns:geo="urn:xml-gov-au:icsm:egeodesy:0.5"
    xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
    xmlns:gmd="http://www.isotc211.org/2005/gmd" xmlns:gco="http://www.isotc211.org/2005/gco"
    xmlns:xlink="http://www.w3.org/1999/xlink"
    xsi:schemaLocation="urn:xml-gov-au:icsm:egeodesy:0.5 ../schemas/geodesyML.xsd">
    <!--
        @Name MOBS_SiteLog.xml
        @Author Laurence Davies
        @Date 2015-06-03
        @Description: Demonstration file using GeodesyML 0.3 to demonstrate encapsulation of a site, site-log,
        regulation 13 site certificate, and a national adjustment weekly solution time series.
    -->
    <geo:Site gml:id="SITE_1">
        <geo:type codeSpace="">CORS</geo:type>
        <geo:Monument xlink:href="#MONUMENT_1"/>
    </geo:Site>
    <geo:Monument gml:id="MONUMENT_1">
        <gml:description>Centre of base of 5/8&quot; spigot on GPS</gml:description>
        <gml:name codeSpace="urn:ga-gov-au:monument-siteName">Melbourne Observatory</gml:name>
        <gml:name codeSpace="urn:ga-gov-au:monument-fourCharacterID">MOBS</gml:name>
        <gml:name codeSpace="urn:ga-gov-au:monument-iersDOMESNumber">50182M001</gml:name>
        <gml:name codeSpace="urn:ga-gov-au:monument-cdpNumber">Not Available</gml:name>
        <geo:type codeSpace="urn:ga-gov-au:monument-type">CORS</geo:type>
        <geo:installedDate>2002-09-15Z</geo:installedDate>
        <geo:notes>antenna mounting plate fixed to 1.5m stainless steel pole. Pole is fixed to 0.6m diameter bluestone
        pillar The GPS antenna is located on top of a stainless steel pillar, which has been secured into the top of a
        bluestone pillar set in bedrock</geo:notes>
```

Figure 11. GNSS Site log information encoded with GeodesnyML v 0.5.

The current version of GeodesyML also allows encoding some quality related metadata elements with data—see an example in Figure 12 with accuracy of a surveyed local tie (an essential information about a GNSS site) highlighted in the red oval.

To serve the requirements of GNSS users as identified in our stakeholder engagement, extension to GeodesyML's information model will need to be made. Moreover, to address the limitations of the XML format (e.g. the scalability issues) alternative formats to XML (such as JSON-LD) need to be considered in GeodesyML's further developments.

[47] http://geodesyml.org/
[48] https://www.ogc.org/standards/gml

```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>
```


Figure 12. Quality metadata element encoded together with the site log information encoded in GeodesyML v0.5.

Extended metadata encoded in or with GNSS data products will help users who subscribe to data services directly without first browsing the metadata catalogue. This will be ensured by improved subscription service offering the best possible product (determined from comparison of expected quality requirement and metadata stored with the product) for an application identified by the subscriber.

This is currently underway as part of follow-up work to the stakeholder engagement presented in this paper. We expect that this work and continued discussions within the geodetic community at IAG/IUGG and within the standardisation communities at ISO/TC211 and OGC will be instrumental in defining the GNSS community standard, and thus providing FAIR data and metadata to the GNSS users.

8. CONCLUSION

In this paper we reported on GNSS users' views on what constitutes FAIR data and metadata in their respective sectors. We also reviewed support for FAIR in existing precise positioning and other related international standards, and investigated whether current standards have potential to address expectations of GNSS users in various sectors. Our results confirm that offering FAIR GNSS data and services is fundamental, but for a confident use of these, detailed and relevant metadata need to be offered to the GNSS community. We outlined the approach towards fulfilling these expectations with standard compliant GNSS community metadata profile and providing relevant metadata with data on-demand through machine-actionable information model for FAIR GNSS data and service.

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AUTHOR CONTRIBUTION

Ivánová, Ivana (ivana.ivanova@curtin.edu.au) initiated the effort, conceived and wrote the first draft of the paper. II, Keenan, Ryan (ryan.keenan@me.com), Marshall, Christopher (cmarshall@frontiersi.com.au) and Mancell, Lori (Lori.Mancell@ga.gov.au) collected and analysed the data, and contributed content to first draft. Rubinov, Eldar (erubinov@frontiersi.com.au), Ruddick, Ryan (Ryan.Ruddick@ga.gov.au), Brown, Nicholas (Nicholas.Brown@ga.gov.au) and Kernich, Graeme (gkernich@frontiersi.com.au) provided research ideas and critical feedback that helped shaping the manuscript. All authors contributed to reviewing and editing of the final version of the article.

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