Can co-location and community CORS add value to GNSS data?

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SUMMARY

What is the value of Global Navigation Satellite System (GNSS) data? It depends on the data quality. Continuously Operating Reference Stations (CORS) within Australia are categorized in a 4-Tier hierarchy. The highest quality Tier 1 and 2 stations are built with station-spacing between 200-1000km for geodetic and other scientific purposes. Tier 3 and 4 sites densify station-spacing between 50-200km to provide commercial real-time positioning services and datum connection to end-users. Higher density station data can augment the utility of GNSS in new industries (transport, telecommunications, consumer) and 'alternative' uses of geodetic data in GNSS-Reflectometry, atmospheric monitoring, interference monitoring, integrity monitoring, and multipath characterization. However, higher density CORS have been largely hidden from the scientific community with questions around quality, stability, and permanence. Tens of thousands of potential stations are currently operating as Real-time kinematic (RTK) bases or geotechnical monitoring sensors. Even more operate as 'low-cost' GNSS receivers in co-location, community networks, and Token Incentivized Physical Infrastructure Networks (TI-PIN). Together, these networks make up over 100,000 sites that are available or can be easily upgraded to provide trusted GNSS CORS data. This paper presents a data valuation method that can be used by network operators to assess site value based on GNSS data quality, security, density, cost, and performance for network RTK (NRTK) services. We assess the GeodesyML standard and Findable Accessible Interoperable and Reusable (FAIR) principles for data sharing in a GNSS CORS data marketplace. This approach to crowdsourced GNSS data aims to support the revival of geodesy, the renewal of the profession, and the Sustainable Development Goals (SDGs).

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1. INTRODUCTION

Data from Global Navigation Satellite System (GNSS) measurements at Continuously Operating Reference Stations (CORS) are used for commercial and scientific purposes. The clearest commercial use is delivering Real-Time Kinematic (RTK) services to users. RTK subscriptions range from $600-$2500 USD per year, however the cost of GNSS data remains unclear.

Scientific and government organizations are promoting open-data access following Findable Accessible Interoperable and Reusable (FAIR) principles to deliver better value for downstream services. GNSS metadata is becoming more accessible, however there are gaps in representing data quality in the existing standards (FrontierSI, 2020). The concepts for effectively delivering GNSS data were proposed during the rise of commercial network RTK services (Rizos & van Cranenbroeck, 2006). More recent studies have identified the need to further densify GNSS CORS (GSA, 2017) and have calculated ideal inter-station density for various applications and performance (Murrian et al., 2016; Yu et al., 2020).

Proposals for commercial business models, data and network management have been discussed following the growth of RTK networks (Hale & Collier, 2006; Higgins, 2008; Raza & Al-Kaisy, 2023; Rizos, 2007). These models generally establish relationships between ***objects*** (CORS infrastructure, measured raw data, and data services) maintained or produced by ***entities*** (government agencies, network operators, data centers, value-added resellers, data service providers, and brokers).

This paper discusses how GNSS data valuation based on a crowdsourced data approach (Quanxi et al., 2022; Wang et al., 2021) can encourage the adoption of geodetic metadata across a global ‘network of networks’ ecosystem. We asses the quality of (2) GNSS infrastructure, (3) GNSS networks, and study the (4) value of GNSS data based on data quality.

2. CORS INFRASTRUCTURE

Geodetic infrastructure comprises instruments and measurement techniques used to accurately determine the physical properties of the Earth. Using measurements from GNSS infrastructure is one of the most popular techniques used by modern geodesy to monitor changes in the physical Earth and generate data products for wider use.

The highest quality networks of GNSS CORS are established and maintained by the international scientific community through the International GNSS Service (IGS) and the

Global Geodetic Observing System (GGOS). The organisations contributing to this effort are national geodetic authorities, space agencies, research institutes, and universities. However, GNSS CORS contribute to a dual purpose, answering ***scientific*** questions (National Academies of Sciences & Medicine, 2020) and providing ***practical*** applications in construction, surveying, agriculture, telecommunications, and mapping (Morton et al., 2021).

