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# Accuracy for All

## Community Land Mapping and the Navigation Satellite Revolution

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## About New America

We are dedicated to renewing America by continuing the quest to realize our nation's highest ideals, honestly confronting the challenges caused by rapid technological and social change, and seizing the opportunities those changes create.

## About Future of Property Rights

The Future of Property Rights initiative engages with policy makers, technologists, academics, civil society, and jurisdictions, as well as the property rights formalization community of practice. Property rights formalization is a powerful tool for creating wealth, opportunity, and security. A number of recent technology developments and advancements greatly reduce the time, cost, and complexity of property rights formalization. As a result, there are many ripe opportunities to apply this policy solution. Our role is to highlight these opportunities, expand the conversation and facilitate instances of property rights formalization improving lives.

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# Introduction

On May 1, 2000, the White House Office of Science and Technology Policy issued a short press release on behalf of President Bill Clinton which began:

> Today, I am pleased to announce that the United States will stop the intentional degradation of the Global Positioning System (GPS) signals available to the public beginning at midnight tonight. We call this degradation feature Selective Availability (SA). This will mean that civilian users of GPS will be able to pinpoint locations up to ten times more accurately than they do now.[1]

With the push of a button, the accuracy of civilian GPS receivers improved from roughly 50 meters to about 5 meters, creating a new and open market for location services—like the now ubiquitous turn-by-turn navigation—that had previously been impossible.[2] In June 2000, Steven W. Berglund, the president and CEO of Trimble Navigation, called the decision to turn off SA "a milestone in GPS history" that "underscores the importance of the technology as a global information utility."[3]

He was right. Today, daily use of global navigation satellite system (GNSS) location services is taken for granted by everyone with a smartphone. In 2013, the direct economic impact of GPS in the U.S. alone was estimated to be between $37 billion and $74 billion.[4] The 2017 EU *GNSS Market Report* predicts that the number of GNSS devices in use will "increase from 5.8 billion...in 2017 to almost 8 billion in 2020 – averaging an estimate of more than one device per person on the planet." They predict further that the "global GNSS downstream market, which comprises both devices (e.g. GNSS receivers) and augmentation services," will grow to €195 billion in 2025.[5]

Now, as investment in the GNSS market continues to increase, we are approaching another milestone that may prove as significant as the end of Selective Availability. That milestone is the emergence of new satellite navigation signals and signal processing capabilities that will, in a few short years, improve the location accuracy of consumer devices—including smartphones—from meters to centimeters.[6] Just as happened with the ending of Selective Availability, this new level of accuracy will enable new applications, from autonomous vehicle navigation to augmented reality. Access to centimeter-level accuracy also opens up another use case, one that is not commercial but could have a far greater economic impact than any other: community land mapping. Community land mapping combines surveying with the collection of information about land ownership and/or occupancy to support the formal recognition of property rights.

In this report, we first discuss the developments that are making high-accuracy location services available to all for the first time. Then, through the lens of a recent case study, we look at the current state of community land mapping and how some of the remaining challenges can be addressed with new tools. Finally, we look at how new identity and trusted data systems can help enhance the non-geospatial half of community mapping, the collection of attribute data.

**Note:** *In the appendices we include some lightly edited earlier writing on these subjects. In addition to providing greater detail on the evolution of GNSS and mobile mapping, these articles introduce and explain in simple terms the technical concepts referenced in the first section of this paper. Readers who are not already familiar with GNSS technology will find it helpful to read the appendices first. We also include a glossary of key technical terms and concepts.*

## High-Accuracy Location Services, Community Mapping, and the Future of Geospatial Data Collection

Across the developing world, nearly a billion people live without legal title to their land. In order to formalize this property, governments need to issue titles and create secure registries in which to record them. But unlike other types of property, parcels of land cannot be registered until they have been defined. Delineating one person's property from another's is a serious technical challenge and a prerequisite for granting secure legal titles.

This challenge is all but insurmountable if approached with conventional methods. Professional surveying is extremely accurate but prohibitively expensive in the developing world. Recent advances in GNSS technology have weakened the correlation between precision and cost, but survey-grade accuracy is not yet widely affordable.

Widespread access to high-accuracy geospatial data is critical for formalization efforts because expense is not the only problem with depending on professional surveyors. Documenting the world's informal property involves a more fundamental issue of scale; there is not enough time for the small number of professional surveyors to register it all. According to the Cadasta Foundation, there are fewer than two professional surveyors per 10,000 square kilometers of land in the Ivory Coast and Tanzania, compared to 41 per 10,000 square kilometers in the United States. There were only 74 registered land surveyors in Uganda in 2015 and an estimated 15 million parcels of informally owned land. With more than 200,000 parcels per registered surveyor, Cadasta calculates that it would take them over a thousand years to finish the job.[7]

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**With more than 200,000 parcels per registered surveyor, it would take Uganda over a thousand years to finish the job.**

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When everyone has access to high-accuracy location data, some of the most time-consuming and expensive parts of the formalization process can be completed more quickly and cheaply at a local level. But collecting accurate, high-integrity geospatial data is only one part of the challenge. Formalization also requires the collection of a great deal of information about the people living in these communities, and this information should be collected in a way that respects local cultural sensitivities and land use practices, as well as the privacy of the landholders. This is the other half of community mapping.

### Accurate Location Data For All: Why Dual-Frequency GNSS is Necessary

One of the primary obstacles to the acceptance of community mapping is that it does not produce data as accurate or trusted as that gathered by professionals. On the surveying side this is largely a technical problem: the hardware and expertise required by traditional geospatial surveying methods is beyond the reach of most communities. But when it comes to gathering non-geospatial information about properties, their attributes, the people who own them, and their rights, there is a problem of trust. Professional surveyors and government officials are considered trustworthy to a degree that members of the community, with their diverse and potentially conflicting interests, may not be. In order for community mapping to have the greatest impact, the information it produces must be trusted enough to be accepted by the authorities who control access to services.

Mapping conducted with cheap and accessible tools is at present unlikely to meet legal standards for property registration, making it of limited use as collateral for a loan. Moreover, lenders may not be willing to accept low-value properties as security for loans, regardless of the formal ownership status.[8] Expanding access to capital is often cited as the primary economic benefit of formalization, but it is only one positive impact of many. Community mapping can be used to increase tenure security and bootstrap financial inclusion, even when it does not result in formal registration. Indeed, increased tenure security can itself be a driver of increased investment in land. The information gathered can provide strong evidence for the legal defense of property rights, increasing security of tenure. For example, in 2011 community maps created by the Basarwa Bushmen helped them to challenge the Government of Botswana in court and "win back the right to live on their land."[9]

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**Community mapping can be used to increase tenure security and bootstrap financial inclusion.**

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Many in the international development community argue that rather than trying to adopt more accurate mapping tools and techniques—which have been prohibitively expensive—it would be better to relax surveying accuracy standards. But there are good reasons to resist this argument, especially now that high-accuracy tools are becoming more accessible. First, governments have little incentive to relax their standards, given the risk of increasing the number of legal boundary disputes. More accurate surveying enhances the clarity and security of land claims. Second, quality of surveying and security of title should not be tied to the income of the property owner. Third, in a rapidly urbanizing world, accuracy is increasingly important: errors on the order of meters, even decimeters, can encompass a large percentage of the area of a small apartment. This is one reason that the focus of formalization efforts has to date been largely on rural surveying. Fortunately, cheap tools are emerging that promise to make professional-grade accuracy accessible to everyone. It is important to note that there will still be a role to play for expert surveyors, who will help design community mapping efforts, train the participants, and provide quality control of data gathered.

## A Second Frequency

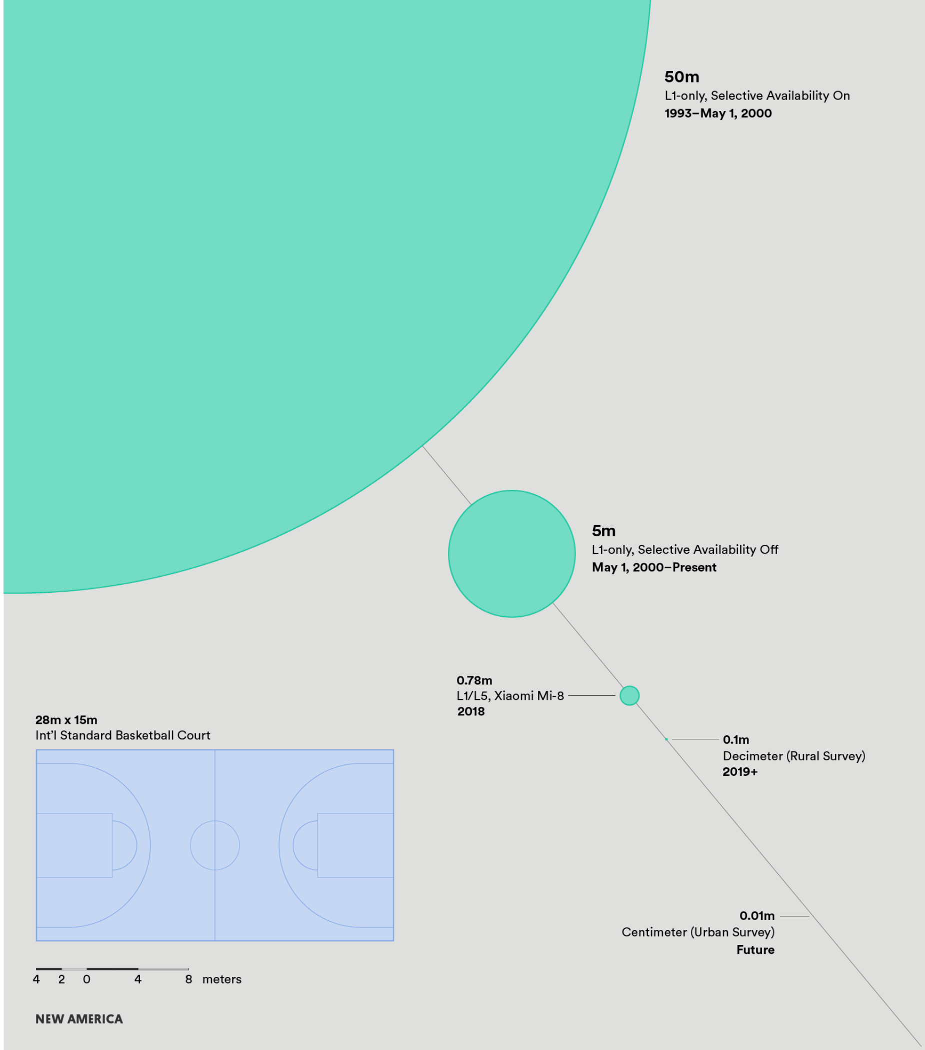
Position measurements using a single frequency are vulnerable to interference and accurate, at best, to about five meters. This is fine for most people's daily use, and in developed areas Wi-Fi signals can be used to augment accuracy. Until May 2018, for example, every smartphone ever released used a single-frequency receiver. But errors on the scale of meters are not good enough for survey work, which should be accurate to the one to ten centimeter range, depending on local standards and the type of surveying.

By making use of a second signal frequency, dual-frequency receivers can correct for delays caused by the ionosphere, which are the greatest single contributor to inaccuracy. Using a second frequency also provides greater signal redundancy, allowing for better error-correction and improved satellite availability in tree cover and urban canyons. With error-checking algorithms that can identify faulty satellite signals, dual-frequency receivers produce measurements that are not only far more accurate but also significantly more trustworthy. This last quality is important when it comes to registering land, as it allows the authorities validating title claims to have confidence in the integrity of the data they are given. Dual-frequency receivers also resolve positions more quickly than single-frequency receivers, so the surveyor does not have to wait as long on a reference point acquiring multiple satellites.[10]

## New Developments

In our earlier writing, we predicted that the imminent availability of new navigation satellite signals and new markets for precision navigation (notably for autonomous vehicles) would bring survey-grade accuracy to mobile devices by 2022.[11] One year later our prediction looks conservative. The number and sophistication of navigation satellite constellations and signals is increasing, and dual-frequency chips are, for the first time, being mass manufactured for consumer applications. As of 2018, sub-meter accuracy is available for the mass market in the Xiaomi Mi-8 smartphone. Decimeter accuracy will be achievable soon, with centimeter accuracy to follow.

**Figure 1** | Positioning Accuracy of Consumer GNSS Receivers




- Until the year 2000, the GPS civilian signal (L1) was intentionally degraded for reasons of national security. This policy, called Selective Availability limited the accuracy of single-frequency civilian GPS devices to approximately 50 meters.

- On May 1, 2000, the Clinton administration turned off Selective Availability, allowing users of the L1 signal to achieve accuracy of approximately 5 meters.

- In 2018 Xiaomi released the Mi-8, the first smartphone to incorporate a dual-frequency GNSS receiver. Using both the L1 and L5 signals, the Mi-8 achieved sub-meter accuracy in testing conducted by the European Space Agency.

- Survey accuracy requirements vary greatly by jurisdiction. For many applications, including rural boundary surveying, allowable errors are commonly measured by tenths of a meter.

- More stringent urban cadastral surveying standards may require centimeter-level accuracy.

