Hidden Risk

How weaknesses in the global geodesy supply chain could have catastrophic impacts on critical infrastructure and national economies

Background report for decision-makers

Version 1.1

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About the UN-GGCE

The United Nations Global Geodetic Centre of Excellence (UN-GGCE) vision is a future where all countries have strong political support for geodesy which enables them to – together – implement the General Assembly Resolution 69/266[1] and accelerate the achievements of the Sustainable Development Goals to derive social, environmental and economic benefits.

At its tenth session in August 2020, the United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM), in making decision 10/104, welcomed and supported an offer by Germany to establish and host what has now become the United Nations Global Geodetic Centre of Excellence (UN-GGCE) at the UN Campus in Bonn, Germany. The UN-GGCE, established in March 2023, is envisioned to be a federated centre and welcomes offers of support from Member States, including financial contributions, in person secondments, and virtual secondment.

For more information about the UN-GGCE please visit: https://ggim.un.org/UNGGCE/

Comments

Your comments on this report are welcome.
Please contact: Nicholas Brown, UN-GGCE Head of Office, E-mail: nicholas.brown@un.org

[1] UN General Assembly Resolution 69/266, 2015, https://ggim.un.org/documents/a_res_69_266_e.pdf accessed 28 May 2024.

Content

1 Introduction

"The most profound technologies are those that disappear. They weave themselves into the fabric of everything in life until they are indistinguishable from it."

~ The Success Paradox | Mark Weiser (Chief Scientist of Xerox PARC [1991])

Modern society is dependent on satellites. In many countries, satellite information is essential for economic growth, the operation of critical infrastructure and is a cornerstone of national defence forces.[2,3,4,5,6]

In some cases, the dependence is so strong, countries have developed sovereign space systems.[6,7] For example, several countries (or a region in the case of the European Union (EU)) have their own Global Navigation Satellite System (GNSS) to provide Position, Navigation and Timing (PNT) services for civilian and defence applications including the Global Positioning System (GPS; USA), GLONASS (Russian Federation), Galileo (EU) and BeiDou (PRC). These countries recognize a loss of PNT services, either due to technological failures or malicious activity, would have catastrophic and cascading effects for their economy and critical infrastructure.[5] This reliance and need for control, is not limited to GNSS satellites which offer PNT services but extends to telecommunications satellites and Earth Observation (EO) satellites.

Operation of critical infrastructure

The U.S. Department of Homeland Security found that 15 of 18 critical infrastructure and key resources sectors relied on the GPS including telecommunications, emergency services and financial exchanges.[8]

Driving economic growth

Over the next decade, revenue from GNSS, EO and satellite telecommunications – which cover over 80% of the space industry market revenue[9] – is expected to grow at a mean annual growth rate of approximately 9%, reaching a total of almost €800 billion.

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[2] Stephen Bartlett et al., A Wide-Area Multi-Application PNT Resiliency Solution' (*GPS World*, 23 Nov. 2015), http://gpsworld.com/innovation-enhanced-loran/ accessed 28 May 2024.

[3] John Garamendi et al., 2015, Letter to Congress of the United States, https://rntfnd.org/wp-content/uploads/Congressional-Letter-to-PNT-Executive-Committee.pdf accessed 28 May 2024.

[4] London Economics, 2023, The economic impact on the UK of a disruption to GNSS, https://assets.publishing.service.gov.uk/media/652eb0446b6fbf000db7584e/20231018_London_Economics_Report_GNSS.pdf accessed 28 May 2024.

[5] UK Government, 2023, National Risk Register, https://assets.publishing.service.gov.uk/media/64ca1dfe19f5622669f3c1b1/2023_NATIONAL_RISK_REGISTER_NRR.pdf accessed 28 May 2024.

[6] Selam Gebrekidan, One satellite rules modern life. What is someone knocks it out? (*New York Times*, 28 Mar. 2024) https://www.nytimes.com/2024/03/28/world/asia/as-threats-in-space-mount-us-lags-in-protecting-key-services.html accessed 28 May 2024.

[7] David H. Milner et al., 2022, BeiDou China's GPS Challenger Takes Its Place on the World Stage, https://ndupress.ndu.edu/Portals/68/Documents/jfq/jfq-105/jfq-105_23-31_Millner-Maksim-Huhmann.pdf?ver=URigiNO3M3gxp9rvEge1OA%3d%3d accessed 28 May 2024.

[8] Dana Goward, NSC director: GPS 'Still a Single Point of Failure', (*GPS World*, 4 Jan. 2022) https://www.gpsworld.com/nsc-director-gps-still-a-single-point-of-failure/ accessed 28 May 2024.

[9] Euroconsult, 2022, Euroconsult estimates that the global space economy totaled $370 billion in 2021, https://www.euroconsult-ec.com/press-release/euroconsult-estimates-that-the-global-space-economy-totaled-370-billion-in-2021/ accessed 28 May 2024.

The role of geodesy

The satellites providing vital defence and civilian applications are reliant on constant updates about their 'place in space' (satellite orbit information) and the Earth's 'place in space' (shape, orientation, coordinate reference frame and gravity field). These are collectively known as geodetic products.

Satellites need new geodetic products uploaded to them constantly because the Earth and satellites are always moving. The Earth does not stay still; it is breathing, spinning and wobbling. To complicate things further, the satellites orbiting the Earth are also constantly moving. Satellites are pushed by solar radiation and pulled by Earth's gravitational force which varies over time and location.