The scientific purpose of GNSS CORS is met by establishing networks of geodetic-grade infrastructure. Ogaja (2022) presents a summary of guidelines for the installation and operation of CORS from different geodetic organisations such as the International GNSS Service (IGS), the US National Geodetic Survey (NGS), the Canadian Geodetic Survey (CGS), and Australia and New Zealand's Intergovernmental Committee on Surveying and Mapping (ICSM).

CORS installation and operation requirements for practical applications are more tolerant than for geodetic application. To differentiate these requirements, Rizos (2008) proposed a CORS hierarchy based on purpose, monumentation type and inter-station distance. This was later adopted by geodetic institutes like Geoscience Australia (Geoscience Australia, 2021). Table 1 presents some CORS criteria based on the 4-Tier hierarchy.

Table 1 CORS Hierarchy within Australia (Geoscience Australia, 2021)

Criteria	**Tier 1**	**Tier 2**	**Tier 3**	**Tier 4**
Owned by Geoscience Australia	●	●	○	×
Owned by local government, research, private	×	×	●	●
Used for International datum definition	●	×	×	×
Used for Regional datum definition	●	●	○	×
Used for Geodynamic research	●	●	○	×
Used for Real-time networks	●	●	●	●
Operational life and site tenure (years)	50	30	15	2
Designed with minimum commitment (years).	20	20	5	2
Nominal distance between stations (km)	> 500	200-500	20-200	<50
Final coordinates derived in alignment with Regulation 13 of the National Measurement Act	●	●	○	○
Data completeness (target)	99%	99%	95%	95%
Antenna has a published phase centre model.	●	●	●	●
The antenna is of survey grade.	×	×	×	●
The receiver is recognised by the IGS.	●	●	●	○
The receiver is of geodetic quality.	●	●	○	○
High-grade monument with stable foundation complying with international best practice, (e.g. reinforced concrete pillar)	●	●	×	×
Monument is permanently mounted on semi-rigid structure (e.g. steel shed or mast) that may be subject to localised deformation, short-term movement or vibration.	×	×	×	●

● Required
○ Optional
× Not required

In summary, the highest quality Tier 1 and 2 stations are built for scientific purposes with station-spacing between 200-1000km for. Tier 3 provides regional datum connection and Tier 4 provides commercial real-time positioning services and support for scientific applications by densifying station-spacing between 50-200km.

3. CORS NETWORKS

The quality of CORS networks is generally defined by their primary purpose. This determines design criteria such as ownership (commercial, government, research), data type (offline or real-time), access type (paid or free), coverage, monument type, inter-station distance, equipment quality, products, and redundancy.

The geodetic community has reason to promoting upgrading CORS from offline to real-time. This enables modern geoscience applications to monitor geohazards, provide Earthquake Early Warning (EEW) (Kawamoto et al., 2017) and GNSS Enhancement to Tsunami Early Warning Systems (GTEWS) (Martire et al., 2023).

For practical purposes, the clearest application of real-time CORS networks is delivering RTK services to users in construction, surveying, and agriculture. Most RTK networks are operated by state government departments like the US Department of Transportation, Germany's SAPOS or by GNSS equipment manufacturers like Trimble and Hexagon. CORS networks in this context are designed to support specific commercial needs, rather than consistent coverage, which limits the potential quality that can be achieved and leads to duplication of infrastructure.

Community networks formed by private individuals, small firms, or cooperatives (WSRN, 2003) are growing in popularity. These networks exist in the same sectors that commercial services are meant to deliver services to (construction, surveying, agriculture). The GSA's 2017 Market Report studied the GNSS market and noted that current RTK network density did not fully meet user needs (GSA, 2017). Inefficiencies in density and cost can explain this duplication of services.

Density can be efficiently built by sharing CORS infrastructure across networks. An example of data sharing ***across applications*** is UNAVCO's PBO network monitoring the San Andreas Fault system also contributing raw data to the IGS network (Murray et al., 2019). Examples of data sharing from ***high-to-low Tier*** networks are regional refence frames, such as the Asia-Pacific Reference Frame. Such projects promote the open sharing of CORS data from government and private networks in the region to create and maintain a densely realised and accurate geospatial reference frame (Geoscience Australia, 2022).