## New Signals

As we have detailed before,[12] the declining cost of high-accuracy location capabilities is the result of several concurrent developments. One is the availability of new satellite constellations broadcasting new, open satellite navigation signals, notably the L5/E5 signals broadcast by Galileo and the new GPS Block IIF and Block III satellites. Progress has been rapid. On October 12, 2018, four new Galileo satellites went online.[13] On November 1, the sixth of ten advanced navigation payloads was delivered for integration into forthcoming GPS III satellites. In its 2018 *GNSS User Technology Report*, the European Global Navigation Satellite Systems Agency (GSA) wrote that all of the major navigation constellations will reach full operational capability in the next five years.[14] In layman's terms, in five years or less the globe will be covered by two different frequencies of free and open signal. Multi-constellation receivers using Russia's GLONASS and China's BeiDou satellites in addition to GPS and Galileo could eventually have access to more than 100 satellites.[15] New satellite-based augmentation networks are also being deployed to improve the accuracy of location services:

> The coming years will see two new GNSS (Galileo and BeiDou), and two RNSS (QZSS and NavIC), reach full operational capability. In parallel, the modernisation of existing GNSS (GPS and GLONASS) is also well underway. Thus, in just a few years there will be four global and three regional satellite navigation systems, and more than 100 satellites providing open access to more accurate and reliable PNT services, including through the use of multiple frequencies. Public augmentation systems, such as EGNOS, are also evolving to become multi-constellation and multi-frequency.[16]

These augmentation systems supply correction data needed to cancel out positioning errors, improving receiver accuracy to decimeter or centimeter levels. A particularly interesting augmentation method for our purposes is Precise Point Positioning (PPP).[17] PPP systems allow dual- and multi-frequency receivers to achieve centimeter-level accuracy anywhere on the globe. The correction data can be supplied via satellite, meaning that this accuracy can be achieved without using differential techniques that require a second receiver and a communications channel. PPP is for the most part only available on a subscription basis, but there is increasing recognition of the value of making it accessible as a public, global utility. Japan's QZSS constellation includes experimental sub-meter and centimeter-level PPP signals for East Asia and Oceania,[18] and the EU is exploring upgrading its EGNOS augmentation system to support centimeter-level accuracy using the L1/E1 and L5/E5 signals.[19] The International GNSS Service (IGS) launched a free, real-time global PPP service in 2013, streaming dual-frequency GPS corrections over the internet.[20] This service allows sub-decimeter accuracy, but requires special firmware and only supports the GPS constellation.[21] Open access to PPP for all satellites would be a huge gain for the developing world, where the infrastructure required for other augmentation and correction systems is often lacking.[22]

## New Hardware

The most notable recent advance in hardware has been the appearance of cheap dual-frequency chips for mobile devices. In 2018, we saw the launch of the Xiaomi Mi-8, the first cell phone equipped with dual-frequency GNSS. The dual-frequency Broadcom BCM47755 chip in the Xiaomi was the first of its kind to market, though numerous other chip makers are expected to follow suit.[23]

We should emphasize that our predictions concerned the convergence of consumer devices towards survey-grade accuracy. Standards vary by jurisdiction, but rural parcels often require decimeter accuracy, and accuracy on the order of one to five centimeters is often needed to meet more stringent urban requirements. Accuracy depends on many factors beyond the dual-frequency receiver, including antenna quality, signal processing software, and satellite availability.

Initial consumer testing of the Xiaomi revealed mixed results. This is likely attributable to uneven regional coverage of the L5/E5 satellites. In its own comprehensive testing, the GSA achieved static accuracy of 0.78 meters, and this can be improved upon with augmentation techniques like Precise Point Positioning and Real-Time Kinematic positioning (RTK).[24] Broadcom claims to have successfully tested both RTK and PPP internally. Broadcom's results have not been made public,[25] but in May 2017 they provided a team of researchers from Trimble Inc. with a development kit for the dual-frequency BCM47755 chip found in the Mi-8.[26] The researchers tested the Broadcom chip against a professional survey-grade receiver and found that both were able to achieve centimeter-level accuracy when using RTK and a professional-grade antenna.[27] They were able to achieve similar results with the Broadcom chip and a cell-phone antenna, though with much longer convergence times. This was accomplished under ideal laboratory conditions, but their conclusion is nevertheless remarkable:

> By connecting this next-generation GNSS chipset to a GNSS antenna typical of a cellular device and comparing the performance from a precision GNSS antenna, we've shown for the first time that it is possible to produce precision positions from a static cellular class GNSS device in ideal conditions at the centimeter level with both an RTK solution and a PPP solution.[28]

## New Software

Since 2016, Google's Android—the operating system for 88 percent of the world's handheld devices, and even more in the developing world—has allowed access to raw navigation signal data, which is required for advanced signal processing techniques.[29] Supporting innovation in the Android ecosystem is a key part of the European Space Agency's (ESA) strategy for promoting "better location performance in mass market applications."[30] In 2017 ESA launched a Raw Measurements Task Force to "share knowledge and expertise on Android raw measurements and its use, including its potential for high accuracy positioning techniques."[31] The task force also organizes workshops, hackathons, and app development competitions.[32] A September 2018 GSA presentation outlines the "four main areas of use...enabled by GNSS raw measurements:"

- "**Scientific/R&D**: As the observations are provided in a much more coarse form they can be used for testing hardware and software solutions and for new post processing algorithms e.g. for modelling ionosphere or troposphere."
- "**Integrity/Robustness**: Access to raw measurements will offer new ways to detect RF interferences and to locate the interference source by combining the measurements from multiple devices (crowdsourcing), or verify the source (OS-NMA). SBAS corrections can be incorporated without the need for additional equipment."
- "**Increased Accuracy**: Subject to hardware limitations, access to raw measurements means a developer can employ advanced positioning techniques (RTK, PPP) and create a solution currently only available in professional receivers. It results in a technological push to develop new applications."

- "**Testing, performance monitoring, and education**: Raw measurements can be used for monitoring performance (data, accuracy, Rx clock), testing and to compare solution [sic] from single constellations, eliminate specific satellites or test for worst scenario performance. Education use for understanding GNSS, Signal [sic] processing or orbits in smartphone is not negligible too."[33]

It is difficult to overstate the R&D value of the Android raw measurements, especially in enabling mathematical signal processing advances which enhance location performance independently from the hardware. For example, a recent paper from the University of Otago in New Zealand demonstrated the potential for multi-constellation, single-frequency (L1) GNSS with RTK to compete with dual-frequency for accuracy:

> By combining signals from four different Global Navigation Satellite Systems (GNSSs), Otago's Dr Robert Odolinski and Curtin University colleague Prof Peter Teunissen, have demonstrated that it is possible to achieve centimeter(cm)-level precise positioning on a smartphone. "It's all down to the mathematics we applied to make the most of the relatively low-cost technology smartphones use to receive GNSS signals, combining data from American, Chinese, Japanese, and European GNSS. We believe this new capability will revolutionize applications that require cm-level positioning," Dr Odolinski says.[34]

The "smartphone implementation" tested here consisted of a DataGNSS D302-RTK receiver with a list price of $1199.[35] Because it used only one frequency it remains sensitive to ionospheric interference. More importantly, multipath interference mitigation is inherently better with the L5 and E5 signals, which is critical in urban areas and places with heavy tree cover. But solutions like this, which leverage a profusion of signals to cancel out errors and mitigate the limitations of consumer grade antennas, could become even more powerful when used to enhance cheap dual-frequency receivers.

## Spatial Collective in Kenya

Where do we stand going into 2019? What do these advancements mean for community land mapping? In a previous article,[36] we covered the MAST mobile mapping app used by USAID to record communal land rights in Africa beginning in 2014. Now we present a more recent example. In 2017, Spatial Collective conducted a study to assess whether current mobile GNSS technologies and community mapping techniques could meet surveying standards in Kenya. Their methodology, reproduced from their report *Putting Community and Rights on the Map in Southern Kenya*, is below.

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**→ BOX 1**

**Methodology of Spatial Collective Initiative in Kenya**

From *Putting Community and Rights on the Map in Southern Kenya*[37]

- The idea of communities demarcating their own land is predicated on a series of assumptions:
  - Cheap and widely available tools that can be used for land demarcation exist.
  - These tools can reach the demarcation threshold required by the Kenyan government in terms of accuracy and attribution.
  - The communities, using these tools, can replicate the work of a professional surveyor.
- To test these assumptions, we conducted a series of experiments in Taita Hills, Taita Taveta County:
  - We examined the process of demarcating land both for new grants and for subdivision of land. Specifically, we focused on the accuracy and attribution of spatial data required by the professional surveyor and government offices.
  - We tested a series of affordable and ubiquitous technologies for capture and demarcation of land to see whether they achieve the thresholds required. We tested these tools under varying

environmental conditions to see how they affect the measurements.

- Finally, we assessed whether communities can replicate the demarcation of land by the professional surveyor using these tools.

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## Their Findings

Spatial Collective found that current mobile devices were not accurate enough to meet the three to four centimeter survey requirements for demarcation of fixed boundaries, but were able to meet the much less stringent requirements (up to three meters) for general boundaries in rural surveying. They also found that the field performance of the smartphones they tested was not constrained by network availability. Access to mobile data had no impact on accuracy, while environmental factors like tree cover had a major impact.

The handheld Bad Elf and Garmin GPS units were far more accurate than the mobile phones, but as single-purpose devices they did not share the phones' usefulness in gathering attribute and ownership data. The same can be said of any single-purpose device, even the $30,000 Leica survey receiver used as a control.

The report emphasizes that community mapping is not just about geospatial data. Additional information must be gathered (e.g. to tie occupants to properties and demonstrate agreement over boundaries). Processes might include taking photos or videos of neighbors agreeing to a boundary between their properties, or filling out and storing digital forms. Smartphones, increasingly prevalent in the developing world, are the best candidate for an accessible, low-cost platform to perform all of these functions. The report identifies bottlenecks and how they can be addressed using the affordable mapping tools tests, which are reproduced below.

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**→ BOX 2**

**Bottlenecks and Related Solutions from Spatial Collective Initiative in Kenya**

From *Putting Community and Rights on the Map in Southern Kenya*[38]

**1) Lack of affordable tools**.

The tools are widely available, affordable, and easy to use by communities.

**2) Local communities have no access to information.**

With these tools, information can be easily collected, stored and shared.

**3) Local communities are not able to value their land.**

Applications can be built to streamline the valuation of land based on the data input.

**4) The registration process is unclear or unknown to the communities.**

The tools can be used for information sharing.

**5) The relationships between Kenyan national, community and individuals in terms of property rights is difficult for communities to comprehend.**

This is a systemic issue that the tools cannot address on their own.

**6) Antiquated procedures sustained through inertia in the titling process and an inability to explore, let alone adopt new technologies to replace old methods.**

This is still an issue in Kenya, however, the tools provide for an excellent alternative to the current system of paper based data storing, etc.

**7) Technical tools used to capture vital information on mapping are often too expensive, difficult to operate, rely solely on connectivity, and require extensive training/maintenance and complex processing solutions. In some cases the skills needed to record information accurately often built up over many years of experience including formal qualifications**.

Training is relatively simple and most processes repeatable to a satisfactory standard, and the possibility of having units available at sub-county level that can be rented out to communities makes it cost effective and affordable.

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Several of these bottlenecks (1, 6, and 7) can be addressed directly by high-accuracy GNSS smartphones. For others (2 and 4), smartphones can help to improve information access and sharing, though this is dependent to a great extent on the degree of device ownership and network connectivity. Systemic and legal obstacles remain and, as the report notes, are issues that "tools cannot address on their own."[39]

The greatest missing element which has prevented a single-device solution for geospatial and attribute data collection is GNSS accuracy. Adding this capability to smartphones can help consolidate both device functions and data collection roles. Trusted members of the community will be able to gather geospatial and attribute data. The collection of this attribute data introduces privacy concerns, especially when it comes to storage and sharing. Fortunately, with the right software, smartphones also provide a platform for secure data handling. Once high-accuracy GNSS becomes standard in smartphones, they will become the best tool for most mapping applications.

## Spoofing, Proof of Location, and Trusted Data

Even if we assume that dual-frequency phones augmented with PPP or RTK will solve the location accuracy problem in the near future, the integrity and provenance of community mapping data, both geospatial and attribute, will remain a serious concern. Indeed, as the latest *GNSS User Technology Report* points out, "high accuracy is not the endgame, but rather 'trusted and resilient' high accuracy remains the ultimate goal."[40]

Many of the new, safety-critical uses for high-accuracy GNSS, most notably aviation and autonomous vehicles, have drawn attention to the possibility of spoofing attacks, in which false signals are generated to disrupt or mislead receivers. Once thought to be prohibitively complex and expensive for any but the most sophisticated actors to execute, successful spoofing attacks were demonstrated in 2012 against targets including drones and ships using hardware that cost only $2,000.[41] In 2018, we saw that fake signals can be broadcast using a software-defined radio and a $5 USB to VGA display adapter.[42]

The use of multiple frequencies and constellations makes spoofing inherently more difficult because more false signals have to be generated at different frequencies. But additional steps must be taken to harden receivers against spoofing. Galileo is working to incorporate a cryptographic message authentication system into its signals, and GPS is considering doing the same.[43] Galileo's version is expected to be fully operational by 2020.[44] There are a number of other hardware and software tools for combating spoofing. Some types of antennas can detect the direction from which a signal originates, allowing spoofed signals (which tend to originate from one location) to be identified and discarded. Other techniques involve measuring qualities of the signals, including signal power and the doppler shift caused by the motion of the satellite.[45] These require access to the raw satellite tracking data.[46]

But spoofing is not a major concern with community mapping. It remains quite difficult to do, especially when directed against multiple receivers, and would be easy to detect when coordinates were overlaid with the base map. Perhaps most importantly, there would be very little incentive for a bad actor to do it in the first place.

