The Future of Ground Marks for Geomatics: Stability and Utility

Nicholas W. HAZELTON, USA and WU Yitong, P.R. China

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SUMMARY

The near ubiquity of GNSS positioning often brings into question the need for ground marks. Can ground marks be replaced with 'marks in the sky,' as some have suggested? In this paper, the authors argue that ground marks remain a critical part of our geospatial infrastructure and that applications from geodetic to cadastral still need good quality ground marks.

Having high quality ground marks is a key point. Stability and survivability are the highest priority. Using a 25-year monitoring study in Australia as a foundation, the stability of different types of marks is examined, together with a basic cost-benefit analysis. Survivability for marks is greatly helped by type and placement, and the authors draw on many years of experience in placing and recovering marks, as well as not recovering them, as a basis for survivability guidelines.

To invest in ground marks means that a return is expected, which is based on the marks' utility. The utility of ground marks can be increased, in current times and the near future, by a number of steps that broaden the way that marks can be included in a wider range of survey work, especially airborne drones. These steps and applications are enumerated. Included in this discussion is the question of maintenance and its funding, as well as the need to educate the public about spatial information infrastructure.

The weakest component of GNSS positioning is vertical location, which is essential for applications involving the movement of water, especially when part of the flow is under gravity. Stable ground marks can provide critical control for these applications in ways that may be difficult for GNSS. Direct gravimetry, rather than leveling, when combined with GNSS observations, may be a more efficient way to provide high quality locations in the field, compared to traditional differential leveling.

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1. INTRODUCTION

At present, the US National Geodetic Survey is developing new horizontal and vertical datums for the US. The vertical datum is a gravimetric geoid model which will allow ready connection between GNSS-derived height and elevations derived from traditional leveling. Part of the work for developing the new geoid has been the ability to obtain GPS observations on existing benchmarks across the nation, a project known as GPS on Benchmarks for the Transformation.

This project has been totally dependent on the existence of tens of thousands of benchmarks which may be over a century old, being both stable and able to be used for GPS observations. Without ground marks, the development of the new datum would have required a great deal more work, in particular gravimetry at far greater cost. The value of ground marks is therefore easy to see from this one project, although putting a numerical value on it may be difficult.

There have been studies into the cost-benefits of various aspects of a ground-based control system, and these suggested returns on investment from 1.7:1 to 4.5:1, based on fairly conservative analyses. See Epstein and Duchesneau, 1984; Angus-Leppan and Angus-Leppan, 1990; Hoogsteden and Hannah, 1999.) A multi-purpose geospatial reference system could be expected to produce returns that are higher than this, especially as it would allow a wider range of operations to be linked and co-ordinated.

A former head of the Ordnance Survey of Great Britain made a critical point concerning the modern surveying and mapping framework that underpins much modern navigation and GIS operation "Curiously, the advent of computerized tools makes the availability and nature of this framework even more important; computers are much less able than trained humans to cope with uncertainty, inconsistency, and missing information. To be effective, the framework must now be in a standardized, easily understood, frequently updated, and well-documented form. **Everything must now be explicit**." (Rhind, 1997, with Rhind's emphasis)

2. BACKGROUND

In the early days of GPS, both before its introduction and immediately afterwards, there was great hype about how it would remove the need for traditional marks in the ground, and how we'd all be using 'marks in the sky' for everything we needed. Then came the start of Operation Desert Storm to remove Iraq from occupying Kuwait in February, 1991, and because of the incomplete nature of the GPS constellation, the movement of a newly launched satellite to provide better coverage on the Middle East, the intermittent failure of one GPS satellite, and efforts to concentrate limited GPS resources over the Gulf region, GPS became unavailable in some other part of the world, often for hours at a time.

While the interruption was brief, many nations realized that having the entire foundation of one's national geospatial infrastructure under the control of another nation's military may not be the wisest strategic and national security move. As the only available high-precision satellite surveying systems were GPS and GLONASS, a 're-think' of the situation was clearly necessary. This led to the development of Galileo by the EU, which system is not controlled by a national military.