More recent models demonstrate data sharing from ***low-to-high Tier*** networks. Geoscience Australia's National Positioning Infrastructure Capability (NPIC) is unifying Australia CORS networks to ensure that consistent, fit-for-purpose data and services are available to users across government, industry, and academia. To achieve this, data streams from government and private sector networks are being aggregated through data licencing agreements with their quality monitored through routine network analysis (Hu & Dawson, 2020). Similarly, the Geospatial Information Authority of Japan (GSI) demonstrated the use of Softbank's private network for crustal deformation monitoring with quality control through the "Performance Standards and Registration Guidelines for GNSS Sites in the Private Sector" (GSI, 2019). Both systems are addressing the need to densify national networks using private sector CORS while guaranteeing data quality and integrity.

3.1. Building network density

We noted that CORS networks are designed for a specific purpose that defines inter-station distance and network density. Station distance ranges from thousands of kilometers for networks monitoring regional geodynamic effects and global satellite tracking down to tens of kilometers for networks monitoring local geotechnical effects and civil infrastructure projects.

Japan's GEONET is the highest density national network, with mean inter-station distances of 20km. It has revealed various crustal deformation phenomena however, it still requires additional densification to model the physical processes of frequent M6-M7 seismic events with 20-40km fault lengths (Ohta & Ohzono, 2022). Figure 1 shows the relationship between GEONET station distance and positioning error with standard deviations (SD) around 7mm horizontal, 15mm vertical at current density.

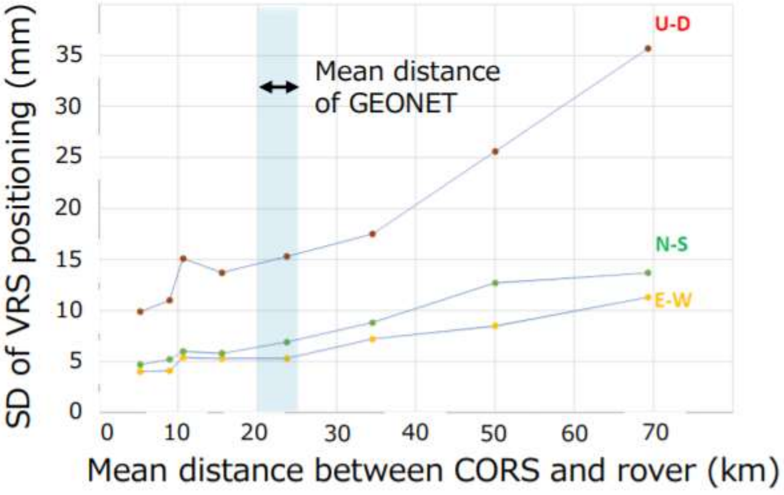

Figure 1 Relationship between network density and RTK accuracy (Tsuji, 2018)

For most networks, current performance is insufficient to consistently reach the vertical tolerances required for construction applications (Heikkilä et al., 2016; McMahon & Paudyal, 2022). These use cases highlight the need for dense networks with 5 RTK stations/1000 km2 or 10-km interstation spacing. The problem is not only in densification, but also in establishing the incentives for deploying CORS in underserved regions such as the South Pacific for disaster risk reduction activities (Melbourne et al., 2021).

The business case for rolling out 10km dense RTK networks has not proven cost effective for national agencies or service providers targeting traditional sectors. But it is being implemented by telecommunication companies like Softbank to serve emerging use cases in Intelligent Transport Systems (ITS) and consumer applications.

GSI used Softbank's dense RTK network and demonstrated that the additional CORS from a private telecommunications company can be used to improve the spatial resolution of real-time crustal deformation monitoring with reasonable precision (Ohta & Ohzono, 2022). One key factor in the use of Softbank's network is that it uses identical geodetic grade GNSS equipment with consistent installation guidelines at cell phone base stations.

Japan's and Australia's CORS registration and monitoring procedures combine private-sector GNSS into a consistent dataset with national coordinates and guidelines for precision. This promotes a level of trust and is a step towards a shared and quantifiable quality control (QC) process. A real-time QC service can benefit private network operators by monitoring site environment, checking data completeness and quality, assessing long-term site performance, addressing local deformation effects, detecting failures, outliers, degradation, and changes. In return, the raw data can be used across scientific disciplines and industries.