There is a much greater risk of mappers submitting falsified data. This is especially true if crowdsourced data collection is done remotely and is driven by economic incentives. There are already several examples of location-based services being manipulated by users faking their GNSS coordinates in order to cheat at games like Pokémon Go or earn cryptocurrency for participating in crowdsourced mapping projects.[47] In the future there will be many more services that require verified location data, including autonomous transportation, supply chain tracking, usage-based insurance, and location-based access control.

## There is a much greater risk of mappers submitting falsified data.

Defenses against spoofing address the trustworthiness of the signals received, not of the receiver. Proof of location addresses a very different problem: how can a third party authenticate location data from an untrusted receiver?

There are several approaches to this problem. One would be to create an aggregated proof of location, cross-checking GNSS data against input from a number of other sensors in the phone, like the inertial measurement unit and barometer, in addition to network-based location information from Wi-Fi and cell networks. Apps like Truepic already do this to verify the authenticity of photographs for their clients, including insurance companies.[48] An obvious drawback to this solution is the reliance on network access, though it would also be possible to store the data on the user's device in such a way that it would be extremely difficult to tamper with it. This could be accomplished with a Trusted Computing architecture in which the data is signed and encrypted by a secure chip attached to the device CPU.[49]

Another solution would be to incorporate a proof of location method into the GNSS signal itself. For example, one proposed system for "Pretty Good Proof of Location"[50] would be to encrypt the navigation signal and have the satellite send the encryption key after a small time delay, perhaps five minutes. The receiver would be able to store the raw data or stream it to a third party, who could decode it upon publication of the key. The forger would be unable to forge the raw data without knowing the key beforehand.[51]

Even in the absence of these technical solutions, community mapping is inherently resistant to forgery of location data because it is a group activity in which claims are made and validated collectively. For community boundary surveys, trained community members supervise the collection of GNSS data, and it is validated against a base map with identifiable landmarks, like trees, fences, and buildings. Moreover, the boundaries of the demarcated plots are reviewed and agreed to by the owners of adjacent plots. This leaves very little room for falsification or manipulation of coordinates.

→ **BOX 3**

**Basic Stages of a Community Land Mapping Program**[52]

1. **Community Planning Meeting:** A meeting with the whole community to explain the purpose and objectives of a land mapping program and to start a discussion with all parties. This should be a public meeting, welcoming everyone, and should be well advertised in advance.

2. **Community Rough Mapping:** The team does a rough map. Rough mapping is a process that records a community's geographic, social and economic features. It can also be a useful tool for identifying specific issues that affect a community.

3. **Land mapping team selection:** Mapping teams are appointed and allocated to each area. Teams should be representative of the community or area that is to be mapped.

4. **Planning and training:** The teams are trained. They learn what is to be mapped and consider the challenges that data collection will raise.

5. **Questionnaire/survey design:** After the rough mapping, a working group identifies key areas where quantitative data would be useful.

6. **Launch:** The program is launched at a public meeting, the results of the rough mapping are shared and a detailed plan and schedule for household mapping agreed.

7. **Survey:** The mapping team goes house to house with questionnaires, explain what the survey is for, and measures plots and house sizes.

8. **Verification:** The data is checked for standardization, any errors or omissions. Incomplete or disputed information may need to be recollected.

9. **Group Discussions:** The information is shared with the whole community at fully inclusive public meetings and smaller group discussions.

10. **Creation of Public Awareness.**

That brings us to the related question of recording attestations between community members. Our recent research into self-sovereign identity provides a possible answer, one that is conveniently amenable to use with smartphones. Self-sovereign identity (SSI) uses cryptography to give individuals a secure digital identity under their control, paired with a platform for storing and sharing verifiable, digitally signed data. This is critical for recording attestations in a way that is secure and easily tracked and audited.

Current community mapping apps can upload scans of signed paper documents and record videos of neighbors agreeing on property boundaries. Video is much harder to fake than a signature, and therefore harder to repudiate. But while it might provide stronger evidence in court, the use of video creates a number of problems. Video files are large and take up a lot of storage capacity. Moreover, they are hard to check. How do you verify the identities of the people in the video? And validating the interaction requires a human to sit down and watch it. By contrast, SSI uses cryptographic signatures to record agreements and attestations in a way that is both secure and easy to validate. Signatures can be indelibly linked to a single digital identity, or even to a natural person using biometry.

SSI architecture can also allow communities to organize themselves and determine group membership. When documenting the claims of a given indigenous community, for example, it might be necessary to know who is and is not a member. In many cases that determination is best made by the community itself rather than by outsiders, for example a foreign NGO organizing the mapping. The community could instead issue membership credentials to its members who could present them to the NGO as necessary.

Finally, SSI can provide a critical infrastructure component for connection to a variety of services, for example subsidies. The SSI firm Everest has partnered with the Government of Indonesia to distribute liquefied petroleum gas subsidies to digital wallets linked to self-sovereign identities.[53] Similarly, a digital credential issued and signed by the land registry could be used to establish entitlement to agricultural subsidies, which could even be delivered to the farmer's digital wallet. SSI can also incorporate a messaging system. If integrated into a digital registry this could be used combat fraud, sending automated notifications to property owners whenever a transfer of their land is initiated or when it is used as collateral for a loan. (For more on SSI and land registries, see the Future of Property Rights report ***The Nail Finds a Hammer: Self-Sovereign Identity, Design Principles, and Property Rights in the Developing World***.)

## Going Forward

The apparent infeasibility of attaining legal survey accuracy standards with community mapping has led many in the development community to argue that the best solution is for survey standards to be relaxed. But once mobile accuracy in the field can meet those standards, the conversation will shift towards persuading governments to trust community mapping data. And it should be an easy argument to make. Many governments make the formalization of land rights a priority in their development agendas but cannot afford to carry it out. This is largely because of the need to go out and collect all of the relevant geospatial and attribute data. The alternative that is emerging might look something like the TurboTax model, where the individual taxpayer combines data from various sources, some self-reported and some imported from his or her employer, and submits it electronically to a government database for processing. This new paradigm is becoming possible, thanks primarily to the advent of high-accuracy consumer positioning technology and digital identity systems capable of managing trusted, auditable data. Governments will have the opportunity to relinquish the burden of data collection and take on the role of validator and auditor.

# Appendix: Background Research for This Report

*The following appendices consist of lightly edited earlier writing related to the report. In addition to providing greater detail on the evolution of GNSS and mobile mapping, these articles introduce and explore in simple terms the technical concepts referenced in the report.*

*The pieces are the following:*

- "Peering into the Future: How Dual-Frequency Receivers Will Democratize Land Surveying," by Michael Graglia and Christopher Mellon (March 23, 2017).
- "The Price of Precision: How Autonomous Vehicles Will Drive Down the Cost of Dual-Frequency Receivers," by Michael Graglia and Christopher Mellon (June 20, 2017).
- "A Mobile Application to Secure Land Tenure," by Michael Graglia and Christopher Mellon (August 3, 2017).
- "Arrival of the Future: Dual Frequency Satellite Receivers, Smartphones, and Property Rights," by Christopher Mellon (July 10, 2018).

## Peering into the Future: How Dual-Frequency Satellite Receivers Will Democratize Land Surveying

*By Michael Graglia and Christopher Mellon*

*This post originally appeared in the Future of Property Rights blog **here**.*

March 23, 2017

### Drawing Lines

Across the developing world nearly a billion people live without legal title to their land. In order to formalize this property, governments need to issue deeds and create registries in which to record them. But unlike other types of property, parcels of land cannot be registered until they have been defined. Delineating one person's property from another's is a serious technical challenge and a prerequisite for granting secure legal titles.

Precise surveying is expensive, requiring specialized equipment operated by professional surveyors. This means that precision is often inaccessible to people in the marginalized populations who most require it.

When professional surveyors are asked to compromise on price, the accuracy of the service they provide also becomes subject to compromise. Walter Volkmann, a third-generation land surveyor and president of Micro Aerial Projects L.L.C.,[54] saw firsthand how one such negotiation combined with the politics of apartheid to jeopardize formalization efforts in Namibia in the 1980s:

> In the late 1970s South Africa decided to no longer rule Namibia, formerly known as South West Africa, as a fifth South African province. Instead it began to follow a policy in terms of which Namibia would gradually be granted administrative autonomy until it would ultimately gain full independence from South Africa. In 1978 the first "one man, one vote" elections were held. Although boycotted by SWAPO, a major anti-apartheid movement, the newly elected "Government of National Unity" decided to extend the right to formally own land in the then racially segregated urban areas to all people, irrespective of skin color. For this purpose, the so-called "locations," townships which were developed and reserved exclusively for the housing of non-white citizens under South African apartheid policy, had to be surveyed and registered in the Deeds Registry. My entry into the land surveying profession fell into that period in the early 1980s when the large volume cadastral surveys of the so-called "locations" were being rolled out. While the small number of professional land surveyors were welcoming this sudden abundance of work, the government was of course facing the challenge of funding these surveys. And, as so often happens when budgets are being discussed for survey work, an attempt was made to negotiate a reduction in fees in exchange for a relaxation in the prescribed accuracy standards. Given the prevailing technology at that time, accuracy standards were indeed a legitimate factor in the cost of cadastral surveying. One could argue that lower fees would result in the survey of a larger number of properties and thereby facilitate formal ownership for more people than would otherwise have been the case. However, this would result in the absurd reality that although formal ownership of land would be made possible for all citizens irrespective of race, an ugly residual of racial prejudice would remain: your skin color would determine the accuracy to which your property was surveyed and thus the security of your title. In the end both parties agreed on reduced fees for the survey of formerly "black townships" without compromising accuracy standards. Although the introduction of the term "black township" in the text of the cadastral survey legislation is not exactly indiscriminate, it certainly is less detrimental and offensive than granting inferior security of title to formerly disadvantaged citizens. And, rather happily, the discriminatory language has long since vanished from the regulatory texts as now all formal townships in

> Namibia enjoy a homogeneous standard of accuracy and hence security of title.[55]

Subsequent advances in global navigation satellite system (GNSS) technology[56] have weakened the correlation between precision and cost, but survey-grade accuracy is not yet widely and cheaply available.

Widespread access to this level of accuracy is critical for formalization efforts because expense is not the only problem with depending on professional surveyors to document the world's informal property. There is a more fundamental problem of scale. A significant percentage of all land in the developing world is informally owned. There is simply not enough time for professional surveyors to register it all.

According to the Cadasta Foundation, there are fewer than two professional surveyors per 10,000 square kilometers of land in the Ivory Coast and Tanzania, compared to 41 per 10,000 square kilometers in the United States.[57]

There were only 74 registered land surveyors in Uganda in 2015[58] and an estimated 15 million parcels of informally owned land. With more than 200,000 parcels per registered surveyor, Cadasta calculates that it would take them over a thousand years to finish the job.[59]

When everyone has access to survey-grade precision, formalization efforts can be expanded and accelerated. With the advent of relatively cheap, dual-frequency satellite receivers, this may soon become possible.

**Dual-Frequency Receivers**[60]

Position measurements using a single frequency are vulnerable to interference and accurate, at best, to about five meters.[61] This is fine for most people's daily use, and in developed areas Wi-Fi signals can be used to augment accuracy. All smartphones, for example, use single-frequency receivers. But errors on the scale of meters are not good enough for survey work, which should be accurate to the one to ten centimeter range, depending on local standards and the type of survey.

By making use of a second signal frequency, dual-frequency receivers can correct for delays caused by the ionosphere, which are the greatest single contributor to inaccuracy.[62] Using a second frequency also provides greater signal redundancy, allowing for better error-correction and improved satellite availability in tree cover and urban canyons. With error-checking algorithms that can identify faulty satellite signals, dual-frequency receivers produce measurements that are not only accurate but trustworthy. This last property is important when it comes to registering land, as it allows the authorities validating title claims to have confidence in the integrity of the data they are given. Dual-frequency receivers also resolve positions more quickly than single-frequency receivers, so the surveyor does not have to wait as long on a reference point acquiring multiple satellites.

Using free, open-source signal processing software,[63] dual-frequency receivers can achieve survey-grade accuracy. The downside of dual-frequency receivers is the cost of the hardware. In 2013, a $2,500 dual-frequency receiver could be described as "incredibly inexpensive."[64]

Two things need to happen in order for hardware prices to continue to drop: the deployment of large numbers of satellites operating civilian signals on at least two different frequencies, and a large, competitive market for survey-grade receivers. It appears that both of these conditions will be met in the near future.

**Open Signals**

When the U.S. launched the first navigational satellite constellation, GPS, it broadcast signals on two main frequencies. The first signal, called L1 (1575.42 MHz), was intentionally degraded, limiting the accuracy of the single-frequency receivers that used it to around 100 meters.[65] The second signal, L2 (1227.60MHz), was available only to authorized users, like the U.S. military, who were issued encryption keys. This policy prevented civilians and foreign governments alike from getting precise GPS coordinates without ground-based augmentation systems. This policy was eventually reversed,[66] but not before a few civilian companies figured out how to use the L2 signal without an encryption key and patented the techniques.[67] Until a second civilian signal becomes available to replace L2, these patents will continue to restrict competition in the development of dual-frequency receivers.

