America's loss of capacity and international competitiveness in geodesy, the economic and military implications, and some modes of corrective action

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Executive Summary

Geodesy is the fundamental science of geospace. It supports and drives innovation in geospatial technology, the ~ $ 1 trillion/year geospatial economy, and the geospatial systems of nearly all military platforms and activities. In the early 1990s the U.S. government, especially the Department of Defense (DOD), largely disinvested in academic research and education in geodesy. In contrast, the countries of the European Union that contributed the most to the development of geodesy in the preceding centuries have maintained healthy academic training and research programs, which is also the case in Japan, Canada, Australia and New Zealand. Furthermore, in the early 2000's, China began to make large and ever-growing investments in geodetic training and research. It now has more Ph.D. geodesists than the rest of the world combined. During this time period the greatest national collapse in geodetic capability occurred in the U.S., as its geodesists steadily retired, and most were not replaced. The Chinese military and defense industries now have access to hundreds of Ph.D. geodesists. Perhaps the most shocking example of the U.S. decline relative to China is that the number of Ph.D. geodesists in the entire DOD, including the National Geospatial-Intelligence Agency (NGA), is now approaching zero. The same is true of the U.S. defense industry. The U.S. is on the verge of being permanently eclipsed in geodesy and in the downstream geospatial technologies. This threatens our national security and poses major risks to an economy that is strongly tied to the geospatial revolution, on Earth and, eventually, in space.

Averting these dangers at such a late date will require the U.S. to invest in geodetic research and training on an *industrial* scale. We recommend three distinct modes of training necessary to reverse the capacity crisis, and a more diverse and robust approach to the funding of geodetic research. There must be a major increase in funding for basic and applied research in geodesy and in the allied disciplines and technologies. This research should take place in academia, industry and government/DOD labs. All of the U.S. government's geospatial agencies and services should be involved in the direction and funding of that research, to make that process more robust, and to ensure that all the important R&D issues are explored and addressed. A parallel educational effort should incorporate three complementary modes of training: (i) open-access, self-paced, no barrier to entry, internet-based instruction in geodesy designed to recruit large numbers of STEM students into the geodesy and adjacent disciplines, (ii) in-house training programs within the geospatial agencies of the U.S., and (iii) specialized training for the next generation of geodetic researchers. The third mode is necessarily tied to a major expansion of basic geodetic research in academia.

The situation in academia is particularly urgent because if it is not addressed very soon the U.S. will lose its ability to take corrective action at the scale required to avoid permanent disadvantage.

Introduction

Geodesy is the most fundamental science of geospace[1]. It underpins all the other geospatial sciences, all geospatial technologies, the ~$ 1 trillion/year global geospatial economy[2], and a large fraction of all DOD platforms and systems. The persistent decline of geodetic capacity in the U.S. over the last 25+ years, and the loss of competitiveness in geospatial technology that this has already triggered, now constitute a threat to our national security, and expose our defense, space and high technology industries to rising levels of risk[3]. Increasing accuracy requirements, and a growing emphasis on real-time applications, require constant improvements in geodetic techniques and infrastructure that are increasingly being developed outside of the US.

This crisis arose due to the combined effects of two opposed and long-sustained developments: (1) the U.S. government, most especially the DOD, greatly reduced their funding of academic (basic) research and graduate training in geodesy in the early 1990's, a disinvestment process largely completed by the year 1995, whereas (2) China began to make massive investments in geodetic training and research in the early 2000's which have continued, and even expanded, up to the present day.

Consider that:

- There are about 150 colleges and universities in China with undergraduate and graduate programs in geodesy, surveying, mapping and geomatics. We estimate that their combined undergraduate enrollment is in the range of 9,000-12,500 students per year, which provides a huge pool of candidates for graduate training in geodesy. Chinese graduate (M.S. and Ph.D.) students in geodesy are also drawn from undergraduate programs in physics, geophysics, mathematics, aerospace and electrical engineering, and astronomy.
- The city of Wuhan with its university, national research centers and institutes is now the single biggest center of geodetic research in the world. The number of geodesy graduate students educated in Wuhan alone exceeds that of the U.S.
- China has been out-training the rest of the world in geodesy for about 15 years. China now has more geodesists than the rest of the world combined, and its numerical advantage continues to grow. During this time period, the largest national decline (worldwide) in geodetic research and training capacity has occurred in the U.S.
- Geodesy researchers in China are better funded than most of their counterparts in the west.
- China is reaching parity with the U.S. and Europe in terms of the number of peer-reviewed scientific papers published per year in pure and applied geodesy, and its publication rate is increasing more rapidly.

