Received: 2 November 2021 | Revised: 26 April 2023 | Accepted: 4 June 2023

DOI: 10.33012/navi.605

ORIGINAL ARTICLE

GEODNET: Global Earth Observation Decentralized Network

Mike Horton[1] | **David Chen**[2] | **Yudan Yi**[3] | **Xiaohua Wen**[4] | **James Doebbler**[5]

[1] Mike Horton: ANELLO Photonics
[2] David Chen: GEODNET
[3] Yudan Yi: EasyRTK
[4] Xiaohua Wen: Tersus GNSS
[5] James Doebbler: VectorNav

Correspondence
Mike Horton
Email: mike@anellophotonics.com

Abstract
This paper explains some design and architecture decisions around the GEODNET network and the GeoDAO decentralized autonomous organization, which aims to create and operate a truly decentralized public GNSS reference sensing network. This paper covers the motivation of the network, the capabilities of current and future reference stations, the blockchain and GEOD token mechanics, and how the network powers applications ranging from climate change monitoring to real-time centimeter-accurate positioning.

Keywords
blockchain, cors networks, ionospheric modeling, precise point positioning (ppp), real time kinematics (rtk), space weather

1 | INTRODUCTION

The use of global navigation satellite system (GNSS) receivers to collect real-time solar and space weather observations is well established (Jakowski et al., 2009). Over the last 20 years, small- and medium-sized networks of GNSS receivers have collected multiple signal measurements, enabling important industrial and scientific applications. However, despite the demonstrated benefits of these networks, there are currently no openly accessible global, dense GNSS receiver networks (Gakstatter, 2014). Furthermore, GNSS receiver signals are easily jammed and spoofed, yet there is no public, cryptographically secure, spatially dense GNSS receiver network to help protect the ~$1T USD in location-aware applications. GEODNET, a public blockchain-based and token-incentivized network, has been designed to fully address these challenges.

2 | DEFINITIONS

The following terms are used in this paper:

- **Base (also base station or station):** A GNSS receiver permanently installed at a known fixed location. A virtual base is a base created by blending data from multiple bases.

- **Blockchain**: A publicly verifiable distributed record of transactions used in peer-to-peer networks. Blockchain operations are secured cryptographically, allowing independent verification of their data without centralized trust.
- **CORS:** A continuously operating reference station (CORS) is a GNSS station that collects GNSS measurement data, usually as part of a regional or global network of similar stations.
- **GEOD Token, Blockchain, and Wallet Address:** GEOD tokens are issued to a wallet address based on proof of location (POL) and proof of accuracy (POA) for GNSS miners and proof of stake (POS) for service validator nodes. Transaction records are stored in the blockchain.
- **GeoDAO:** The decentralized autonomous organization (DAO) that governs the GEODNET network.
- **GNSS:** Global navigation satellite system (GNSS) is the general term for satellite navigation systems that provide autonomous geospatial positioning with global coverage, e.g., global positioning system (GPS), GLONASS, Galileo, and BeiDou.
- **Ground Motion:** Movement in the surface of the Earth that is naturally caused by tectonic plate motion and other factors such as climate change, rising sea levels, and desertification.
- **IGS:** International GNSS Service (IGS) provides an open network of global GNSS stations, as well as other products and services in support of the terrestrial reference frame, Earth observation, and research; positioning, navigation, and timing; and other applications that benefit science and society.
- **NRCAN:** Natural Resources of Canada (NRCAN) is a Canadian government organization. NRCAN provides an online PPP tool used for coordinate determination with high-accuracy geodetic GNSS receivers.
- **NTRIP:** Networked transport of real-time correction message (RTCM) via internet protocol (IP) (NTRIP) is a widely used method for transmitting GNSS correction data over the internet that is commonly used in RTK applications.
- **PPP, PPP-AR:** Precise point positioning (PPP) (optionally with ambiguity resolution [PPP-AR]) is an alternative method for centimeter-accurate positioning that relies on data derived from a network of global stations instead of a nearby base (or virtual base).
- **Public Key Cryptography:** Methods and techniques for encryption and authentication that do not require pre-shared secrets between parties. Public key cryptography is also referred to as asymmetric cryptography.
- **Rover:** A GNSS receiver whose location is not fixed, e.g., a smartphone with a built-in GNSS receiver. The accuracy of the rover can be improved with data from a base or a network of bases and a suitable positioning engine algorithm.
- **RTK:** Real-time kinematic (RTK) positioning is a technique for locating a rover using nearby base data with centimeter accuracy in a global coordinate frame. The method uses differences in the satellite observations of a base and nearby rover to remove common errors, including the influence of space weather.
- **Smart Contract:** A self-executing contract with the terms of agreement between the buyer and seller written directly into lines of code.
- **Space Weather:** Changes in the ionosphere and troposphere that are naturally caused by solar activity and other factors such as air pollution. Space weather can be tracked via changes to GNSS signals.
- **TEQC:** Translation – Editing – and Quality Check (TEQC). TEQC is a family of software tools used for many GNSS preprocessing problems and quality analysis, available from the UNAVCO website (Estey et al., 1999).