Geodesy is the science of measuring the Earth's shape, orientation, gravity field, and the orbits of satellites. It is essential that geodesists constantly make these observations and provide updated geodetic products for satellite operations; without which the satellite applications society take for granted would degrade or fail.

Global geodesy supply chain

The geodetic products are created through the global geodesy supply chain (Figure 1; Appendix A) which includes:

- ground observatories operated by scientists who constantly observe the movement of the Earth and satellites;
- data centres operated by specialists who quality check the data from observatories and make it available to the global geodesy analysis community; and,
- analysis centres, correlation centres and analysts who translate the raw data into geodetic products.

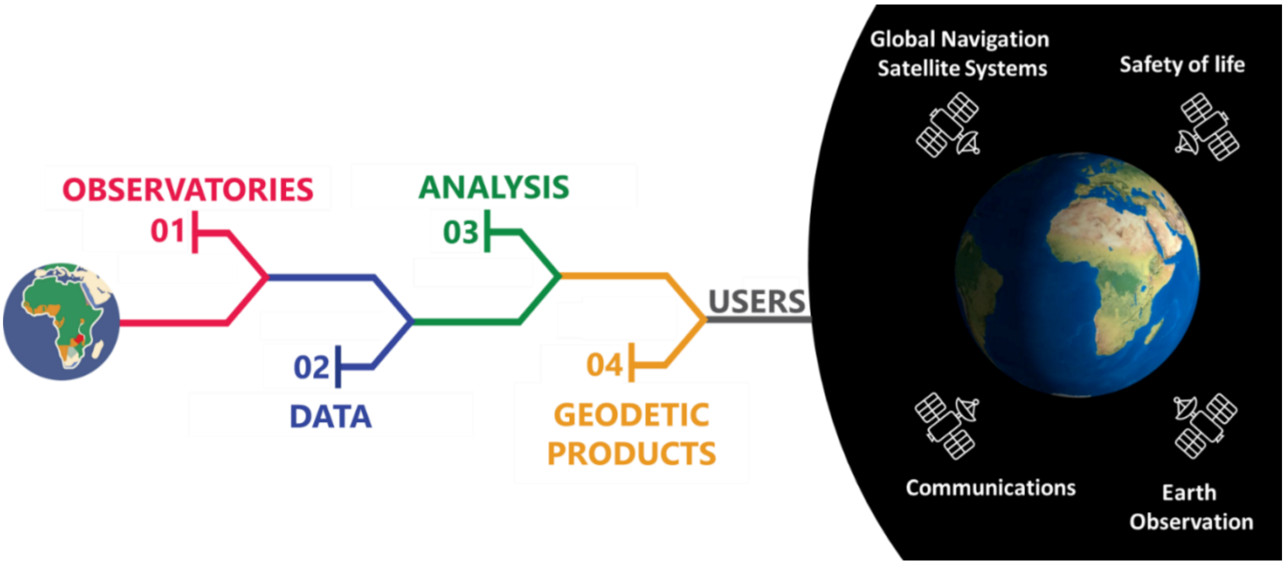

Figure 1: The global geodesy supply chain.

The geodetic products include:

- The global coordinate reference frame and global gravity models. These are like a 'zero point on a ruler' used to locate points on the Earth's surface, make precise measurements, navigate and align geospatial data.
- Earth Orientation Parameters which describe the Earth's 'place in space' at any given time.
- Satellite orbits which describe a satellite's 'place in space' at any given time.

All these geodetic products are needed for accurate and reliable satellite services.

It is a *global* geodesy supply chain because no single country can fulfil all the requirements of accurately and reliably observing and analyzing the Earth and satellites. To measure the constant changes, with the frequency and level of precision required to produce the geodetic products that satellites and users demand, ground observatories and highly qualified people within governments and universities all around the world are needed.

A day without satellites

Imagine this scenario.

7:43 AM

The alarm on your phone didn't wake you up. That's strange.

7:50 AM

You turn on the television and notice that you can't get a signal. No signal on your phone either. While you are making a coffee and scratching your head, others are dealing with their own issues. Telecommunications satellites providing television signals, and GNSS systems that assist in the function of mobile phone towers have stopped working.

9:03 AM

Since the GNSS and telecommunication satellites stopped working, land, sea and air travel has ceased. Those pilots, drivers and captains already on route have switched to analogue devices and maps. Messages are (trying to be) sent out over radio to ground aircraft and for vessels to return to port. The only winners (in the short term) are the tens of thousands of passengers in planes flying at any one time, totally oblivious to the difficulties on the flight deck as pilots struggle to talk to air traffic control. The enjoyment is brief however, because once they land, people are stuck.

10:18 AM

For people driving, they notice that traffic light systems have either stopped working or are very erratic. This is because traffic light systems need GNSS timing information. Accidents are happening everywhere, and emergency services can't be notified because mobile phones aren't working. For those calls still being made on land lines, emergency services can't get to people efficiently due to the lack of central management, route planning, and blocked streets from the chaos.

11:47 AM

All stock exchanges around the world have stopped operating. No international communications from satellites and no timing services from GNSS mean it is impossible to synchronize trades with integrity.

12:34 PM

There is panic on the streets and a run on the banks as people try to withdraw cash, however, Automatic Teller Machines aren't working, and the banks don't stock enough cash to meet demand.

2:02 PM

In a bunker somewhere in Europe, a pilot squadron has lost contact with the armed drones they were flying in a test exercise. The failure of secure satellite communications systems has left soldiers, ships and aircraft cut off from their commanders and vulnerable to attack. Without satellites, world leaders struggle to talk to each other to diffuse mounting global tensions.