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[1] Geospace includes the Earth, its oceans and ice sheets, its atmosphere and ionosphere, etc., and nearby outer space. Geodesy focuses on the representation and measurement of space, mass and time; reference systems, coordinates and orientation; gravity, rotational dynamics, and orbital mechanics; and how all of these processes and descriptions change over time. Planetary geodesy does the same for the moon, other planets and planetoids.

[2] This includes shipping, aviation, the space industry, driverless vehicles, drones, intelligent grids, computer and smart phone ecosystems, smart cities, location-based commerce, precision agriculture, AI, data analytics, the Internet of Things, as well as a many other scientific and engineering disciplines in academia.

[3] In a 2019 letter to NGA, Neil Vancans, VP of Septentrio USA, a leading developer of GNSS technology, stated that "It cannot be plainer that a range of serious threats will develop if we continue to allow the slow collapse of what is one of the most technologically productive of all the sciences".

The Chinese military and defense industries now have access to hundreds of Ph.D. geodesists. Perhaps the most shocking example of America's decline relative to China, in this strategically vital science[3], is that the number of Ph.D. geodesists in the entire DOD, including the NGA, is now approaching zero. The same is true of the U.S. defense industry.

In the modern world, a major competitive advantage in science quickly translates into a major competitive advantage in technology. This 'domino effect' is not some future prospect, it is already underway. For example:

• China's BeiDou system is at least as good as GPS, and arguably it is significantly better. BeiDou now has more world-wide users than GPS.

• The geodetic sub-systems that enable China's satellites and space program seem to have reached parity with our own.

• The collapse of geodetic capacity in NGA, the DOD and the defense industry will undermine next-generation GEOINT technologies, such as those based on artificial intelligence (AI)[4].

• The near disappearance of American geodesists has led to large numbers of young geospatial engineers who are inadequately trained in the scientific underpinnings of their own discipline[5].

In some cases, the science to technology linkage is imminent, but not yet immediate. For instance, NGA's Earth Gravitational Model EGM2008 was indisputably the world's best in 2012, but now Europe's and China's global gravity models—though highly derivative—are competitive, mostly because they are supported by many physical geodesy specialists, which is no longer the case in the NGA[6]. Such models provide 'gravity compensation' to inertial navigation systems (INS), and the need to improve that technology is quite pressing, given the looming dangers of GPS denial. NGA still retains a major advantage over its competitors, in that it owns the largest global gravity database. But to fully leverage that advantage, it must re-incorporate expertise in modern physical geodesy. The gravity-INS connection will become increasingly important on the moon and other planetary bodies, as well.

America's loss of a world-leading position in global positioning is not an isolated occurrence in satellite geodesy. Most of what we know about marine gravity (and a lot of what we know about ocean dynamics, tides, sea level rise and ocean bathymetry) is derived from satellite radar altimetry. For decades the U.S. was the undisputed leader in this field, but with the TOPEX and Jason satellites, that lead was shared with Europe, and more recently Europe has pulled ahead—and China is making great strides to catch up. Similarly, satellite gravimetry was once dominated by the U.S., but during the GRACE and GOCE

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[4] In 2019, Anthony Robbins, NVIDIA's VP for the Public Sector, stated in a letter to NGA: "it is essential that new AI-powered GEOINT capabilities be developed around a fundamental competency in geodesy and geospatial science in order to maximize efficacy and ensure long-term viability".

[5] In 2019, Trevor Greening, CTO of Towill, Inc., a leading geospatial engineering company, stated: "we have noted that the rapid development of many new technologies has placed a premium on geodetic science knowledge" but "we see graduates insufficiently skilled to comprehend the basis of the new technology including hardware, software, and procedures".