3 | NEED FOR A DECENTRALIZED GLOBAL GNSS NETWORK

3.1 | Current Centralized Commercial Networks

Currently, the majority of GNSS reference stations fall into two categories: publicly available CORS installations and commercial real-time networks. CORS stations are generally run by governmental and research entities, providing individual or regional coverage, and do not form a unified globally consistent, spatially dense station network.

In developing regions, there is little incentive to deploy a costly network as a commercial entity or to invest in infrastructure as a governmental or non-profit organization. Consequently, there are many areas in the world with poor GNSS reference network coverage.

Volunteer and "crowd-sourced" network models have existed for many years, but they are not truly decentralized because there is a central organization controlling and sponsoring the core infrastructure to which the volunteers contribute (server costs, software development, etc.). Moreover, the lack of incentivization causes the growth and stability of such arrangements to be slow and uncertain. Additionally, these networks cannot be developed without significant existing infrastructure because the volunteer "nodes" rely on a centralized infrastructure.

3.2 | Goals of a Decentralized GNSS Reference Network

The following goals are proposed for a valuable alternative to current GNSS networks:

- Distributed network with no single point of trust or failure
- Robustness against (non-malicious) low-quality data
- Robustness against malicious manipulation (gaming or spoofing)
- Rapid network development without centralized investment (incentivization)

3.3 | GEODNET Architecture Overview

The architecture proposed for GEODNET aims to meet the above goals by utilizing modern proven distributed consensus and reward technologies in the form of blockchain and tokens. This section presents a high-level overview of the components and technologies used by GEODNET. Detailed descriptions of the roles of the nodes as well as the blockchain and network architecture are presented later in the paper.

GEODNET consists of multiple physical and virtual nodes interacting with each other and with the blockchain. Copies of the blockchain are stored on many nodes as a distributed ledger, and updates to the blockchain are performed in a distributed manner using consensus protocols with no reliance on a centralized or specific set of nodes. The physical GNSS reference stations ("miners") generate GNSS observation data in exchange for tokens. Unlike many other mining approaches that use an energy-intensive proof of work (POW), where the output of the processing work is used to secure transactions on the network, GEODNET utilizes a POS for validating transactions on the blockchain.

The miners are responsible for generating unique and authenticable geolocation data (GNSS measurements) whereas the validator nodes independently verify measurement quality, confirm authenticity, and detect intentional manipulation. Service nodes interface between the miner nodes and external users of the network in order to provide transport and/or derived products from the miner data. Note that a single node may perform both validator and service roles. A user may interact with GEODNET through service providers using established protocols (i.e., NTRIP) with no knowledge of internal GEODNET workings, allowing immediate adoption by existing applications.

Incentivization comes in the form of GEOD tokens, which are awarded to different node types in exchange for their respective contributions. The real-time value of the GEOD token is available at https://coinmarketcap.com and other public blockchain-related websites. Network participants have a vested interest in the success of the network, and the awarded GEOD tokens can be securely exchanged for other tokens, including popular USD-pegged stable tokens (e.g., USDC tokens) on decentralized exchanges. Once the network is fully operational as a public service, GEOD tokens will be exchangeable for GEODNET data services via blockchain transactions.

4 | BENEFITS OF BLOCKCHAIN FOR PHYSICAL NETWORKS

4.1 | Blockchain Project Characteristics

Blockchain protocols are the backbone of secure permissionless and decentralized networks. Blockchain projects encourage open standards and open-source development while economically rewarding participation in network development. Large communities have developed around blockchain and cryptocurrency projects, as evidenced by the emergence of Bitcoin and other tokens as a trillion-dollar asset class and the more than 68M verified accounts on Coinbase (a mainstream digital currency trading platform) as of its initial public offering (SEC, 2021). The ability of a successful blockchain project to rapidly deploy distributed infrastructure makes it an excellent candidate for a global, dense, and secure GNSS receiver network.

4.2 | Related Example: Helium

The Helium network (Haleem et al., 2018) is an existing example realization of the idea of rapidly deploying a distributed physical network using blockchain technologies. The Helium project was created to establish decentralized wireless infrastructure and is now the world's largest wide-area low-power wireless network implementing the long-range wide-area network (LoRaWAN) standard. Within two years of the public availability of Helium miners (hotspots), more than 200,000 hotspots were online, providing dense and inexpensive LoRaWAN coverage in many of the major cities of the world, and as of September 2022, there were over 950,000 hotspots registered to the network. GEODNET's goal is to provide a similar benefit for access to secured GNSS measurement observation streams. Helium's blockchain is based on a proof-of-coverage concept, whereas GEODNET is based on POL and POA algorithms, which are both explained in Section 3 of this paper.