5:12 PM

When the satellites stop, back-up systems using ground-based clocks for timing start. However, within a few hours, without GNSS satellites to synchronize time differences between clocks around the world, problems start to occur. Cloud services begin to fail, internet speeds get slower and slower until finally they stop working altogether. Power cuts come next as suppliers are unable to regulate demand without GNSS timing.

11:30 PM

Within a day, most countries reliant on GNSS for their economies and critical infrastructure announce they are in a 'state of emergency' and there is no clear way out of it given the backup options for GNSS are either untested, or only work in local areas.

11:58 PM

Communications, transport, power and computer systems have been severely disrupted. Global business has ground to a halt and governments are struggling to cope. Politicians have been warned that food supply chains will soon break down. Now they fear a breakdown in public order[10].

Widespread failure in this timeframe is associated with a scenario like a global cyber-attack. If Member States do not address the hidden risk, the impact on the global economy, critical infrastructure and our way of life could be the same. The timeframe in which it happens however will depend on how well Member States are ready to 'gracefully degrade' from the use of satellites.

In 2023, the United Kingdom Government published their National Risk Register Report[11], which included a "reasonable worst-case scenario" for the loss of PNT services based on a severe technical failure. They predicted this would result in inaccurate position and timing data being delivered to users and would have no choice but to cease operations. The economic loss just from an outage of GNSS for 7-days has been estimated to be €8.9 billion (£7.64 billion) in the UK[4]. A study in the U.S. estimated similar losses of US$~1 billion per day.[12]

Assessments of threats to satellite services[11,13,14], associated with space-based infrastructure or the signals they provide, address risks such as solar storms, a coordinated cyber-attack, space debris collision event or deliberate attacks. These reviews, however, exclude the hidden risk, that is, the risk of degradation or failure of the global geodesy supply chain.

Recognizing this, the United Nations General Assembly adopted resolution 69/266[15] in February 2015, entitled 'A Global Geodetic Reference Frame for Sustainable Development'[16] which encourages Member States to work together to sustain and enhance the global geodesy supply chain. Despite the adoption of the resolution, the risk remains hidden to many.

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[10] R. Hollingham, 2013, What would happen if all satellites stopped working? https://www.bbc.com/future/article/20130609-the-day-without-satellites accessed 28 May 2024.

[11] UK Government, 2023, National Risk Register https://assets.publishing.service.gov.uk/media/64ca1dfe19f5622669f3c1b1/2023_NATIONAL_RISK_REGISTER_NRR.pdf accessed 28 May 2024.

[12] RTI International, 2019, Economic Benefits of the Global Positioning System (GPS) https://www.rti.org/sites/default/files/gps_finalreport618.pdf?utm_campaign=SSES_SSES_ALL_Aware2019&utm_source=Press%20Release&utm_medium=Website&utm_content=GPSreport accessed 28 May 2024.

[13] London Economics, 2023, The economic impact on the UK of a disruption to GNSS, https://assets.publishing.service.gov.uk/media/652eb0446b6fbf000db7584e/20231018_London_Economics_Report_GNSS.pdf accessed 28 May 2024.

[14] Euroconsult, 2022, Euroconsult estimates that the global space economy totaled $370 billion in 2021, https://www.euroconsult-ec.com/press-release/euroconsult-estimates-that-the-global-space-economy-totaled-370-billion-in-2021/ accessed 28 May 2024.

[15] UN General Assembly Resolution 69/266, 2015, https://ggim.un.org/documents/a_res_69_266_e.pdf accessed 28 May 2024.

[16] The terms 'Global Geodesy Supply Chain' and 'Global Geodetic Reference Frame' have the same meaning. The UN-GGCE have adopted the use of Global Geodesy Supply Chain as it is easier to explain to a lay audience.

2 The growing reliance on geodesy

This chapter reviews how reliant national economies and critical infrastructure are on satellites, and thereby highlights the increasing risk associated with the degradation or failure of the global geodesy supply chain.

Operation of critical infrastructure

Although best known as a positioning and navigation system, accurate on-board atomic clocks make GNSS wonderful timekeepers. As a global, 24/7 operational, free (to the user) resource, GNSS (predominantly GPS) has become the world's primary system for the distribution of accurate (sub-microsecond) time. However, this heavy reliance on GNSS timing raises concerns about potential weaknesses in the global geodesy supply chain. Accurate and reliable time signals are essential in the operation of critical infrastructure systems[17,18], with failures in timing systems leading to severe consequences, including financial losses, compromised safety and security measures, and even loss of life.

Telecommunications services

Telecommunication services including mobile phone and satellite phone networks rely on GNSS and have relatively high accuracy timing requirements. GNSS provides robust time synchronization for accurate data transmission (e.g. for internet on mobile devices) and for 'handovers' from one cellular phone tower to another as a mobile user roams.[22] Of all critical infrastructure systems, the telecommunications sector would be hardest hit by the loss of GNSS due to the stringent synchronization requirements. Without GNSS, continued operation of mobile phone networks would be impossible.[18]

Stock exchanges and financial systems

Stock exchanges and financial systems have used GNSS for timekeeping and time-synchronization for decades. GNSS provides a globally consistent timestamp of when a transaction occurs with traceability to Universal Coordinated Time (UTC) for regulatory compliance. This is critical to everything from stock exchanges, to banking systems, to the local deli's credit-card machine. [19] They all use GNSS to time-stamp and verify transactions, freeing retailers from the need to transmit sales at the end of the day and enabling the worldwide, ultrahigh-frequency trading so prevalent now.[20]

Without GNSS some stock exchanges would likely continue to operate using alternative timing sources, albeit with reduced protection for investors[18]; however, a loss of GNSS would likely have a more severe impact on banking systems and businesses that do not use alternative timing sources.