This approach to using opportunistic sensors and finding alternative purposes for GNSS data, extracts unrealised value from data, generates an additional source of revenue for data providers, and maximises the value of the data. There are two elements in this interaction, the mechanism to incentivise CORS network densification and the quality estimation of the data. The next sections discuss how we can combine the data and ensure its quality.

3.2. Network of networks model

Discovering, accessing, and re-using data is difficult because it often only exists within individual organizations that may not provide data and outreach services, with domain-specific formats, restricted data licensing, increasing data volumes, and other local regulations. Making data access more efficient, and making better use of existing data are some of the motivations behind the unification of networks and systems across multiple Earth science domains.

New Zealand's GeoNet (GNS Science, 2019) and the MPG-S-NET project (Aichinger-Rosenberger et al., 2023) are examples of established multi-domain sensor networks. They use data models describing the entities and relationships of co-location sites with multiple instruments (GNSS, seismic, InSAR, meteorological). In these frameworks, GNSS receivers are one of the many in-situ sensors sharing data in an Earth monitoring network.

Metadata standards are necessary to efficiently share data across networks at a machine-to-machine level. The Geodesy Markup Language (GeodesyML) is the proposed geodetic metadata standard and is based on the broad ontologies in the SensorML model, that allow semantic search of observations, sensors, networks, and their relationships. GeodesyML currently handles metadata relating to equipment, site logs, measurement, adjustment, quality, monuments, reference frames and data lineage. Figure 2 shows an example of the GeodesyML ‘monumentinfo’ class.

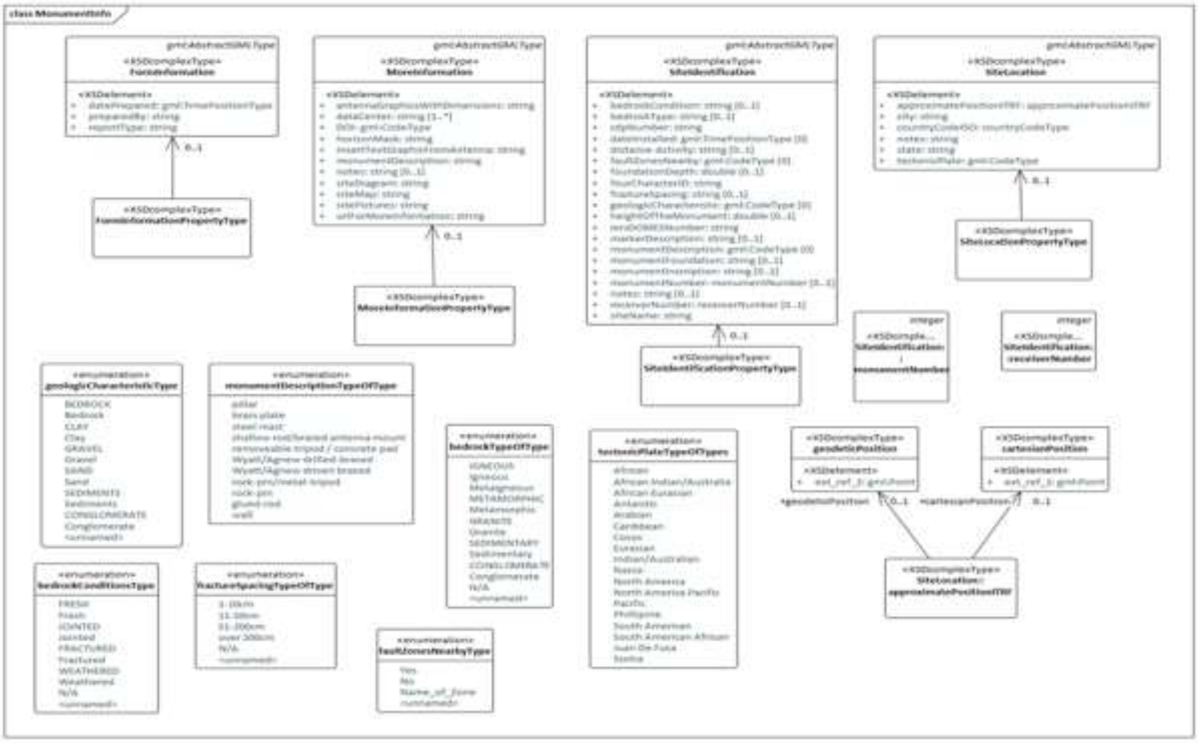

Figure 2 The ’monumentinfo’ package of GeodesyML v0.5 (FrontierSI, 2020)

GNSS data following the GeodesyML/SensorML models can be easily indexed and searched in scientific portals. This opens the opportunity for GNSS data from non-scientific networks to be shared with scientific users.