4.3 | Blockchain vs. Tokenomics

A blockchain distributed ledger offers significant technical benefits that enable decentralized and secure operation of a large-scale CORS network. From a research perspective, these benefits are separable from the specific economic mechanics of a cryptocurrency token, i.e., "tokenomics."

However, it is also a practical necessity to consider the overall operational costs of a large-scale CORS network with the potential to exceed 100,000 stations. Assuming a data plan of $100 per month for reliable real-time data delivery, the recurring operational cost alone may easily exceed $100M USD per year. Thus, decentralized economics enabled by a blockchain utility token are needed to facilitate the transfer of value from network users to station operators in a decentralized manner. The GEOD utility token is issued to facilitate this goal. The tokenomics model is beyond the scope of this paper.

4.4 | Why Now?

Several trends favor the immediate development of GEODNET:

- Increasing mass-market applications for precise location service
- Availability of low-cost high-precision multi-band multi-constellation receivers
- Success of related blockchain projects

As a result of these trends, a community-initiated, decentralized network of high-accuracy GNSS receivers can quickly scale to "mine" space weather data.

5 | SPACE WEATHER GNSS MINERS

High-quality yet affordable space weather (GNSS) miners utilize affordable components with state-of-the-art GNSS receiver hardware. Miners output the same data as traditional CORS stations, but include additional security protections to reduce the probability of fake, relayed, or spoofed data entering the network. Miner designs must be certificated and secured specifically for use on GEODNET. GeoDAO-approved miner hardware is sold globally for installation on homes and buildings with clear sky visibility and stable internet connections. An example of such an installation is shown in Figure 1.

FIGURE 1 Example installation at a residence in Perth, AUS

The GEODNET network depends on the delivery of *honest* GNSS data, and several steps are taken in the protocol design to prevent fake or simulated GNSS data from entering the network, while simultaneously rewarding stable high-quality installations.

Reference designs that include additional ground and atmospheric sensing modalities are encouraged. Examples include meteorological sensors (i.e., temperature, pressure, and humidity sensors), acceleration sensors for strong motion measurement, visual or infrared sensors for celestial imaging, lidar units for spatial information capture, and software-defined radio units for tracking low-earth orbit signals of opportunity and radiofrequency (RF) spectrum measurement. Additional RF interface options, such as the inclusion of Helium LoRaWAN network compatibility and RF time-difference-of-arrival beaconing, are also being considered to provide redundant communication channels and non-GNSS back-up location services.

5.1 | Receiver Hardware

The hardware architecture of a miner is shown in Figure 2. The GNSS chipset is secured, and authenticated data are transferred as described in the next section. The miner may provide Ethernet, WiFi, and/or cellular communication for the transfer of data to the internet. The miner must meet the following minimum requirements:

- Calibrated triple-band, full-constellation GNSS antennae
- Minimum dual-frequency, optional triple-frequency GNSS signal tracking
- At least three of the four major constellations: GPS, GLONASS, Galileo, and BeiDou
- > 50 channels
- < 10 W of total power consumption
- GNSS chipset with a software development kit available for custom secure firmware
- Cryptographically secure key storage for certification

Miners communicate data to service provider nodes using user datagram protocol (UDP) for continuous real-time space weather data and to validators via transmission control protocol (TCP)/IP for configuration and oversight (UDP and TCP/IP are standard internet protocols). To ensure reliable real-time transmission, the number of service provider connections per miner is limited by GEODNET. Miners may be differentiated in the ecosystem based on channels received, additional functionality, and price.

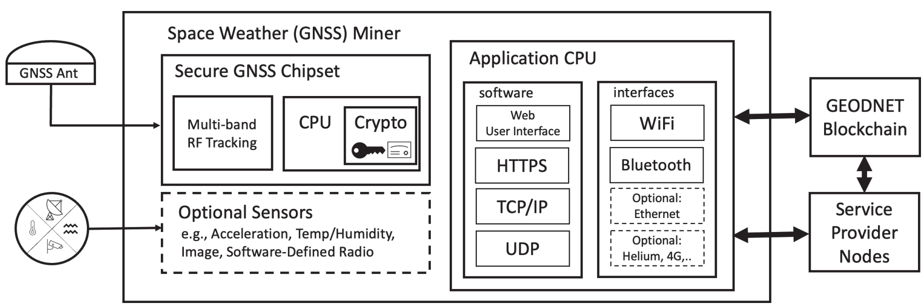

FIGURE 2 Space weather (GNSS) miner architecture

All certificated receiver miner hardware is required to ship with high-quality, phase-center calibrated triple-band antenna. Use of the POA protocol multipath and positional instability are penalized in the form of reduced token rewards.

5.2 | Secure Receiver: Certification and Encryption

Hardware miner designs and manufacturers are first approved by the GeoDAO. Upon approval, the manufacturer creates a root X.509 certified by the GeoDAO. Each miner device receives a unique private and public key pair that is signed with the manufacturer's root certificate. The miner's private key is stored securely within the device and used to authenticate all communication and data from the miner.