Energy distribution

The energy sector is heavily reliant on GNSS for time-synchronization in energy distribution systems. Measurements are made at a variety of strategic locations throughout the grid, including power plants and sub-stations to assist with system planning, control, automatic protection and optimizing operation in response to real-time demand.[19,20]

Without GNSS, the daily operation of the power grid would be more labour intensive and difficult, as daily operations would be severely hampered and diagnostic tools would become less useful.[18] This would cause

[17] Monty Graham, 2012, GPS Use in U.S. Critical Infrastructure and Emergency Communications, https://www.gps.gov/multimedia/presentations/2012/10/USTTI/graham.pdf accessed 28 May 2024.

[18] Michael A. Lombardi, 2021, An Evaluation of Dependencies of Critical Infrastructure Timing Systems on the Global Positioning System (GPS) https://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.2189.pdf accessed 28 May 2024.

[19] EUSPA, Report on Time & Synchronisation User Needs and Requirement, 2019, https://www.gsc-europa.eu/sites/default/files/sites/all/files/Report_on_User_Needs_and_Requirements_Timing_Synchronisation.pdf accessed 28 May 2024.

[20] Paul Tullis, 2019, GPS Is Easy to Hack, and the U.S. Has No Backup, https://www.scientificamerican.com/article/gps-is-easy-to-hack-and-the-u-s-has-no-backup/ accessed 28 May 2024.

financial stress for Member States and energy operators facing the challenges of rising electricity demand and the need to comply with sustainable development objectives.

Economic benefits

National economies are increasingly reliant on revenue generated from satellite services. Over the next decade, global GNSS downstream market revenue is expected to grow at a mean annual growth rate of 9.2%, reaching a total of €492 billion by 2031.[21] Over 82% of the revenue will be generated in mass market user segments (e.g. mobile devices, tourism, health and automotive) along with the industry sectors of agriculture, urban development, and infrastructure.[22]

In the same period, Earth Observation market revenues are set to double from roughly €2.8 billion to over €5.5 billion. Major contributors to this are expected to come from climate services, urban development and agriculture.[22]

The satellite communications market size is estimated at US$193 billion in 2024, and is expected to reach US$297 billion by 2029, growing at rate of approximately 9% between 2024-2029.[23] This is largely driven by increasing demand for high-speed internet, communication services, and data transfer across different industries.

Emergency services

In a recent study, it was found that 43% of the economic benefits to the UK from the use of GNSS (£13.6 billion per annum) are estimated to come from the Emergency Services sector. [24] Emergency Services have a critical reliance on the global geodesy supply chain at multiple stages of their operations. This includes a reliance on telephone network for establishing a phone connection and maintaining a connection when switching between communications towers on route to an emergency, identifying which emergency services can respond fastest based on current traffic conditions and route planning. All these and more translate into cost savings and improved health outcomes for people.

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[21] EUSPA, Market Report 2022, https://www.euspa.europa.eu/sites/default/files/uploads/euspa_market_report_2022.pdf accessed 28 May 2024.

[22] Katherine Dunn, 2019, Signal Failure, https://www.spglobal.com/en/research-insights/featured/special-editorial/signal-failure accessed 28 May 2024.

[23] Mordor Intelligence, 2024, Satellite Communications Market Size Source: https://www.mordorintelligence.com/industry-reports/global-satellite-communication-market accessed 28 May 2024.

[24] London Economics, 2023, The economic impact on the UK of a disruption to GNSS, https://assets.publishing.service.gov.uk/media/652eb0446b6fbf000db7584e/20231018_London_Economics_Report_GNSS.pdf accessed 28 May 2024.

Case Study: Wildfire

You are a firefighter in a forest with poor visibility due to a significant amount of smoke. The wind has changed direction, and you and your team need to retreat to a safer location. You need to contact your team, ensure everyone gets back to the fire truck as quickly as possible, navigate to a safer position and stop at a body of water to fill up the water tanker.

First, you locate your own position on a digital map using GNSS. The digital map also shows the location of your fire truck and team members who have GNSS devices. You contact your team members using a mobile phone network dependent on GNSS for time synchronization and advise them to navigate to the fire truck using GNSS and the map on their digital device which has the most recent image of the fire front taken by a drone. The drone image is spatially aligned with all the other data sources on the digital map. Furthermore, your device has a range of other useful layers of information including terrain height, fire trails, properties, critical infrastructure, and bodies of water all spatially aligned.

As you are navigating back to the truck using the digital map and GNSS, you identify a safe route to retreat from the fire to a dam about 10 km away. Using the water level indicator information sent to your mobile device from the fire truck, you see that it is 32% full of water and you calculate that it should take 25 minutes to refill the truck. You determine that you have time to get everyone back to the fire truck, drive to the dam, fill up the truck and then you can call back to Headquarters for advice on next steps.

The global geodesy supply chain underpins the critical intelligence fire fighters use today and will provide them with tools to work safer and more effectively in the future.

Road and Automotive

The road sector leverages significant benefits from GNSS predominantly from efficiency gains in time and fuel. GNSS provides real-time positioning information and traffic information for the drivers or fleet managers in logistics companies, enabling efficient route planning and turn by turn navigation.