[6] We intend no disrespect of the hardworking geophysicists, physicists and others engaged with EGM at NGA. We simply assert that the world's largest and most complex physical geodesy project needs the active participation of physical geodesists. The Manhattan project at Los Alamos necessarily required the participation of chemists, mathematicians and engineers, etc., but what would have happened if all the physicists had disappeared?

missions Europe reached scientific and technological parity, and given that it now has many more physical and satellite geodesists than the U.S., it seems set to take the leading position. And in terms of civilian (unclassified) satellite missions, at least, Europe now has the leading InSAR technology. This decline in America's competitiveness on Earth has major implications for the moon and space race, too.

The U.S. disinvestment process not only restricted basic research in pure and applied geodesy, thereby reducing the flow of the new ideas and knowledge that drive innovation in our geospatial technologies, it has done tremendous damage to academic programs in geodesy as well. This is particularly worrying, in that the programs that should play a central role in any concerted effort to reverse America's 25- to 30-year blunder might soon be too few and too small to have any significant impact.

The situation is not uniformly bleak. The National Science Foundation (NSF) has had a positive influence on geodesy in this century, especially in terms of America's geodetic infrastructure. It funded the development and maintenance of a national GNSS network (now referred to as NOTA) to support research in the Earth sciences. This remains the most important geodetic network in the US. But NSF's core purpose is supporting scientific discovery and innovation, therefore it cannot divert large parts of its funding to *permanent* operational infrastructure. So, NSF is now disinvesting in NOTA. It would make sense for an operational geodetic agency such as NGS to take over NOTA, but, characteristically, NGS does not have the necessary resources. So, this major geodetic asset is being downsized and slowly degraded instead. While NSF does fund applied geodesy, essentially as a tool for many other sciences, it very rarely funds basic research in geodesy itself. The Directorate of Geosciences in NSF has many dozens of scientific funding programs, but it has never had one in geodesy *per se*.

Today, the single biggest institutional center of basic and applied geodetic research in America is NASA. During the 1980's and early-mid 1990's, NASA was a major funder of academic research in geodesy. Now, nearly all NASA funding in geodesy, most of which is for applied geodesy, is consumed internally. NASA does not play a significant role in geodetic training. While NASA's internal capabilities in geodesy, including at its laboratories, have not suffered to the extent seen in the NGA, DOD, NGS, USGS, etc., it has not been able to stem the national collapse in geodetic capacity, nor prevent the centers of expertise in radar altimetry, satellite gravimetry or GNSS shifting towards Europe and/or China.

Given that the U.S. capacity collapse in geodesy developed slowly, over three decades, most of the relevant government leaders must have failed to recognize what was happening, since no agency intervened. While the consequences of U.S. disinvestment and Chinese investment were not obvious in 2005, by 2015 nearly all experienced geodesists could see what had happened, and what would happen next.

The geodetic and geospatial authorities in China, for the last 15 years at least, were in possession of the facts and their implications that proved so elusive for most of their American counterparts. This 'awareness gap' has worked very powerfully in China's favor, bringing us uncomfortably close to the point of no recovery. We suggest that understanding the *mechanisms* that promoted unawareness, determining which still operate, and what other consequences they might produce, should be a high organizational priority (especially in the DOD), if the U.S. seeks to recover much of the geodetic/geospatial ground it has ceded to other countries. We suggest possible mechanisms in the Appendix and invite additional ideas from you.

The fact that China's large investments in geodesy and adjacent disciplines not only persisted, but have increased over time, suggests that China seeks to pass the U.S. with high forward velocity, while the U.S. continues its slow and backwards drift. This would allow China to take a commanding lead in "one of the most technologically productive of all the sciences"[3], and the downstream technologies, and thereby attain a permanent geospatial ascendancy.