Certification and data encryption secure GEODNET against obvious fake miners, simulated observation data, or use of data relayed from other base station networks. Authenticating the hardware platform ensures that miner hardware meets minimum quality standards, and securing the entire receiver processing and communication path protects the GNSS observation data from manipulation and guarantees authenticity. Thus, a simulated GNSS RF signal remains the only (somewhat) practical way to generate authenticated fake data, which is addressed as part of the POL check.

A GNSS miner is uniquely associated with a wallet address. Miners who do not have an interest in GEOD tokens or are unable to receive tokens can transfer earned tokens to the wallet address of the GeoDAO or an alternative destination.

5.3 | Proof of Location (POL)

The POL process builds on the fact that the miner has a secured data communication channel from the GNSS receiver to the GEODNET network and is designed to achieve two goals:

1. Verify that the GNSS observation data supplied by the miner node match the stated location (low drift), are of high quality (low noise), and are consistent with nearby stations.
2. Ensure that the miner is not synthesizing observation data for the purpose of gaining rewards without contributing unique observation data to the network.

An initial GNSS miner POL validation occurs after a series of successful validation messages are received within a time threshold, $t_{validation}$. GNSS miners are invalidated and removed from GEODNET when they fail to deliver timely validation.

The POL time challenge prevents a dishonest space weather miner from utilizing simulated RF data, e.g., indoor installation connected to a GNSS RF simulator. For a miner to remain joined to GEODNET and eligible for token rewards, the miner must deliver periodic validation messages to the validator nodes within a threshold time $t_{validation}$, as shown in Figure 3.

The validation message is a pseudorandom code derived from a combination of datum in each of the four major constellations' navigation messages. The navigation messages are updated regularly but without advance public notice. An RF simulator attempting to generate dishonest GNSS measurements must first receive current navigation messages from actual satellite vehicles in multiple GNSS constellations and then replay them. In general, the reception and replay of navigation data will incur a delay greater than the threshold time, resulting in the detection of dishonest GNSS data.

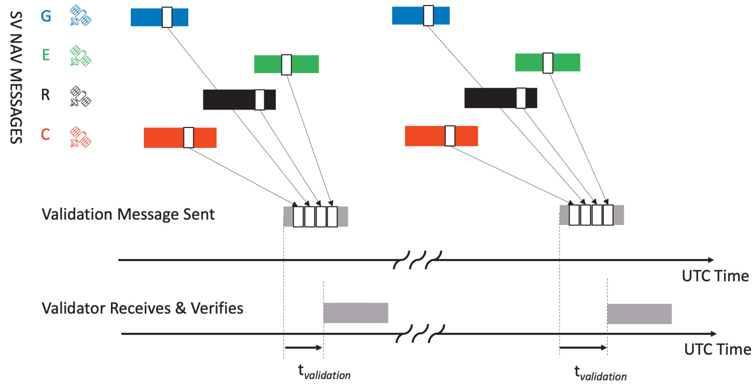

FIGURE 3 POL validation messages

Because inexpensive real-time GNSS simulators do not allow low-latency changing broadcast navigation message bits between nominal bit boundaries, a reasonable minimum expected latency is a single navigation message bit length. At typical GNSS message rates of 25–50 bits/s, a simulation latency of at least 20 ms is expected. Assuming that latency estimates for the node are accounted for first (estimated by roundtrip ping times and also used for POA), a $t_{validation}$ value of 20 ms is initially proposed and can be changed as an algorithm parameter by the GeoDAO. The validator nodes are selected to be proximal to the miners, which can be achieved by geographic location or by simply minimizing communication latency (i.e., "ping") times.

Note that the validated location check does not validate the physical location of the miner node, but rather the location of its antenna; thus, a data retransmission is considered valid for the original antenna location and does not negatively affect the quality of the network, as long as the latency is not excessive.

The validation message checks are combined with differential pseudorange and carrier phase analysis as part of the POL protocol. This approach limits observation errors if a sophisticated attack based on the security code and estimation replay is attempted (Psiaki et al., 2016). While this class of attack can be successfully performed with latencies < 1 ms using custom hardware/software, the costs will outweigh the mining rewards. Any attacker generating invalid data for any reason will be detected based on differential analysis with nearby miner nodes, performed by validation nodes, including spoofing attacks against the network.