The dependence from this sector is expected to grow in developed countries due to demand for autonomous vehicles. The global geodesy supply chain underpins safe, accurate and reliable positioning and navigation from GNSS; building and maintaining high precision maps; and, the alignment of the vehicles', position and speed, with roadside infrastructure detected with onboard sensors (e.g. cameras, radar, and LiDAR) used to support positioning.

> "As a global company delivering global positioning solutions, we rely on global geodetic infrastructure that is trusted and verifiable, ensuring cars on roads, drones in the sky and devices in-hand can locate consistently and reliably."
>
> *~ Swift Navigation*[25]

[25] Swift Navigation – Pers. Comm.

Agriculture

Countries are increasingly adopting modern practices which rely on the global geodesy supply chain. This includes accurate and reliable GNSS positioning and navigation for automatic machine steering, farm machinery guidance, livestock monitoring, and variable rate application to increase productivity and efficiency. These practices are shown to increase yields, reduce costs and reduce environmental impacts in food production. EO satellites and analysis are also used to remotely monitor the performance of crops, allowing farmers to reduce the time and resources such as fertilizers.

Urban Development and Cultural Heritage

Governments are increasingly looking to what is known as 'digital twins' – digital models of towns, cities, infrastructure – to create cities which are better connected and improve the efficiency, safety and livability. Digital twins provide a digital perspective of major projects before being built, in order to assist with design (simulations of options to enhance efficiency of operations) and public consultation. The global geodesy supply chain underpins the development of such digital twins by providing:

- an accurate coordinate reference frame, to plan on;
- a height reference frame based on gravity; and,
- position, navigation, EO data or 3D terrain models of the built environment aligned to the global coordinate reference frame to connect the different data.

With more than 56% of the population already living in urban areas[26] and this number expected to increase, digital twin solutions powered by the global geodesy supply chain will be needed more than ever to support sustainable growth.

Maritime

The maritime sector is highly dependent on a robust global geodesy supply chain including an accurate and reliable global coordinate reference frame, gravity models and a height reference frame connected to tidal information. For safety of navigation, there is a critical need to understand ocean depth and under keel clearance (distance between the bottom of the vessel and the ocean floor). This requires a very accurate height reference frame to compare the height of ocean floor, tide level at a particular time and under keel clearance to avoid damage to ships, crew, and the ecosystem.

The sector needs satellite intelligence for position, navigation, and timing information for monitoring the movement of vessels in the open ocean, safe navigation in difficult channels and ports with highly variable tides or challenging bathymetry and port operations. This is even more important when weather and visibility deteriorate. Close to shore and in port approaches, congestion is higher, as is the risk of collision. Close to landmasses, traffic is essentially parallel to coastlines, forcing all navigators to use the same route, thereby increasing the density of vessels. In larger ports, container terminals can be automated, and the cranes used in this process rely on GNSS for precise positioning of containers.

[26] World Bank, 2024, Urban Development, https://www.worldbank.org/en/topic/urbandevelopment#:~:text=Globally%2C%2056%25%20of%20the%20population,2%20billion%20more%20urban%20residents. accessed 28 May 2024.

Case Study: Suez Canal

In March 2018, ships in and around Port Said, the northern gateway to Egypt's Suez Canal, either lost connection to GPS (jamming) or had them incorrectly positioned (spoofing) up to 150 nautical miles away from their true location. In that month, 1,450 vessels transited the waterway, about a third of which were oil tankers or liquefied natural gas ships carrying about 61 million barrels of crude oil, according to the Suez Canal Authority records.

The economic impact and flow on effects of delay or stoppages in the energy supply chain is only one risk. Other risks from GPS jamming and spoofing include accidents, collisions, confusion, and other costly mistakes, not to mention the risk of straying into contested waters and military conflicts. Mitigation of these risks is possible by making the global geodesy supply chain more resilient.

Air travel

The aviation industry supports $3.5 trillion (4.1%) of the world's gross domestic product (GDP)[27] and has safety at its core[28]. GNSS, combined with high integrity signals provided by Satellite Based Augmentation Systems (SBAS) are now widely deployed and mandatory for air surveillance purposes in many international air spaces, replacing a very costly radar-based infrastructure. GNSS positioning provides timely and rich information that allows for safer and more efficient use of air space, and reduces economic and environmental costs.

[27] Aviation Benefits, 2019, Adding value to the economy, https://aviationbenefits.org/economic-growth/#:~:text=The%20aviation%20industry%20supports%20%243.5,of%20Indonesia%20and%20the%20Netherlands. accessed 28 May 2024.
[28] ICAO, 2024, Safety, https://www.icao.int/safety/Pages/default.aspx accessed 28 May 2024.

3 Major weaknesses in the global geodesy supply chain

"The Global Geodesy Supply Chain exhibits an exceedingly fragile stability and could easily collapse due to a number of material and non-material concerns."

~ JN Markiel
(U.S. National Geospatial-Intelligence Agency)

There are a number of major weaknesses in the global geodesy supply chain. A summary is provided in this section. For a more thorough description, including regional insights, refer to the Global Geodesy Needs Assessment.[29]

Insufficient evidence to influence decision makers

- There is insufficient evidence describing the importance the global geodesy supply chain in ways that decision makers can understand (e.g. societal, environmental and economic benefits realization). As a result, decision makers are unable to evaluate the risk associated with degradation or failure of the global geodesy supply chain.
- Evidence of the importance of the supply chain for high profile and politically relevant topics are needed such as like critical infrastructure systems, key resource sectors, hazards and security.[29] Furthermore, the evidence needs to be presented in a form which enables decision makers to take action, for example through cost-benefit analyses.