In recent years the presence of GNSS jamming systems has become apparent, along with the threat to GNSS usability if the radio spectrum is compromised. While there are strong efforts by GNSS manufacturers to build in anti-spoofing, anti-jamming and general resilience capabilities into more recent receivers, especially those for survey work, that fact that a malevolent actor could compromise a nation's geospatial infrastructure with relatively cheap equipment is a cause for concern. Satellites in low Earth orbit broadcasting false GNSS could easily drown out the very faint signals from real GNSS satellites, allowing a space-based attack on a nation's geospatial infrastructure to be accomplished in a way that avoided easy prevention.

Other parts of the 're-think' included a realization that the precision and reliability of ground marks generally exceeds that of GNSS positioning, especially in the vertical, if the marks are properly placed. Critical parts of national geospatial infrastructure, in particular cadastral boundaries, are linked primarily to ground marks, and many nations' legal systems place monuments among the highest forms of evidence of cadastral boundaries, and derived co-ordinates among the lowest. Deformation measurements often use monuments as the foundation of the observation network, with satellite location used primarily for checking the stability of these control points. GNSS-based measurements are absolutely necessary to modern measurement systems, but the underlying control network tends to remain based on ground monumentation.

It seems reasonable to conclude that ground marks are not going to disappear into history as an interesting artefact, like logarithm tables, at least not in the foreseeable future. If we are going to need ground marks, it seems sensible to design them in a way that maximizes the not-inconsiderable investment involved in their establishment.

3. A BRIEF LOOK AT ECONOMICS

The cost of placing a ground mark is far less concerned with digging a hole and placing the concrete and/or other materials, than it is with the cost of providing the mark's precise location. While a GNSS position is fairly cheap to obtain, the leveling needed for a high-quality vertical location connected to a geoidal datum tends to be very expensive. Gravimetry may lessen this cost on a regional basis when doing geoid modeling, but high-quality vertical location costs a lot of money.

At present, the US National Geodetic Survey (NGS) is determining a new gravimetric vertical datum for the US. To do this, it is (in part) obtaining GPS observations on as many existing benchmarks as possible (in addition to using airborne gravimetry, GRACE data and other sources). However, this operation is far beyond the scope of NGS's budget, so it has asked other groups and individuals in the US to undertake this work. A number of state and regional organization have stepped up to this, funding it by various means, but this simply hides the real cost of developing a gravimetric datum. Without a high-quality gravimetric datum, connecting GNSS-derived heights to geoidal heights is difficult, lessening the utility of GNSS. This lessened utility is another cost that has to be absorbed elsewhere in the system.

This operation to develop the new vertical datum has had its cost effectively hidden and spread across many different budgets. Its importance is undeniable, but even an economy the size of the US's does not seem to be able to bear the full cost of this, at least not openly. This may be due to both the ability to fund what seems an arcane subject to many laypeople and the real cost.

An important point to note is that the entire operation to create this vertical datum would have to be tackled in a very different manner if there were not an existing network of benchmarks all over the country. If these marks disappear, as marks do over time, then the next vertical datum, perhaps 50 years in the future, will have very little existing vertical control that can be used. This may increase the cost of the next datum's creation dramatically.

4. GROUND MARK STABILITY

In the Australian state of Victoria, the State Rivers and Water Supply Commission (SR&WSC), later the Rural Water Commission (RWC, now regionalized), had responsibility for distribution of irrigation water to many parts of the state. A critical part of distributing water under gravity is knowing the geoidal elevations of the ground, which depends upon knowing the elevation of suitable benchmarks. Ensuring a network of reliable benchmarks with high-quality elevations throughout the state's irrigation areas was a critical mission of SR&WSC's Survey Branch.

As a means of determining benchmark stability, SR&WSC established a line of every type of benchmark used by the Commission, from wooden pegs, stools on trees, steel rods and concrete marks, through concrete bridges and water control structures, to 2 m deep benchmarks. This was placed across an area with soil known to have significant expansion and shrinkage properties, and monitored it at regular intervals over a period of about 25 years. The detailed results are currently being prepared for publication, but the summary is that all the marks moved vertically by anything up to 25 to 35 mm through the course of a year. That level of movement was experienced in three-lane concrete bridges over channels and rivers, as well as simple concrete marks placed in the ground to a depth of about 1 to 1.5 meters. This agreed with what was experienced by SR&WSC surveyors in other areas of the state. Because the deep benchmarks that SR&WSC had designed and installed at that time had a serious design flaw, even 2 m deep marks moved by up to 15 mm.