5.4 | Proof of Accuracy (POA)

Validated GNSS miners are rewarded in proportion to the following formula:

$$Q = BWMNTSL$$

Q: POA metric
B: Base reward set by the token supply generation rate
W: 0–1.0 discount factor accounting for sharing rewards with neighbors within a 20-km square, with heavier weighting for earlier miners
M: Reward multiplier based on the number of independent bands observed divided by 6 (such that M = 1 for 6 tracked bands)
N: 0–1.0 linear scaling factor corresponding to the bounded range of 10–30 satellites with $C/N_0 > 40$ *dB-Hz*
T: 0–1.0 exponential scaling factor corresponding to the bounded range of 50%–100% uptime

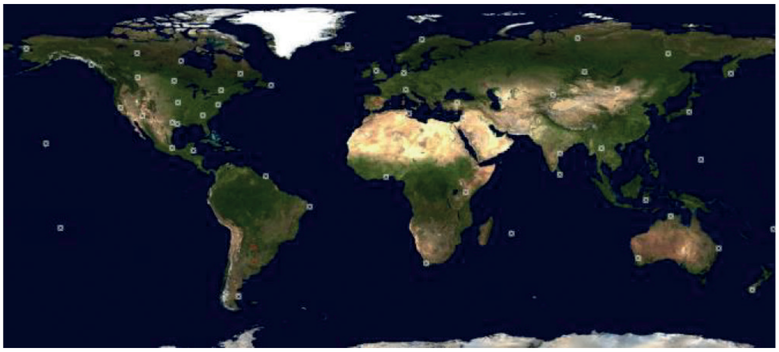

FIGURE 4 *Genesis miners*

S: 0–1.0 linear scaling factor corresponding to the bounded range of 2-10cm of estimated position shift

L: 0–1.0 linear scaling factor corresponding to a bounded range of 1-5cm of latency

These parameters are computed by a validator node, which is described later, with the results stored publicly on the GEODNET blockchain. The parameters may be updated from time to time as the network grows, and additional metrics may be added to the POA rubric. Miners within 10 m of each other are treated as a single miner and are rewarded as such. Incentive programs may increase the base rewards in a specific region to attract miners to low-density areas.

POA is actively used to reward GEODNET miners. Deposit transactions occur daily and can be viewed at the GEODNET Polygon network SmartContract address: 0xAC0F66379A6d7801D7726d5a943356A172549Adb.

Finally, GEODNET uses a PPP processing pipeline to validate and maintain each miner's coordinates with third-party services such as NRCAN as well as internally developed tools.

5.5 | Genesis Miners

To bootstrap the global development of the GEODNET network, a global network of more than 40 survey-grade GNSS stations has been installed, with a target of 100 stations prior to the end of 2022. Figure 4 shows the installation as of September 2021. The locations of these genesis miner stations are evenly spread over the surface of the Earth, providing a baseline network capability to produce the data products necessary for PPP and PPP-AR algorithms. PPP's global capability bootstraps the functionality of the network at a global level.

6 | NETWORK ARCHITECTURE

The GEODNET network consists of space weather miners, validator nodes, and service provider nodes, as shown in Figure 5. Service provider nodes face the end-user and utilize the blockchain to select which miner stream or combination of streams to utilize.

Validators are internet-connected instances that are staked with the GEOD token and participate in a POS consensus protocol to validate GEODNET blockchain transactions. In the initial phase, the number of validator nodes will be limited to 64, with a minimum of 20 to launch the main net. When a new space

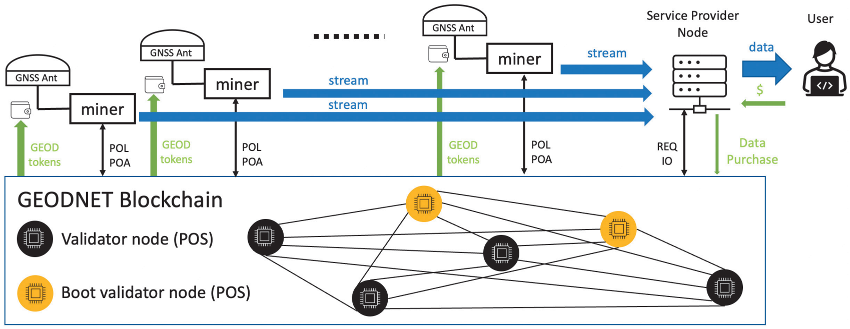

FIGURE 5 GEODNET architecture: Miners, validators, and service providers

weather miner first connects, it will communicate with a validator boot node. The validator boot node will assign the miner to a primary validator. If the assigned validator leaves the network, the process repeats. After the validator confirms the miner's security certificate, the miner begins signed data transmission and the initial validation process. After the initial validation is complete, the validator continues to receive POL validation messages and requests observation data from the miner at random intervals to compute the POA. The consensus protocol determines which node generates a new block at a particular time point. If a miner provides fake or inaccurate data, it will be detected, and the proof will be included in the block.

6.1 | Proof of Stake (POS)

POS is a consensus protocol that has been widely used in recent blockchain projects as an alternative to POW. POS is more energy efficient than POW and can provide improved security. Token owners put up tokens as collateral in exchange for the opportunity to participate in blockchain validation operations, for which additional tokens may be earned as rewards. In GEODNET, validator nodes stake tokens to participate in system consensus, which is required to add new blocks to the blockchain. Each validator node will have an opportunity to produce blocks based on the Boneh–Lynn–Shacham (BLS) signature verification algorithm, weighted by the staked token proportion.