In 2013 the governments of the United States and the United Kingdom announced their commitment to "ensuring that GPS civil signals will remain perpetually free and openly available for users worldwide," agreeing to place all technical information and intellectual property relating to civil GPS signals in the public domain.[68] Manufacturers will be able to patent specific receiver designs, but not techniques needed to track the signals themselves, like the patents filed on the L2 signal. A U.S. Department of State document from September 2013 notes that this commitment to open signals is intended in part to promote "open, market-driven competition" and "equal access for user equipment manufacturing."[69]

One of these new, open signals, the L5 (1176.45 MHz) signal,[70] is the best candidate to replace L2 for dual-frequency use. L5 is the most advanced civilian signal, designed for "safety-of-life transportation and other high-performance applications."[71] An open GPS signal called L2C (1227 MHz) is being introduced to replace the L2 signal, but it will be used by fewer satellites and the U.S. government may not continue to support it once the L5 constellation is complete.[72] Survey-grade receivers need to be able to see at least eight satellites to function optimally, making the L5 signal, which is more powerful than L2C and will be used by multiple satellite constellations, a better option.[73] A modernized American GPS constellation broadcasting both L1 and L5 from its newer Block IIF and Block III satellites is scheduled to be completed by 2024. The European Union's Galileo constellation is deploying satellites with the interoperable E5 signal, meaning that a full complement of 24 L5/E5 satellites will be available before either constellation is completed individually. Multi-constellation receivers that can also use Russia's GLONASS and China's BeiDou satellites in addition to GPS and Galileo could eventually have access to more than 100 satellites.[74]

### New Markets

Recent technological advances are creating huge new markets for accurate GNSS receivers.

Autonomous vehicles, from tractors[75] to taxis,[76] are poised for massive growth[77] and will require more accurate and reliable GNSS receivers for both functionality and safety purposes.[78] Single-frequency receivers can also achieve very high accuracy with augmentation, but the inherent accuracy and integrity offered by dual-frequency receivers makes them more attractive for safety applications.

Aerial drones,[79] used for everything from oil and gas exploration to grocery delivery,[80] will benefit from increased accuracy in vertical positioning.

Commercial aircraft will be able to use dual-frequency L1/L5 receivers for navigation and safety-of-life applications.[81]

The average smartphone user will appreciate more accurate location services for navigation, fitness apps, even virtual reality.[82]

Manufacturers are already developing dual-frequency receivers for these markets. Broadcom, for example, which manufactures GNSS chips for smartphone giants like Apple and Samsung, revealed in 2016 that it was testing a dual-frequency chip for cell phones.[83]

### Future Developments

Survey-grade GNSS receivers will continue to shrink, become cheaper, and may eventually be digitized altogether. A software-defined receiver (SDR) like the Trimble Catalyst[84] can transform an Android phone into a dual-frequency receiver with a software download and a plug-in antenna. The Catalyst requires a monthly subscription to Trimble's augmentation services and accuracy is pay-as-you-go, with meter accuracy priced at $40 per month, and centimeter precision at $350 per month.[85]

But devices with open-source SDR and post-processing software could reduce the total user cost to the price of the antenna. As long as it had enough processing power, an SDR device could be updated to support additional constellations and signals without any hardware development costs.

Antennas for surveying receivers currently cost a few hundred dollars and are fairly large. They must be shielded from reflected signals, especially those bouncing off the ground, and usually have a plate around ten centimeters in diameter built into the bottom of the antenna.

New methods of compensating mathematically for these reflected signals promise survey-grade precision with antennas small enough to fit in a smartphone.[86] A team at the University of Texas, working with Samsung, is using these techniques to achieve centimeter precision with $5 antennas similar to those currently found in smartphones. They estimate that their system, consisting of an SDR and antenna, will "eventually cost less than $50."[87]

The hardware component of the Trimble Catalyst, introduced in November 2016,[88] costs $350,[89] seven times less than the "incredibly inexpensive" X90-OPUS introduced in 2013. With increased competition among manufacturers and increased demand, prices will only continue to drop. It is hard to predict how far, but the fact that a major chip-maker like Broadcom is experimenting with dual-frequency chips in cellphones is telling. Apple is unlikely to accept adding hundreds of dollars to the price of an iPhone for a dual-frequency receiver and antenna.

### What Will This Mean for the Various Stakeholders in Property Formalization Efforts?

**For governments and aid agencies**, it will be easier and cheaper to organize large-scale formalization efforts when surveying is decentralized and pushed down to the local level. The government's focus will move to providing the legal staff and registry system needed to validate and record property claims.

Crowd-sourced surveying will allow more property to be registered more quickly. The more complete a land registry is, the more useful it is to government officials managing land use, natural resources, and public utilities.

**NGOs** will also be able to expand their formalization programs thanks to reduced equipment and personnel costs. As data collection becomes easier and cheaper, they may dedicate more resources to addressing governance issues and bureaucratic obstacles that threaten to negate the positive effects of formalization.

**Occupants** will benefit the most from the democratization of surveying. In areas where the nature of customary ownership or usage does not translate easily into a formal cadastral system (as with shared lands with communal rights or lands used by different parties according to an annual cycle) land use arrangements decided at the local level are preferable.

Cheaper surveying should allow for the reduction of property registration fees, which currently discourage many small landowners from participating in formalization programs. According to the World Bank, registering property in sub-Saharan Africa costs, on average, eight percent of the value of the registered property.[90]

**For professional surveyors**, documenting informal property is time-consuming and not especially profitable. When the task of data collection is crowdsourced, they will be free to focus on more demanding work which requires expertise in managing and analyzing geospatial data. This will include designing and supervising crowdsourced data collection projects.

## The Price of Precision: How Autonomous Vehicles Will Drive Down the Cost of Dual-Frequency Satellite Receivers

*By Michael Graglia and Christopher Mellon*

*This post originally appeared in the Future of Property Rights blog **here**.*

June 20, 2017

*Executive Summary: Investment in autonomous vehicles will reduce the cost of dual-frequency GNSS receivers by a factor of ten within the next five years.*

In a previous article[91] we argued that the price of dual-frequency satellite receivers is poised to fall precipitously with the advent of new satellite navigation signals and new markets. We discussed the dynamics driving this process and its implications for the democratization of land surveying, but we did not quantify this price reduction or say when these new, cheaper devices would be available. In this article we address those questions in detail by looking at the projections that government agencies, think tanks, and market analysts have made regarding the development of dual-frequency satellite receivers for the transportation market. There is a widespread expectation that autonomous vehicles will become the first mass market application for dual-frequency GNSS receivers. The vehicle market is best positioned to adopt this technology both because it has the most pressing need and because it is not limited by the energy consumption, processing power, and miniaturization concerns that restrict the use of dual-frequency in drones, wearables, and cell phones. We anticipate that the mass production of dual-frequency receivers for the vehicle market will reduce their price by a factor of ten within the next five years.

### The Race Towards Automation

There is no consensus on when fully autonomous vehicles will become common. A May 2017 report from the independent technology think tank RethinkX, entitled *Rethinking Transportation 2020-2030*, projects an exponential adoption curve that will result in 95 percent of U.S. passenger miles being served by on-demand autonomous vehicles by 2030.[92] Their conclusion, premised on economic feedback loops making individually owned cars prohibitively expensive compared to Transportation-as-a-Service,[93] is far more optimistic than most other estimates.[94] Market reports from business consultancies, while more cautious, still project rapid growth. PwC said in its *Connected Car Study 2015* that "fully autonomous long-range driving at highway speeds [is] expected between 2020 and 2025."[95] McKinsey's *Automotive revolution - perspective towards 2030*, concludes that anywhere between 15 and 50 percent of cars will be highly autonomous in 2030, depending on the degree of market disruption.[96]

Car manufacturers, tech companies, and ride-sharing services such as General Motors, Renault-Nissan, Daimler, Volkswagen,[97] Waymo,[98] and Tesla[99] are all working towards fully autonomous vehicles. Uber[100] and Ford[101] have announced plans to put highly or fully autonomous cars on the road in high volume by 2021. As a result, enabling technologies are receiving significant levels of investment, both because they improve human-driven connected cars and because they are a prerequisite for autonomous vehicles.[102]

This is particularly true of technologies like dual-frequency GNSS that increase safety. In the words of Craig Giffi, leader of Deloitte LLP's U.S. automotive practice: "to win consumers' trust, automakers will need to integrate limited self-driving and advanced safety features into new product offerings steadily over time to introduce people to the technology, demonstrate the improvement in vehicle safety and develop a proven track record." Autonomy is simultaneously appealing and frightening to consumers, who are enthusiastic about the potential of Transportation-as-a-Service to reduce travel costs, pollution, and urban congestion, but will be reluctant to adopt it until they are absolutely convinced it is safe.[103] Autonomous vehicles have the potential to greatly reduce road fatalities, but consumers fear the loss of control and are likely to judge them by a more critical standard than human-operated vehicles.[104] More people are afraid of commercial air travel than of driving despite the fact that flying is statistically much safer.[105] The confidence of regulators and investors is as critical as the confidence of potential users. PwC notes that in the scramble to control the emerging connected and autonomous car market, "no one will win…if security concerns undermine consumers' trust in connected car technology."[106]

### Why is Dual-Frequency Important for Autonomous Vehicle Safety?

Unlike the current generation of in-dash and phone-based car navigation systems, which only use a single frequency, GNSS systems used for autonomous vehicle navigation must employ at least two frequencies to achieve the highest safety standards, which mandate higher accuracy and signal integrity than single-frequency can provide. As the European GNSS Agency noted succinctly in its *2016 GNSS User Technology Report*: “For safety-critical applications, where redundancy and resistance to jamming is important, dual-frequency (L1/E1 + L5/E5) is undoubtedly the best choice.”[107] The greater integrity[108] possible with dual-frequency allows a navigation system to detect when the navigation signal includes errors outside of a given confidence range and take appropriate action. In most cases, this simply means excluding any faulty data from the position calculation.

Dual-frequency also allows for greater positional accuracy and, crucially, is much quicker to resolve “integer ambiguities” when it has to re-initialize because the signal is interrupted. This means that if a car goes through a tunnel or loses sight of satellites in an “urban canyon” it can re-establish an accurate position fix in a matter of seconds once the satellites are back in view. Since highly urban areas will be the primary market for autonomous vehicles, this is a serious advantage.

New augmented single-frequency receivers—more advanced versions of what you have in your car today—can match the positioning accuracy of dual-frequency receivers under certain conditions, but dual-frequency options are superior because of their greater integrity and the fact that they are not dependent on augmentation from a local network of ground-based reference stations.[109] As the 2017 GSA *GNSS Market Report* says, “It is clear that autonomous driving technology requires highly accurate position and navigation in all scenarios. This means 100 percent position availability at decimeter level or less, anywhere, anytime and under any condition.”[110] The report points out that this is only achievable through the integration of a variety of sensor types, but given the stringency of this requirement, the only reason for a manufacturer to prefer a single-frequency receiver would be the reduced cost.[111]

### Liability

Single-frequency receivers may be cheaper for autonomous vehicle manufacturers in the short term, but skimping on safety-critical technology could be a serious risk. A 2017 Mobile World Live survey found that “only 5.5% of respondents felt the vehicle owner was liable for connected car security, suggesting that security will continue to be the responsibility of vendors and service providers rather than the users themselves.”[112] Every precaution will have to be taken to protect vehicle manufacturers and operators from liability and to protect user confidence in the safety of autonomous transportation services. Investors and adopters alike will be very sensitive to these concerns, and it will be well worth the additional investment in the safest guidance systems. GNSS will be a part of that investment, integrated into sensor packages including lidar, radar, and cameras.

The increased accuracy and integrity provided by precision GNSS will have important financial implications beyond consumer confidence and injury liability, as insurance and ride fees move to usage-based models.[113] Many other location-based services, including tolling, weather updates, traffic information, parking availability, and stolen vehicle recovery, also stand to benefit.

It must also be noted that autonomous and connected cars will provide a massive new target for cybercriminals to steal, hijack,[114] or crash by spoofing guidance signals.[115] Dual-frequency signals are harder to spoof than single-frequency and also more resistant to jamming and other interference. This is due in part to the increased complexity of simulating multiple signals and partly due to simple redundancy. Starting in 2018, the new European Galileo constellation will also help guard against spoofing by broadcasting an authentication signal on a separate frequency.[116]

**Price Reductions**

A 2016 market report from ABI Research, entitled *Low-Cost Precision GNSS Receivers*, estimates that dual-frequency receivers will be available for $50 per unit by 2021.[117] This is consistent with the recent trends in price reduction and mirrors the autonomous vehicle deployment timelines put forward by Uber and Ford. It is also consistent with the forecast of the GSA, which said in 2015 that it expected "low-cost, multi-frequency chipset/receivers to appear on the market in the next few years" driven by "automotive and other machine-to-machine applications."[118] Dual-frequency surveying units traditionally cost upwards of $5,000, but the new, more affordable receivers now available from companies like SwiftNav cost about $600.[119] Another roughly similar decrease to $50 seems plausible as dual-frequency receivers change from specialist, low-volume products to mass-produced car components.