3.3. Adding community networks

Low-cost, small-footprint, and low-power electronic sensors combined with ubiquitous Internet connectivity have allowed the proliferation of citizen science, crowdsourced or community sensor networks. In these networks, community members williwngly host equipment in exchange for some incentive, while network operators aggregate and validate data to generate products or provide services to end-users. Community networks are an efficient method to incentivise data quality, network densification and coverage in underserved areas.

The scale of some community sensor networks are presented in Table 2. The most well-known networks have deployed Automatic Dependent Surveillance–Broadcast (ADSB) receivers to generate ***real-time flight tracking*** data products and personal weather stations to generate proprietary ***weather forecasting*** models. New applications in ***communications***, ***environmental monitoring*** and ***GNSS*** are being deployed as Token Incentivized Physical Infrastructure

Networks (TI-PIN). This approach more accurately measures the value and reward of each community hosted sensor.

Geodnet and onocoy are two projects using data from foundational GNSS CORS and densifying underserved areas using ’low-cost’ GNSS sensors. GNSS data is processed using traditional network baseline techniques and GNSS data quality is validated using real-time GNSS QC tools focused on signal quality, position stability, data integrity and security. Geodnet and onocoy have demonstrated how community networks can rapidly roll out dense GNSS CORS coverage. Figure 3 shows the global coverage of the ADSB Exchange (in purple) and Geodnet (in green) networks as of January 2023.

Table 2 Sensors in Crowdsourced/Community infrastructure networks

Network	**Type**	**Sensors**
ADSB Exchange	ADSB	9,000
Flightaware	ADSB (real-time flight tracking)	30,000
Flightradar24	ADSB (real-time flight tracking)	30,000
OpenSky	ADSB (real-time flight tracking)	5,000
ADSBHub	ADSB (real-time flight tracking)	2,400
RadarBox	ADSB (real-time flight tracking)	26,000
Weather Underground	Weather forecasting	250,000
Helium	Communications	980,000
PlanetWatch	Environmental monitoring	73,000
Geodnet	GNSS	1,800
Onocoy	GNSS	1,500