GEODNET uses the BLS algorithm for fast and reliable Byzantine-fault-tolerant-like consensus (Sousa et al., 2018). Multiple parties use a threshold signature to reach an agreement on a blockchain proposal. The staking will also improve economic security by punishing any misbehaving validators through a loss of staked tokens. Anyone who owns GEODNET tokens can bond (or delegate) their GEOD tokens and become a validator, making the validator set open and permissionless.

6.2 | Service Provider Node Software Stack

The service provider runs a GeoDAO-provided stack written for the node, including several libraries and application programming interfaces (APIs) to interact with the blockchain and receive real-time data streams from miners. These libraries and APIs are extendable by the operator of a service provider node and include hooks to connect code written in other programming languages. As of September 2022, this stack is centralized and run by the GeoDAO Foundation. During 2023, the stack is planned to be decentralized via validator nodes, with significant portions open-sourced. The service provider nodes may output a variety of data products including the following:

- Reliable daily and hourly receiver independent exchange format (RINEX) files for select stations
- Network RTK corrections (RTCM) for real-time RTK via NTRIP
- Precise clock, orbit, and localized ionospheric corrections for PPP-AR via NTRIP

Testing of proposed network data products has already begun, and current performance results were presented by the GeoDAO Foundation at the ION GNSS+ 2022 conference (Horton et al., 2022). Presented data included the following:

- Comparison of GPS orbit accuracy with IGS data, where data were processed with Geoscience Australia GINAN software using exclusively GEODNET station data
- Local RTK results between various neighboring GEODNET stations processed with RTKlib 2.4.3
- Accuracy results obtained by NRCAN and TEQC analysis of station quality

While the GEODNET network has not yet entered full operational function, early results show that its performance is consistent with that of traditional centralized networks.

6.3 | Validator Node Software Stack

The validator will run an open-source GeoDAO-maintained stack that will fully decentralize the operation of the blockchain. The GEODNET blockchain provides benefits over existing POW and POS protocols alone.

Most POW blockchain systems only offer probabilistic finality. Probabilistic finality refers to the fact that, theoretically, some nodes with overwhelmingly high computation power can build an alternative branch and eventually replace the original branch. Additionally, POW consumes a high level of energy to perform a brute-force search for the required hash function input (Xiao et al., 2019).

POS is a consensus protocol that uses stakes as the criteria to vote on new block generation. Unlike POW, POS is a closed system, which means tokens are created without any external entropy. Thus, the POS system will likely suffer from centralization in the initial token distribution and reward system. Another drawback of the POS consensus protocol is that the POS system itself can be easily cloned, resulting in an unlimited token supply (Nguyen et al., 2019).

GEODNET takes an approach that merges the desired features of POW and POS. External resource consumption (external entropy) is critical to the system's security and decentralization. However, instead of using unbounded energy consumption as in Bitcoin or most other POW protocols, GEODNET uses geospatial information as the unique and unforgeable resource to include in the consensus process. The GEODNET consensus protocol uses both geospatial data input (POL, POA) and staked tokens (POS) to efficiently determine block generation.

In this way, GEODNET will be the first and only network to utilize limited Earth surface as a resource, which provides enormous value for the network. Additional services such as localization, high-definition mapping, and autonomous navigation are simply natural derivatives of this network.

7 | GEODAO AND CURRENT STATUS

The GeoDAO Foundation is the DAO that governs the GEODNET network.

7.1 | Organization

A DAO is best described as an effective and safe way to operate a project with a set of individuals around the globe. The GeoDAO Foundation is an organization dedicated to a decentralized blockchain-based network of environmental and space weather collection stations for utilization by the geospatial community and industry.

GeoDAO is organized around an ERC20 SmartContract (Ethereum, 2023), a piece of code that describes the creation and distribution of native GEOD tokens. The GEODNET SmartContract is registered on the Polygon public blockchain, pegging the GeoDAO and the token distribution logic into a well-established public chain that is currently used by companies such as Starbucks. As the GEODNET software stack matures, operations will be transitioned onto a separate blockchain to more fully decentralize the network.

Decisions regarding the GeoDAO can be executed by the blockchain SmartContracts, based on token holder "votes." The GEODNET Polygon SmartContract address is 0xAC0F66379A6d7801D7726d5a943356A172549Adb.

7.2 | Token Supply

The total token supply growth rate halves every two years. The dependence of the token supply over time *t* can be written as follows:

$$\boldsymbol{M(t) = M0 + \int I0 * exp[-ln2 * (t/T)]dt + \int (m(t) + \Delta(t))dt}$$

Here, *M0* is the initial token supply. The first integration term is the staking reward in terms of time *t*, and the second integration term is the mining reward. The number of base stations as a function of time is $\boldsymbol{m(t)}$, and $\boldsymbol{\Delta(t)}$ is the expected miner growth.