There is no reason to believe that the price reductions will stop there. Many of the top chipset manufacturers are investing in dual-frequency systems for both mobile devices and wearables. Their biggest clients, cell phone manufacturers, are not interested in adding $50 to the cost of a phone for improved location services. One startup in Poland, ChipCraft, is developing a multi-constellation, dual-frequency system-on-a-chip with an integrated antenna that they project will cost only $10 per unit.[120] That project is a long way from completion, but it is a clear indication of the direction that receiver development is heading. As ABI principal analyst Patrick Connolly has said, "As the receivers' unit price drops below $50, we expect to see a market develop for location technology services, such as artificial reality and head-up displays in higher-end vehicles."[121] As the entry price for the adoption of the technology is lowered, more and more developers and users can be expected to embrace it for an increasing number of applications, including crowdsourced surveying.

### Implications for Surveying

In the next five to ten years there will be massive new scaling opportunities for organizations who crowdsource surveying. Together with already available open-source post-processing software,[122] $50 dual-frequency receivers would allow parcels to be surveyed with decimeter accuracy—even without any supporting augmentation infrastructure—for a fraction of the current equipment cost. Where satellite-based augmentation or geodetic control points are available, accuracy down to the one centimeter level will be possible.

The rapid initialization and signal acquisition of dual-frequency—which allow parcels to be surveyed more quickly—may be an even more important long-term advantage than reduced equipment costs, which are amortized over long periods when surveying at scale. The speed of surveying can be further enhanced with the use of unmanned aerial vehicles. Drones equipped with cameras and dual-frequency receivers can rapidly create maps of land parcels. The V-Map system, from Micro Aerial Projects L.L.C., uses a dual-frequency receiver to record the drone's location each time the onboard camera takes a picture.[123] Linking 2D images to precise GPS coordinates enables the system to use a technique called "Structure from Motion"[124] to create a detailed 3D map of the surveyed area without the use of ground control points. In March 2017, V-Map receivers were certified to meet the international accuracy standards for first order geodetic control positioning by the National Mapping and Resource Information Authority of the Philippines.[125] (Full disclosure: Walter Volkmann, the President of Micro Aerial Projects L.L.C., served as a technical advisor for this article.)

Crowdsourced surveying is already being conducted in some areas. Through funding from the United States Agency for International Development, citizens of rural African nations are using the Mobile Application to Secure Tenure (MAST) smartphone application[126] to record formal land holdings.[127] MAST was launched in Tanzania in 2015, expanded to Zambia in 2016, and is being rolled out in Burkina Faso. MAST uses GPS in existing cellphones that is only accurate to a few meters, supplementing this GPS data with satellite imagery. Once dual-frequency receivers are widely affordable, programs like MAST will become feasible in countries, like Jamaica, where there is a legal requirement for higher accuracy, as well as in urban and peri-urban settings where greater property density and property value demand increased accuracy and resistance to interference.

Even as hardware costs are reduced, challenges to property rights formalization will remain. It will still be resource intensive and regulations must evolve to allow for these technologies. Governments must be convinced of the trustworthiness of crowdsourced survey data. In most jurisdictions, laws require that surveying is conducted only by licensed surveyors. Crowdsourced data cannot be used to register land no matter how accurate it is. We believe, however, that as the quality of crowdsourced data converges with professional survey standards these policies will change despite resistance from entrenched interests. When trust can be placed in the integrity of the data rather than that of the operator, the argument for restricting surveying services to licensed professionals will be weakened significantly.

More accurate surveys will also help avoid problems down the line when the formalized land is bought, sold, or inherited. When conflicts arise between owners who were not party to the original, mutually-recognized boundaries, inaccurately surveyed land can lead to costly disputes. In such cases, there would be a real risk of deformalization. If a land title is less secure it is less valuable, and there is less incentive to keep an insecure parcel registered.

As we previously noted, there are not enough professional surveyors in developing countries to help formalize all the land that needs attention. Only crowdsourced surveying, enabled by tools like dual-frequency receivers and programs like MAST, can bring about significant progress. The potentially transformative impact of these technologies is hard to overstate, and increasingly hard to overlook. The GSA's May 2017 summary of emerging trends in the GNSS surveying market begins simply: "falling device prices drive the democratization of mapping."[128]

## A Mobile Application to Secure Land Tenure

*By Michael Graglia and Christopher Mellon*

*This post originally appeared in the Future of Property Rights blog **here**.*

August 3, 2017

The Future of Property Rights initiative believes that property rights matter and that technology can play a critical role in helping countries accelerate the pace of property rights formalization while simultaneously reducing costs.[129]

We analyze multiple technologies, looking at the tools that are currently in use, the established technologies that could replace them, and the emerging technologies we believe will be used in the future.[130] We are in the process of doing this for each essential task—from mapping to database management—required for property rights formalization and land administration.

For the task of demarcating informal lands, for example, the prevalent solution is to contract professional surveyors who use expensive tools. A widely available and more cost effective technology which could be used instead is a GPS-enabled smartphone coupled with cloud-based data processing, and the technology we can see improving land demarcation in the immediate future is dual-band GPS,[131] paired with either smartphones or drones[132] to create ortho-maps.[133]

Cadasta illustrates the inadequacy of professional surveying for property formalization in emerging economies with a compelling infographic.[134] They argue that given the scarcity of professional surveyors in the developing world, "documenting land rights through traditional methods [surveying] will take generations." In Uganda, for example, they estimate that it would take the country's "few dozen" surveyors a millennium to survey the "estimated 15 million parcels of unregistered land." They go on to point out that Tanzania only has 1.9 surveyors per 10,000 square kilometers compared to 26 in Norway, and 41 in America.[135] It is fair to assume that wealthy, developed countries like Norway and the U.S. have significantly less informal land. So how can countries like Uganda catch up?

**There's an App for That**

As smartphones have become ubiquitous over the last decade, an ecosystem of mobile data collection apps has emerged, making the prospect of cheap, crowdsourced data collection more feasible than ever before. Most of these apps have been aimed at users in the developed world, where the use cases impose very different cost and accessibility requirements. An app that only runs on a late-model iPhone, for example, would be unsuitable for community mapping in the developing world no matter its functionality.

In her 2016 Master's thesis, "An app for land administration: criteria, functional requirements and a prototype in Ethiopia," Julinda Dyli of the University of Twente examined 30 of these apps for their suitability for community mapping. The two fundamental requirements she identified were that the apps must be "designed to support poor people and communities" (pro-poor) and "designed to support management of land administration systems" (fit-for-use).[136] Dyli breaks these two requirements down into sixteen criteria.[137] Many of these overlap, and for the sake of simplicity we will distill them down to four broad criteria:

**1) Affordability**

The app must be free or very inexpensive. If the purchase price or subscription fee is high, or if the app can only be run on an expensive phone, then it will not be suitable for community mapping.

**2) Accessibility**

The app must be simple and intuitive to use for people with limited education and literacy. If it is too complex to operate it will not fit into the sort of collaborative, inclusive methodology that is best able to guarantee fairness and transparency. The geospatial data cannot be abstract; it must be tied to a map that shows people what it corresponds to on the ground. The data produced must be in format that is easily shared and read by the different parties involved.

**3) Adaptability**

Different regions and jurisdictions have different requirements for land and tenure attribute information as well as GPS accuracy. The app must therefore be flexible in its ability to collect both kinds of data. It must be able to collect complex usage and tenure information across the continuum of rights.[138] The app must include forms to enter attribute data, ideally ones that can be customized without programming. Compatibility with external GPS receivers is also important for simple adaptation to regional accuracy standards.

**4) Accuracy**

The integrity of the information collected must be high so that everyone involved in the process, from the landholder to the government land agency, has trust in the data. The accuracy of the GPS data should be high enough to satisfy legal standards in the area where the mapping takes place, but no higher if increased accuracy will impose greater costs.

Apps designed with these criteria in mind are already being used to record property rights, notably by the USAID Mobile Application to Secure Tenure (MAST) program.

**USAID - MAST**

MAST is an approach that includes a participatory process for land documentation and a suite of open source[139] applications customizable for GPS-enabled smartphones and tablets. After a brief training, villagers can use the app to “map the boundaries of their land and gather the demographic and tenure information that government officials can then use to issue formal land rights documents.”[140]

MAST is designed to address the social, logistical, and legal challenges of property rights formalization, not just the technical ones. At the highest level, MAST’s strategy is to engage citizens in the work of mapping, freeing up government personnel to focus on validating and registering land claims. This process starts with education and capacity building, efforts which are required to build trust in the process among everyone involved, from landholders skeptical of the value of the program to government officials skeptical of the value of community mapping. Special attention is paid to women and other vulnerable groups, ensuring they understand their rights and are empowered to exercise them.

Local committees are formed to represent the interests of customary landholders. Any disagreements that arise, such as boundary overlaps, are reviewed by these committees before being validated by government land officials.[141] USAID does not pass judgment on contested land claims, deferring instead to local authorities.[142]

Landholders and their neighbors walk the boundaries of their lands and overlay the collected data onto a satellite map. In addition to capturing geospatial data, MAST allows users to record the names and photographs of landholders and document various types of property rights arrangements, such as joint holdings between a wife and husband. Critically, MAST allows data to be collected offline and uploaded to the cloud when 3G or Wi-Fi service becomes available. Without this feature it would be useless in many of the rural areas where it is most needed. Once all parties, including community, government, and traditional authorities have agreed on the accuracy of the maps and attribute data, they upload it to the cloud, where it can be accessed by land officials through a web application to be cleaned and validated.[143] By making the data and registration requests available through a browser-based platform, MAST eliminates the need to send it by mail, cutting out a major source of latency in the registration process. After processing, a cadastral map can be rendered in jurisdictions where they are used. In Burkina Faso it took three Rural Land Service officers less than two months to complete this process for 2,638 parcels, with verification taking about 30 minutes each—a dramatic increase over previous methods.[144]

MAST has for the most part been used to issue occupancy certificates, which recognize customary land rights. The rights afforded by these documents vary substantially, and may be communal or individual, depending on the jurisdiction.

In Tanzania, documents called Certificates of Customary Right of Occupancy (CCRO) are issued. These are not statutory freehold titles, but they can be issued to individuals as well as communities.[145]

Burkina Faso issues a document called a Rural Land Certificate of Possession (APFR). Similar to CCROs, these can be issued to individuals, and occupy a middle ground between statutory and customary land rights.[146]

The certificates issued in Zambia, by contrast, were both communal and customary. These certified the landholder's right to occupy as part of a greater, communally-owned parcel, such as a village.[147]

MAST was piloted in Tanzania in 2014 and later scaled up as part of a larger Feed the Future program;[148] it was rolled out in Zambia in the same year;[149] and it was brought to Burkina Faso in 2016.[150] A detailed summary of the results in each country follows, but what is most significant is that MAST was able to use smartphones, a widely available technology, to crowdsource data collection, bypassing the professional surveying bottleneck.

**MAST in Tanzania**

MAST debuted in Tanzania, where the government and USAID recognized that the lack of registered land was having a negative impact on the business climate, ecology, and social institutions of the country.[151] The $1 million initiative—originally called the Mobile Technology Pilot and renamed MAST[152]—ran from 2014 to 2016 and was a successful proof of the crowd-sourced formalization concept, mapping land quickly with low-cost mobile technology.[153]

Laying the groundwork for the project, the village government organized educational councils and committees to teach the community the basic land laws of Tanzania, as well as the technical and procedural details of MAST's operation.[154] The village government also established a special council of land dispute resolution. Groups of young people were trained to be the project's data collectors, known as trusted intermediaries.[155] Women were allotted half of the seats on the council, which performed the critical task of ruling on arguments between landholders.[156]

This measure was intended to safeguard the property rights of women. Women are afforded equal property rights under national law, but are often denied these rights because of customary norms. This proved to be a successful strategy; women became proprietors of 50 percent of the newly mapped land.[157]

The expanded MAST program resulted in CCROs being issued quickly and at low cost. The villagers were able to map nearly 1,000 parcels in less than three weeks, though it took several months for the District Land Office to issue the CCROs.[158]

**MAST in Zambia**

In 2014 MAST expanded into Zambia, where there was widespread public demand for more secure property rights. One survey conducted in rural Zambia found that 91 percent of respondents "stated a desire to acquire some form of paper documentation for their land."[159] According to a 2015 USAID publication, 26 percent of rural households in Zambia's Eastern Province reported having experienced "at least one land conflict in the past three years, with the vast majority [being] over boundaries or inheritance."[160]

According to a Devex article on climate-smart agriculture and tenure in Zambia, this pervasive lack of formal property rights had consequences beyond the frequent land disputes: it discouraged farmers in one of Africa's most fertile countries from investing in their own land to increase food crop yields.[161] Zambians needed to farm more sustainably, for example, by planting nitrogen-fixing fertilizer trees to improve crop yields,[162] but were afraid to do so because of the lack of formal property boundaries.

The land laws in Zambia introduced new complications for MAST. The land system in Zambia is split into parallel statutory and customary systems, which have very little interaction with one another. The customary system is informal and undocumented, while the state system is largely absent in these rural areas.[163] In addition, the process of converting customary land to state land is irreversible under national law, which has created islands of long-abandoned but technically statutory land. According to a 2017 paper presented at the World Bank Conference on Land and Poverty, this includes "hundreds of hectares of pre-colonial farms which technically rest in the state system yet have been inhabited exclusively for decades by local communities."[164] This introduced a risk of formalization efforts exposing customary landholders to these latent statutory claims.