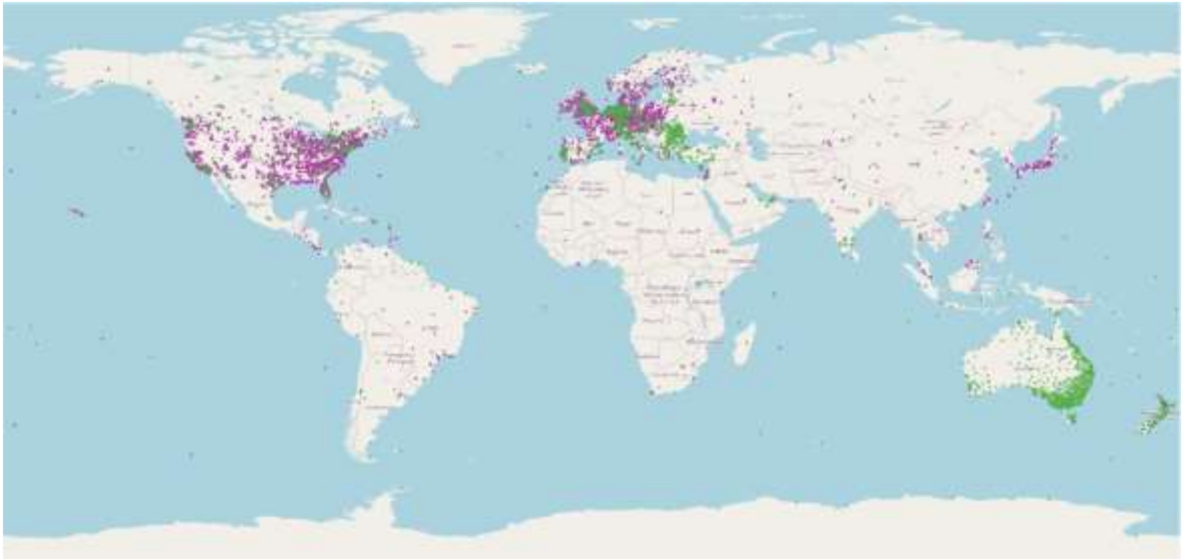

Figure 3 Coverage from ADSB Exchange (purple) and Geodnet (green) /Community infrastructure networks

Low-cost GNSS sensors have demonstrated reasonable precision when used as CORS (Sieradzki et al., 2022). Repurposing CORS data from dense RTK network can be used for scientific purposes but requires real-time QC (Ohta & Ohzono, 2022). By defining a system to monitor data quality for community CORS, it is possible to share and reuse their data for different purposes. This can potentially make use of the 100,000 sites hosting community GNSS devices or collocated with other crowdsourced Earth monitoring sensors.

4. GNSS CORS VALUE

The previous section presented three arguments:

1. we can use existing GNSS data models for data sharing.
2. we can deploy dense CORS network infrastructure using different incentives, and
3. ‘low-cost’ GNSS chipsets are of sufficient quality for CORS,

These conditions allow the operationalization of a network of networks for GNSS CORS data. However, to implement a data market ecosystem that shares fee-licensed data, a framework must be determined to reduce confusion about data value and to increase the willingness of market participants to share their data. For this purpose, we propose a quantitative data valuation method to assess CORS based on GNSS data quality, security, density, cost, and performance for network RTK services.

Data value in a market can be framed as the utility of ‘uncertainty reduction’ to solve decision-making problems (Wang et al., 2021). The value of GNSS CORS data can be determined by the uncertainty reduction it provides to a data product or service. In the case of RTK services, we can assume GNSS CORS data of specified quality that reduces Positional Uncertainty (PU) (Bernstein & Janssen, 2021) when added to a network solution has some value expressed as:

GNSS CORS data value = Data quality x Network quality improvement

The change in PU obtained by adding CORS data to a least-squares network adjustment can be presented as its value. This assumes that the data and site are of sufficient quality and can be trusted.

4.1. GNSS data quality

A model for real-time QC is used to validate or ’trust’ station quality (Figure 4). The system determines a ’station quality’ estimate expressed by the combination of quality parameters for position, data, signal, and monument. The aim of the model is to detect types of error and data quality dimensions estimated from station metadata, measurement data (carrier wave, pseudorange, SNR) or processed data (position estimates, clock error, latency).