Today's deep benchmark designs have avoided this flaw and so remain far more stable over time, if properly installed. These designs do cost a little more than simpler marks, and take longer to install, requiring being driven to refusal by a jackhammer. But the vertical stability benefits are significant.

Horizontal stability is more difficult to determine, although GNSS can help here. Large structures tend to be more stable than smaller ones, although all structures are moved by regional earth movement, even those attached to bedrock. Monitoring is important for guaranteeing the stability of marks in all directions, and for general marks without included sensors (i.e., marks that are not Continually Operating Reference Stations (CORS) or equivalent) there are advantages to regular monitoring by GNSS observations. This is a reminder that maintenance is a necessary part of a geospatial reference system and should be an on-going cost commitment to the system. A system that is not maintained will soon cease to be a usable system.

5. GROUND MARK UTILITY

For many years, ground marks tended to serve a limited range of purposes, and different types of ground marks were used for different purposes. One type of mark was used for vertical control. A different set of marks (usually of a different type) was used for cadastral boundary definition. Horizontal control points were often different to vertical control marks, although these types converged over recent decades.

Given the real cost of ground marks, it seems sensible to use them for as many purposes as possible. In the US in the states where the Public Land Survey System (PLSS) is utilized, all the boundary points in a section can, in theory, be tied to the section corners, usually represented by a physical mark at one time. This means that there is, in theory, a ground mark within a mile of almost every point that allows determination of the cadastral boundaries. Modern surveying methods allow connections to ground marks several miles (or kilometers) away with precisions better than those at which properties were marked on the ground. General purpose marks at these intervals would allow boundaries to be readily determined from local ground control marks.

Traditionally, ground control mark were used for leveling, so the mark would be placed in a location with good lines of sight close to horizontal. Today, this limits the ability to use GNSS at the ground mark. Even if the mark is placed with good sky visibility for GNSS observations, current thinking tends to focus on GNSS visibility at the mark, rather than the mark's visibility from above.

While there is much that can be done while collecting aerial imagery and aerial image analogues (e.g., LiDAR) by GPS/INS in the flight platform, some ground control is critical. Pre-marking ground control points, whether through painted targets, identified object clusters, pre-placed reflectors or InSAR target arrays, provides applications of the ground control points to a wide range of geospatial needs, without the need for users to visit every point.

Ground control for various applications does not need to be placed exactly at the ground control point. Painted targets can be placed on roads, reflectors can be placed on top of poles or other object nearby, and connected to the ground control point during installation. If the establishment of a new benchmark included ground control targets of various kinds, this would add significantly to the mark's utility, and allow a better return on the investment in placing the mark.

By making ground marks more useful more easily for more applications, there is greater justification for making the installation of a mark a multi-function process. Targets for multiple sensors are installed, the mark is readily accessible for users needing to place a GNSS receiver on the mark, and the mark has had gravimetry determined and GNSS position measured. This allows marks to be placed less frequently spatially, while allowing wider usage. For marks in areas with higher-than-usual usage, an eccentric point may allow multiple users to occupy the mark simultaneously, while an azimuth point can also permit more traditional terrestrial survey work.

6. GROUND MARK PROTECTION

During the last two years, one of the authors (NWH) has visited almost 2,000 ground marks as part of the NGS GPS on Benchmarks project, a community effort to support development of the new gravimetric geoid for the US. Several conclusions can be drawn from this experience.

The loss rate for marks (meaning that the mark could not be found) in the range of 70 to 90 years old is in excess of 75%. Some of the losses are caused by physical removal, often because of development (especially road widening and improvements in design), but also because of 'landscaping.' A very small percentage are lost to vandalism, and often in restricted area, i.e., all the marks in a small area will be damaged. A significant percentage may still be in existence, but cannot be found because of a poor description and the loss of reference points. Some are destroyed by the installation of phone and water lines, and other infrastructure, but road work is a far greater cause of losses.