Insufficient resources to sustain the supply chain

- There are insufficient resources (dedicated funds and people) to sustain the global geodesy supply chain and ensure it can meet operational requirements for key resource sectors and critical infrastructure.[30]
- The operational funding currently being allocated to the operation of the global geodesy supply chain is estimated to be between €60-90 million per year worldwide which is less than 0.05% of revenue generated from GNSS- and EO- services.[29]
- Experts from around the world have declared the global ground observation station network as fragile with too many single sources of failure.[29] Approximately half of ground observation stations are not-productive due to their age or lack of operational funding.
- The collection of data from ground observatories along with quality checking, analysis and development of geodetic products is undertaken by several Member State governments and

[29] UN-GGCE, 2024, Global Geodesy Needs Assessment, https://ggim.un.org/UNGGCE/documents/20240509-Global_Geodesy_Needs_Assessment.pdf accessed 28 May 2024.
[30] UN-GGCE, 2024, Expert Consultation meeting on Strengthening the Global Geodesy Supply Chain, https://ggim.un.org/UNGGCE/Expert_Consultation/Summary_of_Decisions_and_Meeting_Notes-v2.pdf accessed 28 May 2024.

universities who collaborate under the coordination of a science organization – the International Association of Geodesy (IAG). Much of this work is provided in-kind, and on a best-effort basis. If Member State governments and universities choose to cease their in-kind support for the global geodesy supply chain, it could cause significant degradation of the supply chain.

Inadequate governance mechanisms

- There is no international governance body, e.g., the World Meteorological Organization (WMO), with responsibility for ensuring the global geodesy supply chain meets Member State requirements, including the provision of accurate and reliable geodetic products critical to people's lives.
- In lieu of having an international geodetic organization run by Member States, a science organization, the IAG, is responsible for the operational duties in addition to its scientific role. Nonetheless, the IAG has very few dedicated people to assist with this function and no official mandate like WMO to provide high-quality, authoritative products for Member States.
- Although Member State governments are heavily reliant on each other to sustain the global geodesy supply chain, there are very few intergovernmental arrangements in place. The limited number of (in)formal arrangements that are in place are often based on 'best-effort' collaboration, with no guarantee of continuity in the long term.
- There is an over-reliance on academic community to perform operational activities. Many highly-qualified people working in roles which are critical to the operation of the global geodesy supply chain have short-term contracts with academic institutions or are paid through research grants. If academic institutions choose to cease the funding, and they do, it causes degradation of the global geodesy supply chain.

Decreasing capacity

- In many parts of the world, there is a decline the number geodesists. This has been labelled a 'crisis' in the U.S. causing significant risks to national security, safety of navigation and the ability to measure and mitigate the effects of climate change.[31]
- The decline is due to:
    - lack of awareness of geodesy as a career;
    - less formal geodesy training options in universities predominantly due to universities not seeing geodesy courses as financially profitable;
    - competition for maintaining personnel when better incomes are available in other businesses and sectors;
    - a perceived lack of career paths.[32]
- Some Member States and organizations offer a range of geodesy training through workshops and conferences; however, recent surveys indicate that developing countries need more personalized and detailed training specific to their situation[33]. This highlights the complexity of geodesy and the need for dedicated resources to assist Member States over a long period of time.

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[31] Michael Bevis et al., 2022, America's loss of capacity and international competitiveness in geodesy, the economic and military implications, and some modes of corrective action, https://aagsmo.org/wp-content/uploads/2022/02/TheGeodesyCrisis_Final.pdf accessed 28 May 2024.

[32] UN-GGCE, 2024, Global Geodesy Needs Assessment, https://ggim.un.org/UNGGCE/documents/20240509-Global_Geodesy_Needs_Assessment.pdf accessed 28 May 2024.

[33] Ryan Keenan et al., Global Survey Reference Frame Competency – 2021, https://www.fig.net/resources/proceedings/fig_proceedings/fig2023/ppt/ts05g/TS05G_keenan_craddock_et_al_12230_ppt.pdf accessed 28 May 2024.

Lack of awareness

- Member State governments are highly dependent on the supply chain for GNSS, EO and satellite communications applications, however, there is a severe lack of awareness and engagement between government science, policy and defence organizations.[34]
- There is a very low level of awareness of what modern geodesy provides even in closely related or adjacent industries.[32] Increasingly industries are reliant on satellite services for position, navigation and timing services such as mining, agriculture, construction, maritime, intelligent transport etc.; however, the scientists and engineers (let alone the owners) of these companies are unaware of the global geodesy supply chain, its risk of degradation and the risk to their stakeholders.
- There are numerous reports which describe the economic, environmental, and societal benefits of satellite services[35,36,37,38], however, these reports fail to mention their critical reliance and dependency on the global geodesy supply chain. Furthermore, there are satellite user segments which are heavily reliant on the global geodesy supply chain with visible public profiles (e.g., climate science community) who publish reports widely read in government (e.g. International Panel on Climate Change). These are a good opportunity to demonstrate a strong dependence on the global geodesy supply chain. Nonetheless, geodesy is rarely if ever mentioned in these reports.

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34 UN-GGCE, 2024, Global Geodesy Needs Assessment, https://ggim.un.org/UNGGCE/documents/20240509-Global_Geodesy_Needs_Assessment.pdf accessed 28 May 2024.