A dawning but nationally incomplete recognition of the crisis

In 2017, Juliana Blackwell, the Director of the National Geodetic Survey (NGS), told Ohio State University (OSU) leadership that "the rapidly shrinking pool of well-trained, American geodesists now threatens our ability to achieve core aspects of the NGS mission, and we are sure this concern is shared by NGA and other agencies of the Federal Government"[7]. In 2018, Director Blackwell noted in a letter to the NGA that "the reduction in the population of graduate students training in this field is clearly tied to declines in government funding of geodetic research in academia". The DOD was long established as the largest funder of geodesy training and research circa 1990, so its subsequent disinvestment had a particularly large impact on American geodesy in academia, in industry[8] and, eventually, in the DOD itself.

While the recognition and the diagnosis of the problem by the NGS is very welcome, we have not observed any vigorous and concrete actions that suggest this understanding extends 'upwards' to NOAA, at the top of the organizational chart, or has led to a determined effort to revitalize geodesy in the NGS or in academia, before it is permanently eclipsed.

Some geospatial agencies have a detailed understanding of the crisis, but cannot seem to communicate it upwards; for other agencies the understanding itself is incomplete.

During an extended OSU-NGA-NGS study[9] of the U.S. geodesy crisis, which began in early 2018 and continued through early 2020, nearly all the NGA scientists engaged with global gravity modeling had an understanding similar to that of geodesists in academia and the NGS. Some NGA administrators shared this view, but others seemed uncertain as to whether the capacity crisis was focused in geodesy, or was

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[7] Indeed, in 2019, Kevin Gallagher, the Associate Director of the U.S. Geological Survey wrote to the NGA saying "The USGS shares the concerns expressed by both the NGA and the National Geodetic Survey (NGS) that the candidate pool of trained geodesists eligible to work for U.S. government agencies is currently inadequate to support our missions in the future".

[8] In 2019, Dawn Wright, the Chief Scientist of ESRI stated in a letter to NGA: "We are well aware of the alarming shortage of geodetic scientists in the USA, and the fact that far fewer Americans have been trained in this discipline in the USA than is true in Europe, Japan and China. The American shortage has grown to its present crisis stage over a period of about two decades. China's spending on fundamental research and development, and on higher education, in geodetic science and geomatics, is probably now an order of magnitude greater than in the USA, and that gap appears to be growing".

[9] This study led to the white paper "*The Case for a DOD University-Affiliated Research Center (UARC) focused on Geodesy and Geospatial Technology*" by M. Bevis, R. Salman, D. Caccamise and C. Sanford (2020), available on request from the NGA Office of Geomatics.

uniformly distributed across all the geospatial disciplines—even though NGA had ~2,000 GIS specialists, but only 2 Ph.D. geodesists (one close to retirement age.)

Curiously, exactly the same misunderstanding—that geodesy is not the epicenter of the geospatial crisis—was and remains common among university administrators, despite the fact that there are more than 50 very good and viable GIS programs in American universities, while only a handful of tiny geodesy programs remain. In some universities, remote sensing groups can be found in many different colleges and departments focused on Earth and environmental sciences, biological science, engineering, forestry, agriculture, economics, and geography. But in most of these universities there is not a single geodesy program. We suspect that the mechanisms responsible for this administrative indifference to geodesy are peculiar to academia (*e.g.*, resource battles between disciplines and sub-disciplines, and a tendency to equate value with size), but its consequences—the slow but continuing decline of U.S. geodetic capacity—are not.

If an agency, institution or institutional sector (such as academia) remains uncertain about the structure of the U.S. geospatial crisis, then any corrective actions it adopts are likely to be off-target and sub-optimal. Therefore, we consider the NGA's recent (December 2021) RFI expressing interest in a future consortium focused on expanding research and training capacity in geodesy and adjacent geospatial disciplines to be a very encouraging development, particularly because the statement of work places so much emphasis on pure and applied geodesy. Much will depend on the scale, speed and the success of this initiative.

At the time of this writing (Oct-Dec 2021), it seems that the military services and their scientific research offices either have not recognized the U.S. geodesy crisis, or place relatively little importance on it. It is not surprising that the part of the government which led the disinvestment process, and which no longer contains any geodesists, would take longer to understand the problems driven by its withdrawal. Disengaging with a science obviously discourages awareness of that science and its role in adjacent disciplines, technologies and applications.