An important methodological development in Zambia was the introduction of a randomized control trial evaluation to measure the program's effectiveness.[165] The mapping process was otherwise similar to the one in Tanzania. It was implemented in 150 villages by a team of less than 50 people with less than three weeks training. The program issued over 6,000 customary land certificates, one-quarter of which were issued to women.[166]

USAID, in partnership with Tetra Tech, Terra Firma, and the Petauke District Land Alliance, is also engaged in a follow-up activity in which MAST would be brought to a larger customary territory with a diverse set of resource management challenges to be tested for scalability.[167]

### MAST in Burkina Faso

Burkina Faso's USAID MAST pilot,[168] which began in late 2016, required a customization of the MAST-Tanzania approach and applications in order to meet the requirements of a major land reform law passed in Burkina Faso in 2009.[169] The law was enacted in response to "pervasive and increasingly violent" land conflict, driven by a variety of factors including migration, drought, and rising demand for natural resources.[170] The land law it replaced, the Agricultural and Land Tenure Reform law of 1984, sought to bring all customary lands under the centralized control of the national government. Though it was intended to bolster development, the law has itself been cited as a major driver of land conflict. The intent of the 2009 law was to replace this system with a more decentralized and inclusive one which would formalize customary land rights instead of excluding them from the statutory system as the old law had done. The recognition of customary rights was seen as key to ensuring equal access to agricultural land, promoting investment and productivity, reducing conflict, and promoting more sustainable resource management.

To this end, the law created a system of rural land departments and village land commissions to be responsible for land registration and management. The law also called for the technical departments of the state government to provide management and capacity building assistance to the rural land departments, and established a national fund to finance these activities.

Also introduced was a three meter accuracy requirement for rural land surveying, which necessitated the addition of external GPS receivers to the USAID MAST platform. The unit selected, the Bad Elf GPS Pro, cost about $200 per unit in Burkina Faso. These receivers were paired to the mappers' phones by Bluetooth and powered by external batteries. Including the 32GB Android phone, the total cost of each handheld data collector was $720, still a substantial reduction in cost compared to the $3,000 sub-meter GPS unit used by the government topographer in the previous survey system. Other changes to the original mobile app, data model, workflows and server application were required, including the translation of the app into French.

As in Tanzania and Zambia, the result was a dramatic increase in the pace of mapping compared to the traditional system MAST replaced. It took less than two weeks for a dozen data collectors to map nearly 2,700 parcels. Between October 2016 and February 2017, they were able to prepare 2,638 land claims in single commune, compared to 3,706 prepared by the old mapping method in 47 communes from 2013 to 2016.[171]

**The Future of MAST**

In early 2017, USAID launched a new program—called Land Technology Solutions—to expand its successful Mobile Applications to Secure Tenure (MAST) initiative, designed to refine MAST and support its expansion into new countries.[172]

For now, MAST is only used in rural areas. This is due in part to high need in these areas, though MAST and similar crowdsourced mapping programs are also limited by urban accuracy requirements, which cannot be easily met with the type of GPS (single-frequency) currently available in cell phones and affordable external receivers.

Within the next five to ten years this limitation may be removed by the availability of affordable dual-frequency GPS units capable of centimeter precision in urban environments.[173] In addition to being very precise, dual-frequency GPS is easier to operate in cities, where there is more interference and lower signal availability. This gives us hope that the MAST concept can be extended to the African urban setting, where there is a pressing—and growing—need for it.

Globally, 54% of the population is already urban.[174] In Africa, according to a February 2017 World Bank report, entitled *Africa's Cities: Opening Doors to the World*, the urban population is expected to double over the next 25 years.[175] This growth is making Africa's cities increasingly critical to their countries' economic development, but it is at risk of being derailed by unclear property rights. If this growth is to be protected, the report concludes, the first priority is to formalize land markets, clarify property rights, and institute effective urban planning that allows land to be brought together.[176]

*For more on GPS, see our articles on dual-frequency GPS and surveying[177] and the forces driving the falling price of dual-frequency hardware.[178]*

### Arrival of the Future: Dual Frequency Satellite Receivers, Smartphones, and Property Rights

*By Christopher Mellon*

*This post originally appeared in the Future of Property Rights blog **here**.*

July 10, 2018

In 2017 we wrote a pair of blog posts[179] highlighting the arrival of new satellite technologies that offered to make high-precision location data widely and cheaply accessible for the first time with affordable dual-frequency receivers. Compared to single-frequency devices, dual-frequency receivers are more accurate, better in urban environments, and more resistant to interference, making them a powerful tool for mapping as well as for safety-critical applications like autonomous vehicle navigation.

The increasing availability and affordability of these receivers has two major causes. The first is the increasing number of satellites broadcasting a new, open navigation signal called L5 (or E5, the equivalent for the EU's Galileo constellation) which can be used alongside the L1 signal. It is supported by all of the major constellations, including GPS, Galileo, BeiDou, QZSS, and IRNSS. Although the individual satellite constellations broadcasting this new signal have not yet been completed, as of 2017 they collectively provide enough coverage to make the L5 signal useful. Only four visible satellites are technically required for a position fix, but eight is preferable for the best service, a level of coverage that has only just become a possibility for large parts of the earth. This has helped to create a ballooning market for accurate location services, most notably for transportation, but also virtual reality and wearable medical devices.[180]

In a previous article we estimated that investment in dual-frequency GNSS receivers for these mass market applications would see prices fall to $50 within five years and that this hardware would eventually appear in smartphones once battery and antenna limitations were addressed.[181] That prediction was in some ways a conservative one. In September 2017 the chip manufacturer Broadcom announced that it was releasing a dual-frequency GNSS chip for the smartphone market called the BCM47755.[182] The cost and performance of that chip were unknown, but Broadcom's announcement that it would appear in a smartphone from a major manufacturer in 2018 signaled that a massive leap in mobile location technology was on the horizon.[183] But Broadcom did not disclose which manufacturer they were partnering with. In May 2018 the Xiaomi Mi-8 was announced as the first phone to incorporate Broadcom's new chip.

### Mi-8 Cost and Performance

The Mi-8 may have a dual-frequency GNSS chip, but location accuracy is dependent on many factors beyond the use of multiple frequencies, including the quality of the antenna and signal processing software. The company claims that the Mi-8 is capable of 30 centimeter accuracy, which would be a drastic improvement from the five meter achievable with a standard single-frequency chip. In urban settings where more signal paths are obstructed by buildings and there are many reflective surfaces, the accuracy difference will be even more pronounced, as the L5/E5 signal is designed to make it easier to identify and discard reflected signals. Anyone who has ever called an Uber in the downtown area of a major city can appreciate the difference this would make. In addition to the 16x greater accuracy, Broadcom claims the new chip actually improves battery consumption, requiring 50 percent less power than the previous generation of single-frequency chips.[184]

As for cost, the new chip makes no discernible contribution to the cost of the phone, which starts at a little over $400, well below the price of flagships from Apple and Samsung.[185] In 2017 a Broadcom representative told *GPS World* that OEM manufacturers would probably pay the same amount for the BCM47755 that they did for the older L1-only chips.[186]

Xiaomi has emphasized the advantages of the Mi-8's dual-frequency receiver for in-car navigation, conducting a demonstration in which a car with blacked-out windows navigated a closed road course using only the phone GPS.[187] It is very likely that the first major impact for the consumer will be the ability to support lane-level navigation.

The real-world performance of the Mi-8 is not yet known. Some users have found that the location accuracy is no better, or even worse than that achieved with single-frequency devices in their areas.[188] This may be due to inadequate signal availability or to software issues. Daily usage and experimentation with different augmentation methods will reveal the true capabilities of the device. And while the Mi-8 does not deliver centimeter-level accuracy like a professional survey receiver, access to raw signal data means that differential techniques like RTK can be developed for Android devices.

### Ecosystem

While the first appearance of a dual-frequency chip in a smartphone is a major step forward, the development of a high-precision location data ecosystem also requires software and services. The open-source Android operating system now gives developers access to raw signal data (including pseudoranges, doppler, and carrier phase) from multiple satellite constellations.[189] Organizations betting on expansion of location services are helping to promote their growth and development. In June 2017 the EU launched a GNSS Raw Measurements Task Force to "boost innovation around this new feature" and "share knowledge and expertise on Android raw measurements and its use, including its potential for high accuracy positioning techniques."[190]

### Impact for Land Rights

The introduction of dual-frequency GNSS in mobile devices has enormous implications for land rights. As access to high-accuracy location data becomes ubiquitous, it will become a powerful tool for anchoring claims of occupancy and land usage.

For example, the Interethnic Association for the Development of the Peruvian Rainforest (AIDESEP) has been using drone imagery to document the encroachment of palm oil, mining, and logging companies on indigenous lands. According to an article in *Fast Company*, AIDESEP had previously "equipped community leaders with smartphones that allowed them to take GPS-tagged photographs of changes and infractions," but "found that the evidence they were presenting was always questioned or pushed back on. But with drones, community leaders can present continuous footage that starts at a known location, and tracks over the site of whatever violation they're trying to document."[191] Dual-frequency GNSS data has higher integrity than single-frequency data, and combined with proof of location and image hashing could allow photographic or video evidence from a $400 smartphone to provide the same assurance as video from a $25,000 drone.[192]

In Puerto Rico roughly half of all properties are informal. In the aftermath of Hurricane Maria, many residents of these informal communities were unable to access FEMA aid because they had no legal documentation of their ownership. This became such an obstacle to the relief efforts that FEMA began accepting affidavits as evidence of property ownership in lieu of titles.[193]

As mobile accuracy converges towards legal surveying standards there will be greater opportunity for crowd-sourced surveying projects like USAID's MAST[194] to bypass the surveyor bottleneck we have described elsewhere.[195] Crowdsourced data collection will not replace surveying for the time being, but it will be a powerful tool to document the property rights of vulnerable populations.

# Appendix: Glossary

## The Basics

*Control Segment*

The **control segment** of a navigation satellite system includes a ground-based network of master control stations, monitor stations, and data uploading stations. The master control stations adjust the satellites' orbit parameters and onboard high-precision clocks when necessary to maintain accuracy. Monitor stations, usually installed over a broad geographic area, monitor the satellites' signals and status, and relay this information to the master control stations. The master control stations analyze these signals, and then transmit orbit and time corrections to the satellites via data uploading stations.[196]

*GNSS Receiver*

A **GNSS receiver**—or a satellite receiver—processes the signals transmitted by satellites, and is the user interface to any global navigation satellite system (GNSS). A **GNSS receiver** displays a navigation solution after computing user position, velocity, and time (PVT).[197]

*PNT (Positioning, Navigation, and Timing)*

"**Positioning** [is] the ability to accurately and precisely determine one's location and orientation two-dimensionally (or three-dimensionally when required) referenced to a standard geodetic system...**Navigation** [is] the ability to determine current and desired position (relative or absolute) and apply corrections to the course, orientation, and speed to attain a desired position...**Timing** [is] the ability to acquire and maintain accurate and precise time from a standard...anywhere in the world and within user-defined timeliness parameters. When **PNT** is used in combination with map data and other information (weather or traffic data, for instance) the result is...the modern navigation system better known as [a global navigation satellite system]."[198]

*Space Segment*

The **space segment** of a navigation satellite system consists of satellites orbiting about 20,000 kilometers above Earth. Each system has its own constellation of satellites, arranged in orbits necessary to provide the desired coverage. Each satellite in a constellation broadcasts a signal that identifies it and provides its time, orbit, and status. Satellites receive orbit and time corrections from master control stations via data uploading stations.[199]

*User Segment*

The **user segment** of a navigation satellite system "consists of equipment that processes the received signals from...satellites and uses them to derive and apply location and time information. The equipment ranges from smartphones and handheld receivers used by hikers, to sophisticated, specialized receivers used for [high-end] survey and mapping applications."[200]

## Performance

*Accuracy*

**Accuracy** is a statistical measure of performance for navigation satellite systems. It is the degree of conformance of an estimated or measured receiver position, velocity, and/or time with the true receiver position, velocity, and/or time. Because **accuracy** is a statistical measurement of performance, navigation satellite system accuracy is meaningless unless it includes a statement of uncertainty regarding the relevant position, velocity, and/or time.[201]

*Availability*

**Availability** is a statistical measure of performance for navigation satellite systems. It is the percentage of time that system services are usable by a receiver within a specified coverage area. **Availability** is a function of the physical environment, the technical capabilities of the transmitting satellites, and constellation figuration.[202]

*Integrity*

**Integrity** is a statistical measure of performance for navigation satellite systems. It "is the measure of trust that can be placed in the correctness of information supplied by a navigation [satellite] system. **Integrity** includes the ability of [a] system to provide timely warnings to users [if and] when the system should not be used for navigation."[203]

*Precision*

**Precision** is a statistical measure of performance for navigation satellite systems. It is an expression of how closely a measurement is repeated over time. Importantly, **precision** has no relation to any given value or benchmark.[204]

*Time to First Fix*

"**Time to First Fix (TTFF)** is a measure of performance of a GNSS receiver."[205] **TTFF** is the measure of the time required for a GNSS receiver to acquire satellite signals and navigation data, and to subsequently calculate a position solution.[206] [207]