35 UK Government, 2018, Satellite-derived Time and Position: A Study of Critical Dependencies, https://assets.publishing.service.gov.uk/media/5a82c84ced915d74e34038ab/satellite-derived-time-and-position-blackett-review.pdf accessed 28 May 2024.

36 London Economics, 2013, The economic impact on the UK of a disruption to GNSS, https://assets.publishing.service.gov.uk/media/652eb0446b6fbf000db7584e/20231018_London_Economics_Report_GNSS.pdf accessed 28 May 2024.

37 EUSPA, Market Report 2022, https://www.euspa.europa.eu/sites/default/files/uploads/euspa_market_report_2022.pdf accessed 28 May 2024.

38 John Garamendi et al., 2015, Letter to Congress of the United States, https://rntfnd.org/wp-content/uploads/Congressional-Letter-to-PNT-Executive-Committee.pdf accessed 28 May 2024.

4 Call to action

To implement United Nations General Assembly resolution 69/266, Member States and partners are forming a Joint Development Plan (to be released in August 2024) describing how they will work together to strengthen the supply chain to enhance the reliability and integrity of the geodetic products. Member States are urged to take action. Examples include:

Strengthening collaboration and coordination within each country by:

- Establishing a geodesy working group with representatives from within government (e.g. defence, science, policy) and industry. The working group could focus on:
  - Assessing the societal, environmental and economic risks due to degradation or failure of the global geodesy supply chain.
  - Translating the risks into evidence to which can be used to influence decision makers.
  - Developing national strategies to access and utilize resources to mitigate the risks.
- Officially recognizing and resourcing the global geodesy supply chain as 'critical national infrastructure'.
- Developing outreach programs that make the global geodesy supply chain more visible and understandable to society.

Strengthening collaboration and coordination within each region, and globally, by:

- Establishing a geodesy working group with regional and global representatives from within government (e.g. defence, science, policy) and industry. The working group could focus on:
  - Discussing the societal, environmental and economic risks due to degradation or failure of the global geodesy supply chain.
  - Translating the risks into evidence which can be used to influence decision makers.
  - Developing regional and / or global strategies to access and utilize resources to mitigate the risks.
  - Sharing data, sharing knowledge and building capacity.
- Developing formal bilateral or multilateral agreements to address gaps in the global geodesy supply chain.
- Investigating options for foreign aid investment which would support the global geodesy supply chain in foreign countries.
- Working with the UN-GGCE on efforts to strengthen the global geodesy supply chain.

Appendix A: Global geodesy supply chain

This section provides a description of the elements of the global geodesy supply chain.

Observatories, data and analysis

Ground station observatories (Figure 2) are where measurements of the Earth and the satellites are made using one or more types of geodetic instruments. The different geodetic instruments (see below) are complementary; each able to measure something different about the dynamics of the Earth and satellites. When the information from these instruments is combined, they tell a four-dimensional story of the movement of the Earth, and satellites through time and enable accurate and reliable communication with satellites.

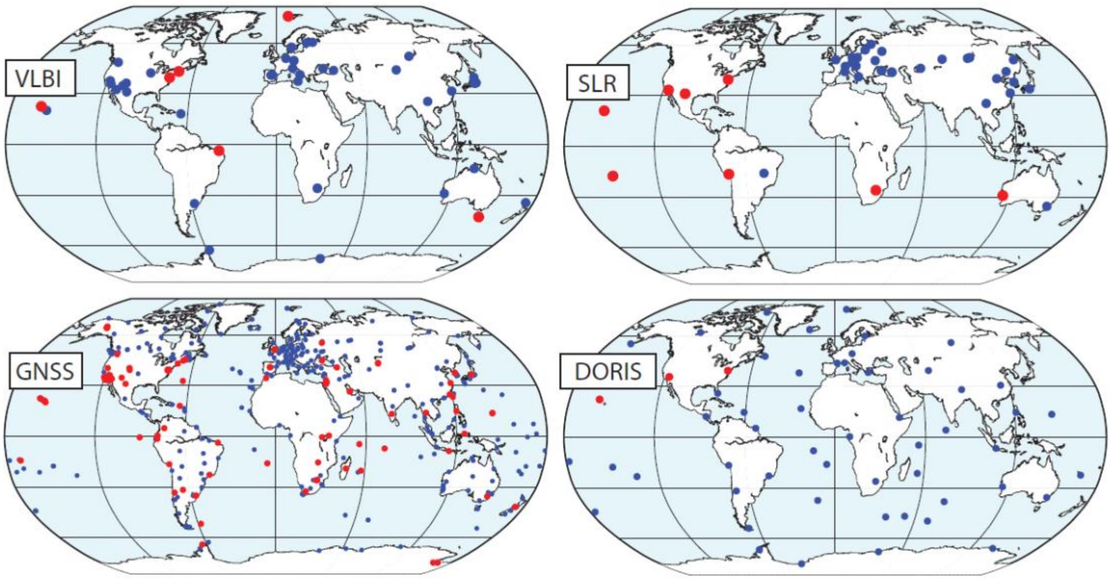

Figure 2: The positions of ground station observatories which are contributing to the creation of geodetic products. (Upper left) VLBI sites (47), (Upper right) SLR sites (39), (Lower left) GNSS sites (496), (Lower right) DORIS sites (55). Red dots denote those operated by, or hosted by, U.S government or U.S institutions. Blue dots denote those operated by, or hosted by, other governments or non-U.S institutions. Figure from National Academy of Sciences, Engineering and Medicine[39].