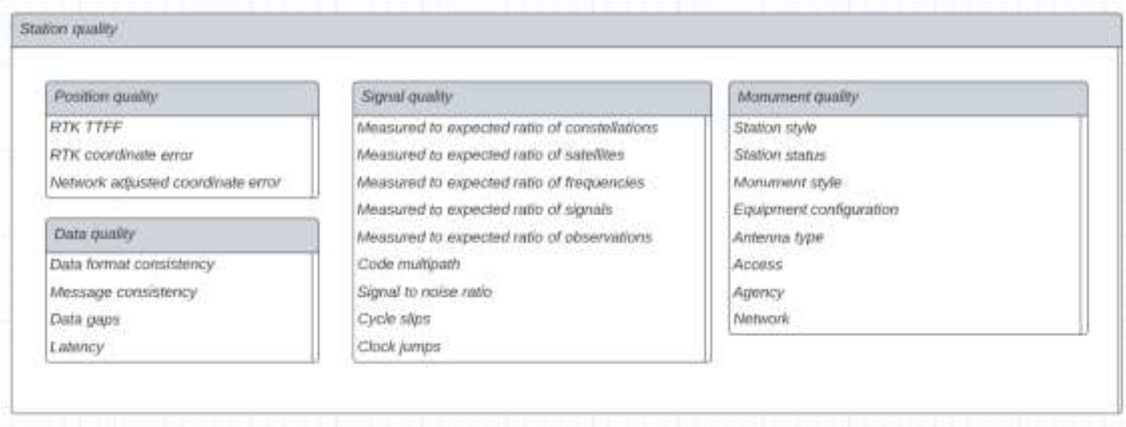

Figure 4 Real-time QC data used for trust model

Position quality is based on the coordinate error computed in real-time and compared to a fully constrained least square adjusted network solution. ***Signal quality*** is a factor that combines availability, visibility, multipath, SNR, cycle slips, ambiguities, receiver clock corrections and measurement precision. ***Data quality*** is a factor based on format and message consistency, data gaps and communication channel latency. ***Monument quality*** attributes are tagged based on station metadata.

Figure 5 shows the data processing model to obtain the station quality estimate. Real-time data processing includes automatic error detection tools and monitoring components. Position estimates using network processing and real-time processing from higher Tier stations can be cross-validated by different service providers. Raw data and summary statistics can be logged by service providers, analysis centers or other entities. This allows entities to validate quality and check whether observations have been tampered with. Batch processing to determine position displacements and signal quality outliers can use machine learning and statistical methods (Dye et al., 2022; Kiani Shahvandi & Soja, 2022). Real-time alerts can be triggered based on pre-defined criteria.

GNSS station quality can be determined by any entity that can process GNSS data (network operators, processing centers, data service providers). Procesing can include addtitional analysis based on the sites' physical properties, spatio-temporal data and statistical tests. The result should provide a traceable component where the QC result passes or rejects observations or stations compared to data from Tiered CORS. Multiple third-party processing centers can provide redundancy in quality estimates fulfilling the role of a ***validator*** entity in the model.

CORS data value can be expressed in terms of the PU and data quality. Optimization of PU can be done using ontology-based methods, such as combining only heterogeneous data sources or CORS selection using spatiotemporal parameters which require accurate metadata. Data quality can be improved by detecting outliers, bias, low quality sensor effects, and data problems during QC. Tagging large GNSS datasets with QC criteria allows more efficient reuse of data and is essential for generating ML algorithms used in real-time detection of position displacement and signal quality outliers.

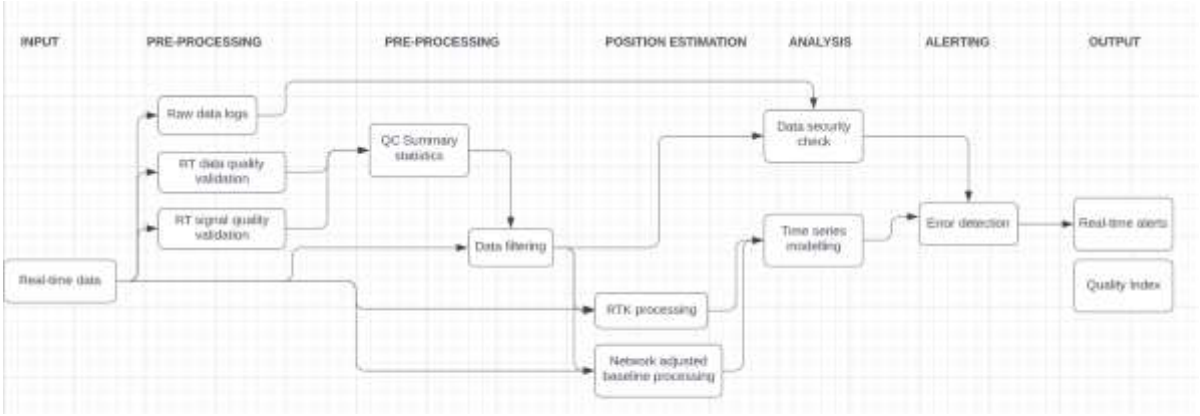

Figure 5 Real-time QC processing model

The outputs of a 'validator' can provide recommendations to station operators on ways to improve individual CORS data quality. By adding metadata classes representing data security, network density, service cost, real-time data attributes, and performance based on end-user profiles or applications (transport, telecommunications, consumer, GNSS-Reflectometry, atmospheric monitoring), it is possible to build a more comprehensive estimate on the value of GNSS data.