### Various Global Navigation Satellite Systems

*BeiDou*

**BeiDou** is a space-based global navigation satellite system (GNSS). It is a Chinese system, and will soon be capable of providing positioning, navigation, and timing (PNT) services to users on a continuous worldwide basis. It began offering services to the public in the Asia-Pacific region in late 2012. **BeiDou** is expected to provide global navigation services, similar to GPS, GLONASS, and Galileo, by 2020.[208]

*Galileo*

**Galileo** is a space-based global navigation satellite system (GNSS) that provides a highly accurate, guaranteed global positioning service. It is an independent European system under civilian control, unlike GPS, GLONASS, and BeiDou, which are technically military systems, under military control, providing a civil service. **Galileo** initiated services in late 2016 and it is interoperable with GPS and GLONASS.[209]

*GLONASS (Global Navigation Satellite System)*

The **Global Navigation Satellite System (GLONASS)** is a space-based global navigation satellite system (GNSS). It provides reliable positioning, navigation, and timing (PNT) services to users on a continuous worldwide basis. **GLONASS** is operated by the Government of Russia and is freely available to civilians. It is an alternative and complementary to other GNSSs, such as the American GPS, the Chinese BeiDou system, and the European Galileo system.[210]

*GNSS (Global Navigation Satellite System)*

A **global navigation satellite system (GNSS)** "is a constellation of satellites providing signals from space that transmit positioning and timing data to GNSS receivers. These receivers then use this data to determine their location [globally]."[211]

*GPS (Global Positioning System)*

The **Global Positioning System (GPS)** is a space-based global navigation satellite system (GNSS). It provides reliable positioning, navigation, and timing (PNT) services to civilian and military users on a continuous worldwide basis. **GPS** is operated by the United States Government and is freely accessible to anyone with a GPS receiver.[212]

*IRNSS (Indian Regional Navigation Satellite System)*

The **Indian Regional Navigation Satellite System (IRNSS)** is a space-based regional navigation satellite system (RNSS). It is owned by the Government of India with coverage area including India and the surrounding region. It is an independent and autonomous system and includes seven satellites in its constellation. **IRNSS** was expected to be operational by early 2018, but was delayed by the failures of a satellite and its replacement. Of note, **IRNSS** was renamed the Navigation Indian Constellation (NavIC) in April 2016.[213]

*QZSS (Quasi-Zenith Satellite System)*

The **Quasi-Zenith Satellite System (QZSS)** is a space-based regional navigation satellite system (RNSS). It is the Japanese system, providing coverage of the Asia-Oceania region, while maintaining compatibility with GPS. The system, which includes a constellation of four satellites, began to provide services in late 2018. Enabled by the reception of signals from satellites such as GPS satellites, **QZSS** provides highly precise data and stable positioning services that cannot be obtained merely by GPS.[214]

*RNSS (Regional Navigation Satellite System)*

A **regional navigation satellite system (RNSS)** "is a constellation of satellites providing signals from space that transmit positioning and timing data" to receivers within a specified region.[215] These receivers then use this data to determine their location regionally.

## GPS Blocks

*GPS Block IIF*

**GPS Block IIF** is a generation, or block, of GPS satellites that is part of the GPS modernization program. The block notably includes "the addition of a third civil signal in a frequency protected for safety-of-life transportation...Compared to previous generations, [**GPS Block IIF**] satellites have a longer life expectancy and a higher accuracy requirement."[216] The block includes a total of twelve satellites; the first was launched in May 2010 and the last was launched in February 2016.[217]

*GPS Block III*

**GPS Block III** is a planned generation, or block, of satellites that is part of the GPS modernization program. **GPS Block III** "will provide more powerful signals in addition to enhanced signal reliability, accuracy, and integrity, all of which will support precision, navigation, and timing services."[218] Other key advances for **GPS Block III** include a fourth civilian GPS signal (LC1) and a 15-year life expectancy.[219] Launch of the first satellite is planned for December 2018.[220]

## Augmentation Systems

*Augmentation*

**Augmentation** is a method of improving—or "augmenting"—the performances of a global navigation satellite system (GNSS), such as precision, accuracy, integrity, and availability, through use of external information.[221]

*Differential Correction*

"**Differential correction** is a class of techniques [used to improve] the accuracy of [GNSS] positioning by comparing measurements taken by two or more receivers."[222]

*EGNOS (European Geostationary Navigation Overlay Service)*

The **European Geostationary Navigation Overlay Service (EGNOS)** is the European satellite-based augmentation system (SBAS). "**EGNOS** was the first pan-European navigation satellite system—a precursor to the Galileo system—and augments various GNSS for safety-critical tasks such as guiding aircraft and navigating ships."[223] The system is mainly operational over Continental Europe and its surrounding islands.[224]

*GBAS (Ground-Based Augmentation System)*

A **ground-based augmentation system (GBAS)** "aims to enhance global navigation satellite system (GNSS) services for aviation during departure, approach, and landing, as well as during surface operations. It has local coverage —the surroundings of an airport—and helps to ensure aviation requirements in terms of integrity, accuracy, and safety...A **GBAS** includes two or more satellite receivers, which collect pseudoranges for all primary satellites in view, then computes and broadcasts differential corrections and integrity-related information...Any aircraft may use these corrections to compute its position."[225]

*Safety-of-Life*

**Safety-of-Life (SoL)** "applications augment GNSS services intended for safety-critical transportation systems. Target domains include aviation, maritime navigation, rail travel, and automobile travel, where degradation in navigation system performance without a timely alert would endanger lives."[226] Different jurisdictions enforce different standards, adhere to different regulations, and use different technology. Nonetheless, "the key performance parameter for **Safety-of-Life** applications is integrity, or the trust that a user can have in the functioning of a navigation satellite system."[227]

*Signal Authentication*

**Signal authentication** is a concept related to navigation satellite systems. "The basic idea is that a GNSS receiver would like to ensure that a received signal is identical to the originally transmitted signal, and that it was transmitted by a trusted source."[228] **Signal authentication** signatures can be generated through cryptographic techniques. The concept can help to mitigate deliberate signal interference. **Signal authentication** has been proposed for both GPS and the Galileo system.[229]

*SBAS (Satellite-Based Augmentation System)*

A **satellite-based augmentation system (SBAS)** is used "for the safety-critical task of guiding aircraft—vertically and horizontally—during different operations, such as approach and landing...It supports wide-area and/or regional augmentation through the use of geostationary satellites, which broadcast augmentation information related to integrity and differential corrections...An **SBAS** can help to mitigate satellite position errors, satellite clock—or time—errors, and errors caused by the delay of a signal passing through the ionosphere...While the main goal of an **SBAS** is to provide integrity assurance, a system can also increase accuracy."[230]

*WAAS (Wide Area Augmentation System)*

The **Wide Area Augmentation System (WAAS)** "is the American satellite-based augmentation system (SBAS). **WAAS** is managed by the Federal Aviation Agency (FAA) and is specially developed for the civil aviation community. Operational since 2003, the system currently supports thousands of aircraft instrument approaches at more than one thousand airports throughout North America...The **WAAS** program is continuously in evolution...There are currently plans to improve the capability of the system, in parallel with the evolution of SBAS standards, towards a dual-frequency augmentation service."[231]

## Augmentation and Surveying Techniques

*Differential GNSS*

**Differential GNSS** "is an augmentation system involving enhancement to primary GNSS data through use of a network of ground-based reference stations...This network enables the broadcasting of differential information to the user in order to improve position accuracy; integrity is not ensured. There are several **differential GNSS** techniques, including Real Time Kinematics (RTK)."[232]

*Geodetic Control Point*

A **geodetic control point** is a monumented, or otherwise marked, survey point. As part of a larger geodetic control network, it is established for the purpose of providing geodetic reference for mapping and surveying activities.[233] **Geodetic control points** help to obtain precise accuracy in surveying—often in the order of millimeters.[234] A particular point is normally identified by a number, an alphanumeric symbol, or a concise, intelligible name, which is usually stamped on the disk marker.[235]

*PPK (Post-Processed Kinematics)*

**Post-processed kinematics (PPK)** "is a technique similar to RTK, but the baselines[236] are not processed in real time. **PPK** involves the use of one or more rover receivers and at least one reference receiver remaining stationary over a known control point.[237] GNSS data is simultaneously collected at the rover and reference receivers. The data is downloaded from the receivers, and the baselines are processed via software."[238]

*PPP (Precise Point Positioning)*

**Precise point positioning (PPP)** "is a positioning technique that removes or models GNSS errors to provide a high level of position accuracy from a single satellite receiver. A **PPP** solution is dependent on GNSS satellite clock and orbit corrections, which are generated from a network of global reference stations. Once corrections are calculated, they are delivered to the end user via satellite or the internet...A **PPP** system is similar in structure to an SBAS system, providing corrections to a satellite receiver to increase position accuracy. However, **PPP** systems typically provide a greater level of accuracy—up to three centimeters—and allow for a single correction "stream" to be used worldwide."[239] This technique is notably available on Android devices.

*RAIM (Receiver Autonomous Integrity Monitoring)*

**Receiver autonomous integrity monitoring (RAIM)** "is a technology developed to assess the integrity of GPS signals in a GPS receiver system. **RAIM** is of special importance to safety-critical GPS applications, such as aviation or marine navigation. GPS does not include any internal information about the integrity of its signals. It is possible for a GPS satellite to broadcast slightly incorrect information that will cause navigation information to be incorrect, but there is no method for the receiver to determine this fault using standard techniques."[240] "**RAIM** detects faults with redundant GPS pseudorange measurements. That is, when more satellites are available than needed to produce a position fix, the extra pseudoranges should all be consistent with the computed position. A pseudorange that differs significantly from the expected value may indicate a fault in the associated satellite or another signal integrity problem."[241] Of note, **RAIM** is considered available if 24 GPS satellites or more are operative.[242]

*RTK (Real Time Kinematics)*

**Real time kinematics (RTK)** is a specific "differential GNSS technique. **RTK** provides high positioning performance in the vicinity of a base station...The technique utilizes a base station, one or several users,[243] and a communication channel allowing the base to broadcast information to the user in real time...The base station will transmit its well-known location to all in-view satellites. Utilizing this data, a user is then able to determine their location relative to the base with high precision. The user is then positioned globally...The **RTK** technique can yield accuracies of a few centimeters to the true position and is extensively used for surveying."[244]

*RTKlib*

**RTKlib** "is an open source GNSS toolkit for performing standard and precise positioning. Through use of raw GNSS data, **RTKlib** is capable of real-time and post-processing computing to accurately determine a position. It is possible to use precise point positioning (PPP) or real time kinematics (RTK)...With professional receivers and antennas, it is possible to achieve centimeter accuracy. Low-cost single frequency equipment can achieve decimeter accuracy...The software supports all major satellite constellations --GPS, GLONASS, Galileo, BeiDou, QZSS, and SBAS...The **RTKlib** toolkit runs on Windows, Linux, and Android."[245]

## Receiver Capabilities

*Dual-frequency*

A **dual-frequency** GNSS receiver utilizes two signal frequencies. Through use of a second frequency, these receivers can correct for transmission delays caused by the ionosphere, which is the greatest single contributor to inaccuracy.[246] Use of a second signal also provides greater signal redundancy, allowing for better error corrections and improved satellite availability, particularly in tree cover and urban canyons. With error-checking algorithms that can identify faulty satellite signals, **dual-frequency** GNSS receivers provide measurements that are not only accurate, but trustworthy. Manufacturers are currently developing **dual-frequency** GNSS receivers for smartphones,[247] and related prices are expected to lower to the $50-range by 2021.[248]

*Frequency*

**Frequency** is "the particular wavelength at which a [GNSS] broadcasts or transmits signals."[249]

*Multi-constellation*

A **multi-constellation** GNSS receiver can "access signals from several satellite constellations, such as GPS, GLONASS, BeiDou, and Galileo...As a larger number of satellites can be in its field of view, a **multi-constellation** GNSS receiver benefits from reduced signal acquisition time; improved accuracy of position and time; and a reduction of issues caused by obstructions such as buildings and tree cover...Redundancy is also built into a **multi-constellation** GNSS receiver. If a particular signal is blocked due to the working environment, there is a very high likelihood that the receiver can locate a signal from another satellite constellation."[250]

*Multi-frequency*

A **multi-frequency** GNSS receiver utilizes more than two, or multiple, signal frequencies. Use of the technology is an effective method to remove ionospheric error from position measurements and improve accuracy. A **multi-frequency** GNSS receiver also provides greater protection against signal interference.[251] Low-cost **multi-frequency** GNSS receivers are expected to appear on the market in the near future.[252]

*Single-frequency*

A **single-frequency** GNSS receiver only utilizes one frequency to determine a position measurement. These measurements are vulnerable to interference and are accurate, at best, to roughly five meters.[253] A **single-frequency** GNSS receiver is adequate for most daily civilian uses, and Wi-Fi signals can be used to augment accuracy in developed areas. But related measurement errors are insufficient for survey work, which should be accurate to the one to ten centimeter range. Most smartphones use **single-frequency** GNSS receivers.