Very Long Baseline Interferometry

Very Long Baseline Interferometry (VLBI) is a geodetic technique that measures time between microwave signals propagating from distant objects in space (called quasars) to antennas on the Earth surface. Based on the times recorded at different locations, it is possible to determine the absolute orientation of the Earth, spin-rate of the Earth and the distance between the antennas (which can be 1000s of km apart) with millimetre precision. This information is critical because it makes it possible to measure the diameter of the Earth, which is necessary to develop the global coordinate reference frame and provides vital information about Earth's movement which is needed for communication between space and Earth.

Satellite Laser Ranging

Satellite Laser Ranging operators fire lasers from ground observatories at satellites and measure the time it takes for the laser light to return. Based on the time delay, geodesists can monitor the orbits of satellites with centimeter accuracy. These observations allow geodesists to monitor satellite positions with centimetre

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[39] U.S National Academies of Sciences, 2020, Evolving the Geodetic Infrastructure to Meet New Scientific Needs, https://doi.org/10.17226/25579, accessed 28 May 2024.

accuracy. With the laser measurements, geodesists determine the size of the Earth, the strength of its gravity field, and its centre of mass (the origin of the global coordinate reference frame).

Global Navigation Satellite Systems

GNSS is predominantly the way people access PNT. A position (latitude, longitude and height) can be determined by a GNSS receiver (e.g., a mobile phone) on or above the Earth's surface just from working out the time it took for signals to arrive from four or more GNSS satellites. The positioning accuracy achievable from GNSS varies from millimeter scale to meter scale depending on things like the quality of the equipment, the length of the observation, and how accurately the position of satellites is known when their signals are received.

Doppler Orbitography and Radiopositioning Integrated by Satellite

Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) is a French satellite system used to help determine and monitor satellite orbits and for positioning. The principle of DORIS is similar to GNSS but in reverse. Ground-based radio beacons send out a signal which is detected by receiving satellites. A frequency shift of the signal occurs, which is caused by the movement of the satellite (Doppler effect). From this observation, satellite orbits, ground positions, as well as other information can be derived.

Gravity

The strength of the Earth's gravity field varies due to differences in the mass distribution of rock, air, water and ice. The gravity field also changes over time as these properties change. By taking measurements at different heights (space, airborne and land based), geodesists can develop an average model of the Earth's gravity field, and monitor its changes over time at local, regional and global scales. This is fundamental to many fields of science including climate change, to measure and monitor changes in ice loss and sea level rise.

Figure 2 displays the positions of ground station observatories which are contributing to the creation of geodetic products. Accurate and reliable geodetic products are dependent on having observatories equally distributed around the world. The current configuration has a strong bias to the north, particularly for VLBI and SLR stations.

Geodetic Products

Geodetic products are developed by Member State government, science and defence agencies, and universities all around the world. These groups collect, quality check and analyze the data from ground station observatories and translate complex geodesy information into products which are used by satellite operators and mission planners. Coordination of the development of these products is performed by the IAG. A brief description of the critical geodetic products is listed below.

Earth Orientation Parameters

Think of the Earth as a spinning top — it doesn't spin perfectly upright all the time. Instead, it wobbles and undergoes slight variations in its rotation primarily driven by tidal forces of the Sun and Moon as well as movements of the atmosphere, ocean, ice and the Earth's interior. Earth Orientation Parameters (EOP) describe how the Earth's orientation in space changes over time. Geodesists around the world work together through the IAG to create updated EOP on a daily basis.

Global coordinate reference frame

Knowing where you are, and where things are around you, is key to effective decision-making. The global coordinate reference frame is a three-dimensional model of the Earth, which allows for the unique identification of the location (i.e. latitude, longitude and height) of things on, above or below the Earth's surface, and consequently to navigate between points. The global coordinate reference frame is necessary to monitor change (e.g. sea level), position (e.g. dam wall, earthquake) or speed (e.g. glacial motion), and to combine and align geospatial data (e.g. roads, critical infrastructure, hospitals, high tide heights, water inundation paths) to assist with social, economic, and environmental decision-making. Any error in the global coordinate reference frame will be translated into error in the things you are monitoring or datasets you are aligning. The IAG, work to create an updated global coordinate reference frame every few years using measurements from satellites and ground stations distributed all around the world.

The accuracy of EOP and Global Coordinate Reference Frame currently available are suitable for most space and satellite applications, however, there is a growing demand for increased accuracy from the space community for interplanetary navigation and from the scientific community and policy makers to measure the impacts of climate change and for natural hazard mitigation planning. Of greater concern is the reliability of the production of EOP and the Global Coordinate Reference Frame. This is due to a range of factors including ageing infrastructure and reliance on in-kind contribution.

Model of the Earth’s gravitational field

Gravitational field models provide a description of the variations in Earth's gravity caused by mountains, valleys, rock of different density, ocean tides, groundwater movement, ice mass changes, atmospheric changes and Earth’s rotation. These models are important to convert heights observed using GNSS (which are relative to a simplified mathematical representation of the Earth) to more physically meaningful heights (i.e. mean sea level). The differences can be over 80 m in height. Models like this are provided in various software packages used for positioning and navigation including mobile phones. These models are also very useful for resource exploration, mining, environmental monitoring, and water management.

Document version	
1.0 – 5 June 2024	First release.
1.1 – 20 June 2024	Removed duplicated line in SLR section of Appendix A.