7.3 | Software Development

GeoDAO developers will deliver a baseline set of open infrastructure necessary to bootstrap the community. These deliverables include initial miner reference designs, validator and service provider reference code, and user-facing tools.

User-facing tools include the GEODNET website, a user-facing web console application, and a mobile GEOD wallet application with miner registration features. GeoDAO will contribute other tools as the need arises.

7.4 | Current Status

As of January 2023, i.e., less than one year since the launch of GEODNET, the network has grown to over 1700 deployed stations, and approximately 2500 stations have been delivered for installation. By the end of 2022, it is anticipated

FIGURE 6 GEODNET station map, January 2023

that there will be three certified GNSS manufacturers producing GEODNET mining hardware. Community interest in this network has been consistent and growing since the original presentation at the ION GNSS+ 2021 conference (Horton et al., 2021). Real-world testing of the GNSS correction network for agriculture machine control and civil survey is ongoing at several locations. A real-time deployment map of GEODNET CORS stations can be found at https://console.geodnet.com, and a snapshot image is shown in Figure 6. Recent test results from GEODNET were presented at the ION GNSS+ 2022 conference (Horton et al., 2022).

8 | APPLICATIONS

A public, secure, dense global reference station network will transform numerous scientific and commercial applications.

8.1 | Climate Monitoring

High-accuracy geodetic position data from dense and diverse global locations help scientists predict the effects of rising sea levels and changing precipitation patterns. Monitoring of shoreline changes, forest fire threats, desertification, and air quality have all utilized data from existing CORS networks (Yao et al., 2017; Goncalves et al., 2017; Knight et al., 2020).

8.2 | GNSS Spoofing and Jamming Detection

The European GNSS Agency estimates that the global installed base of GNSS receivers is 6.5B units; however, commercial GNSS receivers are easily spoofed and jammed. In the United States, 14 of 16 critical infrastructures depend on GPS (USTTI Report, 2012). Current consumer receivers provide little to no protection against well-documented attacks utilizing easily acquired low-cost hardware. A dense network of secure GNSS receivers can provide an important alert and warning capability against localized GNSS attacks (GSA, 2019).

8.3 | Geodeformation Hazard Warning

According to the EU Commission on Science, more than one in three people live in areas exposed to earthquakes. While GEODNET cannot prevent earthquakes or other natural geohazards such as sink-holes and landslides, accurate real-time data help in predicting disasters and identifying at-risk infrastructure (Lin et al., 2021; Pesaresi et al., 2019).

8.4 | Precise Positioning and Timing

Many of the existing networks of GNSS receivers are maintained to enable precise positioning and timing services on rover devices. Trimble and numerous other companies have supplied receivers used for survey, farming, and other precise geographic information system applications for more than 20 years. Both the rover receiver and GNSS data correction services for these applications have traditionally been quite expensive; however, a great deal of enthusiasm has recently emerged for lower-cost rovers for autonomous automobiles, drones, and even mobile phone applications. These applications are driving a growing need for low-cost highly available correction streams. A large decentralized network can meet this need with secured global data at a fraction of the cost of alternatives.

9 | NEXT STEPS AND ROADMAP

The GEODNET architecture was first introduced at the ION GNSS+ 2021 conference (Horton et al., 2021), and the initial response has been favorable. The GEODNET network is growing, with additional stations coming online every day. The goals for initial public operational service in February 2023, fully qualified data products by the end of 2023, and 100,000 online stations within three years are highlighted in Table 1.

GEODNET (https://geodnet.com) regularly posts new information regarding project status and provides links to additional resources.

TABLE 1
Completed and Anticipated GEODNET Milestones

Date	Milestones		
	Event	***Description***	***Miners***
2022.1	Testnet launch	Initial token distribution and test net running	100
2022.6	Mainnet	GeoDAO created, SmartContract issued, token rewards initiated, private tests of GEODNET data products started	500
2023.2	Service provider launch	GEODNET data products publicly available	2,500
2024.1	Mainnet 2	GEODNET fully operational	30,000
2025.1	Global RTK available	RTK on-demand globally, largest single network worldwide	100,000

10 | CONCLUSION

Decentralized infrastructure promises a scalable and rewarding way to enable high-precision measurements at Earth scale. GEODNET has proposed and is currently implementing an approach for building, running, and maintaining this decentralized infrastructure by utilizing ideas and technologies successfully demonstrated by innovative projects in the blockchain space over the past decade. Compared with the current sources for GNSS measurement data, GEODNET will allow participation in this valuable area by many more people (both as providers and users), with a relative benefit over the current state, particularly in developing and underserved areas. The GEODNET team has been excited to see the interest in and early growth of the project to date and looks forward to continuing to grow and improve the network with a global community.