In some areas, the move away from animal-based agriculture to silviculture and crops means that fences may be removed and land use moved into the road area. Preparation for pine plantations, to give one example, often involves deep ripping the ground, endangering marks. Clear felling forested land involves heavy machinery moving all around the area, including over marks. Similarly, moving cropping even a little way into the road area involves plowing the land, often damaging or removing marks.

Marks that have seen even a little maintenance, in particular the placement of a witness post, a steel rod to aid magnetic location, and an improved and up-to-date description with photos, have a far better rate of recovery. More recent marks are more often found, even without a GPS location from a handheld device, because they have not had as long to experience events leading to their loss.

In order to protect ground marks, several steps are important. The first is placement. Putting the mark somewhere that is less likely to be developed is a great start. This means getting the mark well back from the road itself, seeking places that are likely to remain unchanged over time, and looking for places with few nearby trees and buildings. Cemeteries and graveyards can be good choices here, as can public parkland. Large structures, such as bridges, can provide stable locations, as well as places for ancillary targets. Access to the location for future users is an important consideration, as is avoiding overhead steel objects to minimize possible multipath effects on GNSS.

In almost all cases, ground control points are placed flush with the ground surface, or possibly just below it, using a cover. Very rarely, concrete columns may be used, but these are usually associated with a specific project. Protection for ground-level marks in part depends on their being invisible, but this invisibility can also lead to them being removed inadvertently. Infrastructure of other types may be protected with concrete or steel pillars a short distance away, and perhaps this should be considered in situations where the risk is higher. Protection can be complicated, as accessibility, visibility (especially from above) and avoidance of possible multipath effects are important.

Perhaps the two most critical means of protecting marks are public education and regular maintenance. Both require on-going funding, but this is necessary for maintaining the geospatial reference system in the first place.

Public education should be easier to achieve today than in the past. Almost everyone has a smartphone, which is a geospatial location, data collection and dissemination device. Getting the users of these devices more interested in both the applications of their device and the infrastructure that support it should be easy. This can be done through public education channels, through targeted advertising, and can be combined with regular school education, plus outreach and recruitment for the profession. Getting people more interested in the infrastructure that supports their daily lives is a means of protecting it: remarkably few people destroy power lines and roads because they don't understand them. A strong global education effort will also help recruit more people into the geospatial professions.

System maintenance is also an important way to maintain the physical aspect of a nation's national geospatial reference system. Many nations can raise the funds to build such a system, but may not be able to find the on-going funds to maintain it. This leads to a deterioration of the system, which may be cheaper to rebuild than bring back, all of which tends to be far more expensive than on-going maintenance. On-going maintenance also allows any new system to build easily upon the existing system, significantly reducing the cost of upgrading and replacing the existing system.

Combined with public education and systems to allow people and organizations to alert a maintenance team if a ground mark may be removed for development will allow a more pro-active effort to maintain the overall geospatial reference system. Regular visits to marks for maintenance by a dedicated team is also a relatively cheap way to avoid losing the physical system over time.

7. MAINTENANCE OPERATIONS

What is involved in mark maintenance? Put simply, it is keeping the geospatial infrastructure at a usable standard indefinitely. That can be divided into two complementary and overlapping set of operations.

The first is regular, scheduled maintenance. In most cases, this can be done at intervals of five or more years, depending on the number of marks to be visited. Marks can also be allocated a priority, so marks that have targets and the like associated with them may be visited more frequently than marks that can only be used for leveling. The assumption here is that the marks are not deteriorating or requiring significant change.

Regular maintenance involves tidying up around the mark, ensuring that it is in good condition (undamaged), that sky visibility is maintained, that witness objects are still there and updating the description if there have been changes, that targets connected to the mark are visible and usable, and simply keeping the area usable and accessible. Some clearing of foliage may be needed from time to time, as well as clearing vegetation around the mark. While the maintenance crew is there, upgrades to the make can be made, such as adding RFID material or new targets. The time required may be quite short or may run to several hours if a lot of work needs to be done. GNSS and gravity observations could be made at the same time if they are needed.