So far, this model has captured the data quality components of a CORS. To capture the value of a site, it is necesary to represent other spatial attributes that contribute to data quality of CORS networks.

4.2. GNSS site and network quality

CORS site suitability has been studied in an automated decision making approach using Multi-Criteria Decision Analysis (MCDA) and Weighted Overlay Analysis (Kakoullis et al., 2022; Kumar, 2022). These geostatistical models use raster data representing terrain, vegetation, and land use, combined with site selection criteria and constraints to output 'site suitability maps' as binary values or scalar dimensions.

Decision making systems are used by tower management companies to detemine lease rates for 5G tower or rooftop sites, and by satellite services companies when selecting a new ground station site. This type of analysis is merited in these scenarios because the value and complexity of selected 5G or satellite antenna sites is large. The same approach has not been widely applied to CORS sites, in part, because of their smaller value. However, management of dense community networks can develop decision making systems to deploy infrastructure in locations where it increases value to existing and future networks.

The combination of planning tools like site suitability maps and geometric network design with real-time station quality can provide a solution. This modelling includes the ***Cost*** reduction of an end-user deploying CORS infrastructure and the improvement in ***Network quality*** in terms of precision and reliability of adding the CORS to a least-squares adjustment.

5. CONCLUSIONS

This paper presented a data valuation method to assess CORS based on GNSS data quality and positional uncertainty. The value of GNSS station data should take into consideration the CORS infrastructure Tier model, network attributes, the GeodesyML standard data model, and real-time station quality.

The growth of crowdsourced and community sensor networks provides an opportunity to efficiently deploy GNSS infrastructure and incentivize data quality. By encouraging community CORS aggregators to adopt geodetic data models and standards it is possible to define and increase the value of GNSS data for the scientific and commercial appliactions. Metadata models can be extended to include attribtutes for real-time products, data value, pricing, quality, validation, crowdsourced data from CORS or mobile sensors.

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BIOGRAPHICAL NOTES

Luis Elneser holds an MSc Geospatial Science from RMIT University. His research work focuses on high precision GNSS and Big Data analytics. He is currently Senior Positioning Engineer at FrontierSI and Director of Lurra Systems.

Xiaohua Wen is the founder and CEO of Tersus GNSS, providing real-time, cost-efficient, centimeter-level GNSS positioning capability as well as flexible interfaces for applications, including surveying, mapping, precise navigation, precision agriculture, UAVs (unmanned aerial vehicles), and deformation monitoring.

Ryan Ruddick is the Director of GNSS Infrastructure and Informatics at Geoscience Australia, where he is leading the establishment of a National Positioning Infrastructure Capability. He is an active member within the International GNSS Service sitting on the Governing Board and Infrastructure Committee.

Mike Horton graduated from UC Berkeley with a Master's degree in Electrical Engineering and Computer Science. Upon graduation, Mike founded Crossbow Technology, a pioneer in MEMS-based Inertial Measurement Units. In 2009, he sold Crossbow Technology to MOOG Aerospace and began an active career in Angel Investments. In 2019, he co-founded ANELLO Photonics, the Creator of the Silicon Photonic Optical Gyroscope. In 2021, he started GEODNET, a blockchain-based decentralized CORS network. He holds over 15 patents in the field of Navigation and Inertial Measurement.

Dr. Yudan Yi received his PhD in satellite geodesy from The Ohio State University in 2007. As one of the top experts in GNSS positioning, he has served as Senior Director with Aceinna, leading the development of automotive grade GNSS/INS system. He was previously a Research Scientist responsible for the core development of the GNSS algorithms with Qianxun SI, and Senior Research Scientist as key member of the TopNET Live GNSS engine with Topcon Positioning Systems.

Garret Seepersad's research centres around GNSS measurement processing to generate OSR and SSR correction data, as well as utilization of the corrections to enable high-precision positioning. As a GNSS measurement processing specialist, Garrett Seepersad contributes to onocoy, a community-owned and decentralized platform, to ensure that reliable and trusted GNSS measurements are consistently submitted. Garrett Seepersad works full-time as a Senior Research Scientist at TuSimple, where his primary responsibility is leading the development of the GNSS measurement processing component within a multi-sensor navigation engine focused on enabling autonomous trucking navigation.

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