## Signals & Frequencies

*E5*

**E5** is a GNSS band, and refers to two GNSS signals, **E5a** and **E5b**. They are two of the four Galileo signals. Several Galileo system services are available through **E5a** and **E5b**, notably Open Service (OS) and the Safety-of-Life (SoL) service. Open Service is free and available for positioning and timing applications. The Safety-of-Life service provides increased guarantees regarding integrity monitoring, and will be available globally. **E5a** and **E5b** are both public assets, and are compatible with L1 and L5.[254] The frequency of **E5a** is 1176 MHz and the frequency of **E5b** is 1207 MHz.[255]

*E6*

**E6** is a GNSS signal. It is one of four Galileo signals. The Public Regulated Service (PRS), a Galileo system service, is provided on **E6.** "PRS is encrypted and is meant to assist public security and civil authorities. The service is under government control, providing significant jamming protection, with likely applications including emergency services, law enforcement, intelligence services, and customs...The frequency of **E6** is 1278 MHz...and it is part of the radio navigation satellite service (RNSS) for Galileo."[256]

*L1*

**L1** is a GNSS band. It is one of two main frequencies broadcast by GPS. **L1** "is the most important band for navigation purposes, and it is the basis for the majority of current GPS applications. Signals are transmitted using a number of codes: the open Coarse/Acquisition (C/A) code signal is the most important signal for mass market applications; the P Code is used for precision measurements; the modernized military signal (M-Code) is designed exclusively for military use; the L1C code is the new civil signal...The frequency of the **L1** band is 1575 MHz."[257] It was subject to Selective Availability measures, enforced by the United States Government, until 2000.[258]

*L1C*

**L1C** is a GNSS signal. "It will be the fourth civilian GPS signal, designed to enable interoperability among international navigation satellite systems...Design will also improve mobile signal reception in cities and other challenging environments...The name **L1C** refers to the radio frequency used by the signal --1575 MHz or L1-- and to the fact that it is for civilian use...The United States and Europe developed **L1C** as a common civil signal for GPS and Galileo...The United States will launch its first **L1C** signal with GPS Block III.[259]

*L2*

**L2** is a GNSS band. It is one of two main frequencies broadcast by GPS. At first, the **L2** band was available only to authorized users, such as the United States Armed Forces. These users were issued encryption keys for access to data. This policy prevented both civilians and foreign governments from obtaining precise GPS coordinates without the assistance of ground-based augmentation systems. Several civilian companies eventually discovered how to use the **L2** band without an encryption key and patented their various techniques. As a result, the policy of restricted access to **L2** was reversed by the United States Government. Yet the related patents continue to restrict competition in the development of dual-frequency receivers.[260] L2C, a preoperational civilian signal, may soon replace the original **L2** signal.

*L2C*

**L2C** is a GNSS signal. "It is the second civilian GPS signal, designed specifically to meet commercial needs...When combined with the legacy L1 C/A signal in a dual-frequency GNSS receiver, **L2C** enables ionospheric correction, boosting accuracy...and enables faster signal acquisition, enhanced reliability, and greater operating range. **L2C** also broadcasts at a higher effective power than legacy signals, strengthening reception under tree cover and even indoors...The name **L2C** refers to the radio frequency used by the signal—1227 MHz or L2—and the fact that it is for civilian use...The first GPS satellite featuring **L2C** launched in 2005. Every GPS satellite fielded since has included an **L2C** transmitter...However, the signal is still considered preoperational."[261]

*L5*

**L5** is a GNSS signal. "It is the third civilian GPS signal, designed to meet demanding requirements for safety-of-life transportation and other high-performance applications...**L5** is broadcast in a radio band exclusively for aviation safety services. It features higher power, greater bandwidth, and an advanced signal design. Future aircraft will be able to use **L5** in combination with other signals to improve accuracy, via ionospheric corrections, and robustness, via signal redundancy. In addition to enhancing safety, **L5** will increase capacity and fuel efficiency within US airspace, railroads, waterways, and highways...The name **L5** refers to the U.S. designation of the radio frequency used by the signal, 1176 MHz...The U.S. Air Force began broadcasting civil navigation (CNAV) messages on **L5** in April 2014, but it is still preoperational."[262]

*Selective Availability*

"**Selective availability (SA)** was an intentional degradation of public GPS signals implemented for American national security reasons. In May 2000, at the direction of President Bill Clinton, the United States Government discontinued its use of **Selective Availability** in order to make GPS more responsive to civil and commercial users worldwide. In September 2007, the United States Government announced its decision to procure [GPS Block III] without **SA.** This made the May 2000 policy decision permanent and eliminated a source of uncertainty for GPS performance."[263]

## GNSS Raw Measurements

*Carrier-phase*

"The **carrier-phase** measurement is a measure of the range between a satellite and a GNSS receiver. It is expressed in units of cycles of the carrier frequency.[264] The **carrier-phase** measurement can be expressed with very high precision—in the order of millimeters—but the total number of cycles between satellite and GNSS receiver is ambiguous."[265]

*Code-phase*

The **code-phase** measurement is a measure of the travel time of a signal from a satellite to GNSS receiver. It is also used to calculate positioning. The **code-phase** measurement is based on pseudo-random code—C/A code or P Code—and is expressed in sequences of zeros and ones. After differential correction, the **code-phase** measurement technique results in one to five meter accuracy.[266]

*Doppler*

"The **Doppler** effect, or the **Doppler** shift, is the change in frequency for an observer, such as a GNSS receiver, moving relative to its source, such as a particular satellite."[267] Using **Doppler** data, a GNSS receiver can estimate its velocity,[268] augment its position, and determine its range rate.[269] [270]

*GNSS Raw Measurements*

"**GNSS raw measurements,** such as pseudoranges, Doppler measurements, and carrier-phase measurements, are directly accessible to application developers via smartphones that feature Android 7.0 or higher. This access creates the possibility of using alternative, and possibly more advanced, techniques for position, velocity, and time (PVT) computations."[271] Use of **GNSS raw measurements** can lead to increased GNSS performance—notably increased accuracy—as well.[272]

*GNSS Raw Measurements Task Force*

The **GNSS Raw Measurements Task Force** was launched by the European Global Navigation Satellite Systems Agency (GSA) in June 2017, following the release of GNSS raw measurements on Android.[273] "The task force aims to share knowledge and expertise on Android raw measurements and their use, including the potential for high accuracy positioning techniques. The [**GNSS Raw Measurements**] **Task Force** includes GNSS experts, scientists and GNSS market players, and promotes a wider use of [GNSS] raw measurements."[274]

*GNSS Software-Defined Receiver*

A **GNSS software-defined receiver** "is a GNSS receiver that has been designed and implemented following the philosophy of software-defined radio...Traditionally, GNSS receivers have been implemented in hardware, which is conceived as a dedicated chip that is designed and built with the single purpose of being a GNSS receiver. In a **GNSS software-defined receiver**, all digital processing is performed by a general purpose microprocessor. In this approach, a small amount of inexpensive hardware is still needed to digitize a signal from a satellite. The microprocessor can then use this raw digital data to implement GNSS functionality."[275]

*Pseudorange*

"The **pseudorange** is an approximation of the distance between a satellite and a GNSS receiver...The **pseudorange** of a particular satellite is obtained by multiplying 'the time taken for a signal to reach the receiver' by 'the speed of light'...As there will inevitably be accuracy errors in the time measured, the term **pseudorange** is used in place of range."[276]

## Common Sources of Signal Interference

*Integer Ambiguity Resolution*

**Integer ambiguity resolution** occurs when a GNSS receiver must reinitialize because a signal was interrupted. This process is often necessary when an automobile passes through a tunnel or is within an urban canyon—locations where a GNSS receiver can lose sight of satellites. Once the satellites are back in view, the GNSS receiver can re-establish an accurate position fix, usually in a matter of seconds. Dual-frequency receivers allow for more rapid **integer ambiguity resolution**. Of note, this capability is a serious advantage within the autonomous vehicle sector, as highly urban areas will be its primary market.

*Ionospheric Delay*

"**Ionospheric delay** is the amount of additional transmission time a signal incurs as it passes through the ionosphere,"[277]—a region of the earth's atmosphere extending from 60 kilometers to 1,000 kilometers in altitude.[278] The amount of **ionospheric delay** varies with the frequency of the passing signal, and also varies based on the electron density of the ionosphere. This density, in turn, can vary based on geographic location and sunspot activity.[279]

*Multipath Interference*

**Multipath interference** is generated when a signal arrives via multiple paths at a GNSS receiver, rather than from a direct line of sight. Reflected signals can interfere with signals that reach the GNSS receiver directly from a satellite. The principle cause is close proximity of a GNSS receiver to reflecting structures, such as buildings. **Multipath interference** can also be caused when a signal is transmitted by a satellite with low elevation.[280]

## Deliberate Signal Interference

*GNSS Spoofing*

**GNSS spoofing** "is the broadcast of false signals with the intent that the victim receiver will misinterpret them as authentic signals. The victim [receiver] might deduce a false position fix, a false clock offset, or both. A coordinated sequence of false position or timing fixes could induce dangerous behavior by a user platform that believes the false fixes. For example, [**GNSS**] **spoofing** has been used to send a hovering drone into an unplanned dive and to steer a yacht off course."[281]

*Location Spoofing*

"**Location spoofing** refers to a variety of emerging online geographic practices that allow users to [intentionally] hide their true geographic locations."[282] There are presently a number of **location spoofing**, or mock location, applications available to users. Many are readily available on Android devices. The applications will usually alter a user's latitude and longitude.[283] The proliferation of **location spoofing** in recent years has created controversy and debate regarding the reliability and convenience of crowdsourced geographic information.[284]

*Meaconing*

"**Meaconing** is the interception and rebroadcast of navigation signals. These signals are rebroadcast on the received frequency, typically with higher power than the original signal...Consequently, aircraft or ground stations are given inaccurate bearings...**Meaconing** is often used in warfare to confuse enemy navigation...Successful **meaconing** can cause aircraft to be lured into ambush-ready landing zones or enemy airspace, ships to be diverted from their intended routes, bombers to expend ordnance on false targets, and ground stations to receive inaccurate bearings or position locations."[285]

*Proof of Location*

**Proof of Location (PoL)**, or location assurance, is a concept that would allow a user to record their location, and the related timestamp, at their choosing.[286] The user could then reveal this information at their discretion through presentation of a location claim. "**Proof of Location** can provide consensus [about] whether [a user] is verifiably at a certain point in time and space."[287]

## Related Technology

*Connected Car*

"A **connected car** is a car equipped with internet access, and usually also with a wireless local area network (LAN). This allows the car to share internet access with other devices, both inside and outside the vehicle. Often, a **connected car** is outfitted with special technologies that tap into the internet or wireless LAN and provide additional benefits to the driver,"[288] such as real-time traffic, roadside assistance, and parking services. **Connected cars** are often considered as part of the Internet of Things.[289]

*Orthophoto*

"An **orthophoto** is a uniform-scale photograph, or a photographic map...A conventional perspective aerial photograph contains image displacements caused by the tilting of the camera and terrain relief, or topography."[290] An aerial photograph can also be distorted by the curvature of the earth if taken from a very high altitude. "These images do not have uniform scale, and distances therefore cannot be measured accurately using the photographs. The effects of tilt and relief [can be] removed from an aerial photograph via a rectification process to create an **orthophoto**. Since an **orthophoto** is uniform in scale, it is possible to measure directly on it, similar to other maps. An **orthophoto** can [also] serve as a base map onto which other information can be overlaid."[291]

*TaaS (Transportation-as-a-Service)*

**Transportation-as-a-Service (TaaS)**, or Mobility-as-a-Service (MaaS), "describes a shift away from personally-owned modes of transportation and towards mobility solutions that are consumed as a service."[292] "**TaaS** may take a variety of forms, offering more consumer choices and business opportunities."[293] Ride-hailing, on-demand delivery services, car sharing, bike sharing, and public transportation services are all forms of **Transportation-as-a-Service**. In the future, **TaaS** may include autonomous driving services.[294]

## Organizations and Initiatives

*ESA (European Space Agency)*

"The **European Space Agency (ESA)** is an intergovernmental organization of 22 member states dedicated to the exploration of space...Headquartered in Paris, **ESA** has a worldwide staff of about 2,000 and an annual budget of about €5.25 billion. The **ESA** space flight program includes: human spaceflight, mainly through participation in the International Space Station program; the launch and operation of unmanned exploration missions to the Moon and other planets; Earth observation, science, and telecommunication; designing launch vehicles; and maintaining a major spaceport in French Guiana."[295]

*GSA (European Global Navigation Satellite Systems Agency)*

The **European Global Navigation Satellite Systems Agency (GSA)** "is the European Union (EU) agency that aims to ensure that essential public interests are properly defended and represented in connection with [the EU navigation satellite programs]: Galileo and EGNOS...It is also responsible for managing and monitoring the use of the navigation satellite programs' funds...The **GSA** was established in 2004 and is based in Prague."[296]

*MAST (Mobile Application to Secure Tenure)*

The **Mobile Application to Secure Tenure (MAST)** project is a United States Agency for International Development (USAID) initiative to address land tenure insecurity and related socioeconomic problems. "The project [included the use of] an easy-to-use, open-source smartphone application [to] capture the information needed to issue formal documentation of land rights. Coupled with a cloud-based data management system to store geospatial and demographic information, the [**MAST**] project was designed to lower costs and time involved in registering land rights" through community mapping.[297] Importantly, the initiative also made land administration processes more transparent and accessible at the local level. **MAST** has been implemented in Tanzania, Zambia, and Burkina Faso.

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