Special maintenance would be used to deal with out-of-the-ordinary situations, such as a mark being damaged, or to reset a mark that will be removed owing to construction or similar action. Part of the maintenance process will be the establishment of a system to allow reporting ahead of construction where marks may be affected, allowing the maintenance crew to initiate a resetting process, allowing the 3-D location of the mark to be preserved or used to locate a replacement mark.

In the event that a mark is going to be removed, the maintenance crew can place a suitable replacement mark or a temporary mark, depending on the circumstances, then return after the expected operations are complete and the mark can be reset, or a replacement mark placed and located. In some cases, the regular resetting processes may be followed, while in others a completely new mark may need to be placed and located.

Special maintenance can also be used to relocate marks to more useable locations. There are many marks along abandoned rail lines that would be far better relocated to closer to roads. This can be a special maintenance operation, bringing these older marks into the larger system. As this may involve some leveling, a larger crew may be needed.

It is expected that in most cases, a maintenance crew of one or two people should be sufficient. For simple checking and cleaning up, one person will often suffice, while for clearing it is useful to have two people. Leveling to transfer marks to a more usable location, or setting new marks, will often require more people to allow efficient work.

The purpose of maintenance is trying to keep mark losses to a minimum by being proactive about finding and fixing potential problems in the geospatial infrastructure. In this way, any new marks that may be placed are sufficient to cover occasional unavoidable losses.

8. FUNDING MAINTENANCE

"Alas, there are no votes in mapping." (Bomford, 1979).

Funding maintenance is a serious political problem. In the 1980s it was discovered (by accountants) that if maintenance was cut back dramatically in such areas as geospatial infrastructure and transportation infrastructure, that there was a positive effect on the balance sheet for that year, as maintenance money was saved and there was no significant change in needed work. Repeating this for another year allowed more maintenance money to be saved without significant adverse consequences. This seemed sufficient evidence to support the inductive conclusion that maintenance was largely unnecessary and an unneeded burden on the public purse.

Unfortunately, that inductive conclusion proved to be false, as bridges eventually started collapsing, roads started to fall apart, and the geospatial infrastructure quietly started fading away. It was found that fixing the lack of maintenance was far more expensive than the cost of the maintenance, so cutting back on maintenance is very much false economy. However, maintenance is an attractive item to cut, as the consequences tend to occur in the next political incumbent's term, while the financial benefits accrue in the current financial year.

A better approach to funding maintenance needs to be developed. Projects need to have maintenance built into the full lifespan of the project, meaning a commitment to maintenance for an indefinite time. It may be sensible to allocate funds for several years after the end of construction to be placed into a self-supporting fund to cover maintenance, thereby placing maintenance outside the annual budgeting process. Fees for infrastructure use, if appropriate, can be paid into this fund to help with maintenance.

Similarly, our economic theory and accounting practices need to include maintenance as a necessary part of the project, and realize that the project doesn't end with construction.

Of critical importance is the cost of rebuilding a system if it fails, and how long a system can continue with insufficient maintenance until it fails. We can consider this to be the degree of *entropy* of the system, to level of disorder present in the system. Maintenance reduces disorder and so the entropy of the system. We should be able to develop reasonable measures of entropy in a wide range of systems.

Tied to entropy is the *inertia* of the system, which related to how long it can continue in a rundown state until it suffers a serious failure. Many systems can continue to operate through various work-arounds and band-aids, but at some point there will be a failure. How big the failure is depends upon the inertia of the system.

Some systems do well with significant entropy. There is enough built-in duplication to allow proper operations despite some disorder. An example of this is the land ownership system in the US. Despite significant levels of uncertainty in many parts of the system, there are enough patches and work-arounds to allow it to function reasonably well. (The number of patches and work-around can be seen if one contrasts the process of buying or selling a regular parcel of land, such as a suburban home, in the US and somewhere like Australia. The amount of paperwork in the US dwarfs that required in Australia.)

At the same time, the system of land ownership in the US has massive inertia, because most parcels of land change hands relatively infrequently. If a major problem in the location of land occurred, invalidating many deeds, it may take decades before the full extent of the problem became apparent. This level of inertia means that fixing a serious problem can take a huge amount of effort, with a commensurate cost.