REFERENCES

Estey, H. L., & Meertens, C. M. (1999). TEQC: The multi-purpose toolkit for GPS/GLONASS data. *GPS Solutions, 3*(1), 42–49. https://doi.org/10.1007/PL00012778

Ethereum Foundation. (2023). *ERC-20 Token Standard.* https://ethereum.org/en/developers/docs/standards/tokens/erc-20/

Gakstatter, E. (2014). *Finally, a list of public RTK base stations in the U.S*. GPS World. https://www.gpsworld.com/finally-a-list-of-public-rtk-base-stations-in-the-u-s/

Goncalves, R., & Wange, J. (2017). Three most widely used GNSS-based shoreline monitoring methods to support integrated coastal zone management policies. *Journal of Surveying Engineering, 143*(3), 05017003. https://doi.org/10.1061/(ASCE)SU.1943-5428.0000219

GSA. (2019). *GNSS market report* (issue 6). https://www.euspa.europa.eu/gnss-market-report-issue-6-october-2019

Haleem, A., Allen, A., Thompson, A., Nijdam, M., & Garg, R. (2018). *Helium: A decentralized wireless network*. Helium Systems, Inc. http://whitepaper.helium.com/

Horton, M., Wen, X., & Yi, Y. (2021). Blockchain for CORS networks. *Proc. of the 34th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS+ 2021),* St. Louis, MO. 290–310. https://doi.org/10.33012/2021.17882

Horton, M., Chen, D., & Yi, Y. (2022). GEODNET: Secure geo-spatial infrastructure & service for business and metaverse. *Proc. of the 35th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS+ 2022),* Denver, CO. https://www.ion.org/gnss/virtual-abstract-view.cfm?paperID=11439

Jakowski, N., Mayer, C., Borries, C., & Wilken, V. (2009). Space weather monitoring by ground and space based GNSS measurements. *Proc. of the 2009 International Technical Meeting of the Institute of Navigation*, Anaheim, CA. 729–735. https://www.ion.org/publications/abstract.cfm?articleID=8353

Knight, P., Plater, A., Bird, C., & Sinclair, A. (2020). A low-cost GNSS buoy platform for measuring coastal sea levels. *Ocean Engineering, 203,* 107198. https://doi.org/10.1016/j.oceaneng.2020.107198

Lin, J., Melgar, D., & Searcy, T. (2021). Early warning for great earthquakes from characterization of crustal deformation patterns with deep learning. *JGR Solid Earth*, *126*(10), e2021JB022703. https://doi.org/10.1029/2021JB022703

Nguyen, C., Hoang, D., Nguyen, D., Niyato, D., Nguyen, H., & Dutkiewice, E. (2019). Proof-of-stake consensus mechanisms for future blockchain networks: fundamentals, applications and opportunities. *IEEE Access*, *7*, 85727–85745. https://doi.org/10.1109/ACCESS.2019.2925010

Pesaresi, M., Ehrlich, D., Kemper, T., Siragusa, A., Florczyk, A., Freiere, S., & Corbane, C. (2019). *Atlas of the Human Planet*. JRC Science for Policy Report. European Comission. https://doi.org/10.2760/709471

Psiaki, M., & Humphreys, T. (2016). GNSS spoofing and detection. *Proceedings of the IEEE*, *104*(6), 1258–1270. https://doi.org/10.1109/JPROC.2016.2526658

Sousa, J., Bessani, A., & Vukolic, M. (2018). A Byzantine fault-tolerant ordering service for the hyperledger fabric blockchain platform. *Proc. of the 48th Annual IEEE International Conference on Dependable Systems and Networks (DSN 2018), Luxembourg,* Luxembourg. 51–58. https://doi.org/10.1109/DSN.2018.00018

United States Securities and Exchange Commission. (2021). *Coinbase Global form 10-Q*. https://www.sec.gov/ix?doc=/Archives/edgar/data/0001679788/000167978821000010/coin-20210331.htm

USTTI Report. (2012). *GPS use in U.S. critical infrastructure and emergency communications.* [Technical report]. https://www.gps.gov/multimedia/presentations/2012/10/USTTI/graham.pdf

Xiao, Y., Zhang, N., Lou, W., & Hou, T. (2019). A survey of distributed consensus protocol for blockchain networks. *IEEE Communications Surveys and Tutorials, 22*(2), 1432–1465. https://doi.org/10.48550/arXiv.1904.04098

Yao, Y., Shan, L., & Zhao, Q. (2017). Establishing a method of short-term rainfall forecasting based on GNSS-derived PWV and its application. *Nature Scientific Reports, 8*, 12465. https://doi.org/10.1038/s41598-017-1259N3-z

How to cite this article: Horton, M., Chen, D., Yi, Y., Wen, X., & Deobbler, J. (2023). GEODNET—Global Earth observation decentralized network. *NAVIGATION, 70(4)*. https://doi.org/10.33012/navi.605