To give some idea of the size of potential problems, the value of private land in the US is estimated to be around $23 trillion. Any damage to that system has the potential for catastrophic damage to the US economy. Similar situations apply to many other nations. Preventative maintenance and general protection of the system simply makes good economic and national security sense. A system that operates with significant entropy is a far easier target for terrorism or cyber-attack, compared to one with little entropy, where efforts to destabilize the system would be seen very quickly. The inertia of such a system would hide the damage for many years. The same can be applied to many other large systems.

The same applies to any massive system, such as a geospatial reference system. The system's inertia allows it to operate with progressively greater entropy, which means a collapse, when it comes, can be catastrophic. As modern economies have become very dependent on geospatial data, the general public have relied on the inertia of the existing system, combined with a lack of understanding of the underlying geospatial reference system, to assume that it somehow magically happens. 'GPS' as a term is considered to encompass navigation systems as a whole and people wonder why GPS doesn't immediately provide a compass function. The idea that GPS and maps are separate entities and that maintenance is a necessary part of the overall system seems to escape most people's attention. To quote Arthur C. Clarke, "any sufficiently advanced technology is indistinguishable from magic," and many people seem to consider spatial location and navigation as magic.

9. FUTURE WORK

Maintenance of the geospatial reference system is a matter of such critical importance that the authors are planning to work on developing pilot reporting and maintenance systems for the physical geospatial infrastructure in Alabama. This will allow estimates of ground mark utility and loss rates, as well as cost considerations, to be made using real data. In conjunction with education efforts to promote geospatial infrastructure and its use across a wider community, we hope to see what impact a focused maintenance effort can have over several years, and use what we learn to develop progressively better systems.

Of critical importance is being able to show realistic costs, coupled with the benefits of having and maintaining the physical infrastructure. This will allow suitable budgeting, as well as the potential to create dedicated funds to support system maintenance over decades. Improvements in the physical infrastructure, including upgrading CORS and installation of InSAR targets, are planned to happen in conjunction with this research, so we will be able to see the effects of improved conditions resulting from improved maintenance.

10. CONCLUSIONS

Ground marks as a central part of the physical infrastructure of a geospatial reference system are still economically and operationally important. While much of modern surveying practice has moved away from the ground marks in daily operations, the importance of ground marks to the overall reference system does not appear to have been significantly diminished. Since their importance remains critical, as the current NGS GPS on Benchmarks project has shown, maintaining this infrastructure also remains critical.

Well-designed and properly placed ground marks provide high-quality location information, but to increase the return on investment into the system, the marks should be able to be used for a wide variety of purposes. To this end, the authors suggest thinking of a ground mark not as a single entity, but as a location where multiple targets for different data collection systems (e.g., aerial imagery, LiDAR, InSAR) can be deployed in a way that allows them to be used without having to visit the ground mark itself. As different systems are developed in the future where ground control is relevant, ways of incorporating this with the existing marks can help the longevity of the physical infrastructure.

Critical to the long-term utility and benefits from the geospatial reference system is the need for maintenance. This has always been difficult to fund, but more creative ways of establishing long-term funding may help overcome this difficulty. Keeping a solid foundation of useful, high-quality ground control marks will help ensure the long-term stability of the reference system, improving its inertia while reducing its entropy. This will help keep costs down and benefits up well into the future.

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BIOGRAPHICAL NOTES

Prof. Hazelton has a long career in surveying and related geospatial fields in Australia and the US. He has published extensively on a wide range of geospatial topics. A member of the US National Society of Professional Surveyors and the Alabama Society of Professional Land Surveyors, he regularly runs workshops for surveyors on a range of subjects.

Ms Wu recently completed an MS in Applied Geosciences at the University of Hong Kong. She has published several articles on surveying, GIS, education issues and archaeology. She currently works with a major water diversion project in China.

CONTACTS

Associate Professor N.W.J. Hazelton
Geospatial Informatics Department,
Troy University,
Troy, AL, 36082, USA.
Tel. +1 334 670-3575
Email: nhazelton@troy.edu

Ms Wu Yitong,
Science and Technology Development Department,
China South-to-North Water Diversion Corporation Limited,
Lingion Rd., Haidan District,
Beijing, China.