Several of the authors of this white paper have encountered strange misconceptions among individual scientific administrators in U.S. geospatial and defense agencies. One member of a scientific funding agency within the DOD has repeatedly stated to several of us that there has been no need to fund geodesy research for decades because all important geodesy problems were solved many years ago. We wonder why this person thinks China is investing many tens of millions of dollars in geodesy research every year—because they are deeply curious about the unimportant? If there is a crisis of the imagination here, it is not in the science itself. The number of interesting scientific questions in geodesy today, all pregnant with possibilities for geospatial technologies and applications, greatly exceeds the numbers of open questions and opportunities that prevailed 25 or even 15 years ago. Beliefs to the contrary are worrying in an office whose central purpose is the funding of strategically-important R&D.

Another example: a DOD scientist-administrator has remarked in encounters with academia (that included more than one of us) that there *is* a serious capacity crisis in geodesy, but it can be resolved by recruiting physicists, engineers, and other members of the STEM community. This is roughly equivalent to saying that a shortage of quantum physicists might be resolved by recruiting and repurposing mechanical engineers and statisticians. So why are Europe and China making such very large investments in the training of geodesy specialists? Presumably because they understand that they will win an increasingly complex and challenging geodetic contest (on Earth and in space) if their competition is almost entirely composed of non-geodesists.

We do not mean to single out any one institution, since there is plenty of blame to share. The academic geodesists co-authoring this white paper know, only too well, that the 'awareness gap' pervades American academia, just as it does much of our government and the DOD. This is why the few remaining American geodesy programs are small and mostly shrinking, while larger programs in Germany, for example, remain viable[10], and much larger programs in Chinese universities are vigorous, well-endowed and growing.

We are convinced that the fate of geodesy in U.S. academia, NGS and the NGA are all bound together.

Corrective action: Some objectives

It is not too hard to *imagine* the national situation of geodesy *if and when* the U.S. had reversed its disastrous course. There would be many more geodesists in the government, in the defense, high tech, space and geospatial industries, and in academia. There would be much larger budgets focused on geodesy and its interface to downstream technologies and applications. Not only would the NGS be far more active in geodesy, but so would its parent organization NOAA[11]. The NGS, in partnership with state survey agencies, would take over the NOTA GNSS network that NSF no longer wishes to support, and further develop its capabilities and applications. The NGA Office of Geomatics and the NGA Research Directorate would have been assigned the resources that allow them to make much larger internal and external investments in geodesy. Military research offices such as AFOSR and ONR would have re-engaged too. The USGS would have more geodesists than it did in 1995 and not far fewer, and, like its sister agencies, it might choose to emphasize methodologies, technologies and applications of special interest to it (e.g., real-time earthquake hazard warnings, or geodetic imaging of flood plains). There would be far more government-industry-academic partnerships in geodesy and the adjacent disciplines and applications, and forums in which all three stakeholder groups could explain their experiences, perspectives and ambitions to the others. There would be a national movement to recapture America's place as a leading global player in pure and applied geodesy, and to translate that gain into more advanced geospatial technologies, novel applications, and improved national and economic security.

To ensure that the renaissance of geodesy was robust, the funding of geodesy research and training would be decentralized. Geospatial agencies, such as the NGS, which had been designated 'non-funding agencies' by the central government, would be reclassified as funding agencies. It makes sense that geodetic agencies be intimately involved in the funding of external geodetic research and not just focused on their internal geodetic activities. The renaissance will be more successful, and more rapid, if agencies

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[10] German geodesy graduate programs are often based in research institutes, and often benefit from considerable support from China. For example, the Space Geodetic Techniques section of GFZ's Department of Geodesy has more than 30 Ph.D. geodesists, and roughly half of them were trained in China.

[11] Why is it that GPS Meteorology, which was invented in the USA, was perfected in Europe, where it has helped to produce the best numerical weather predictions in the world, despite that fact that the necessary collaboration between geodesists and meteorologists required an international collaboration in Europe, versus a domestic collaboration here? It is ironic that NOAA contains both the National Weather Service and the National Geodetic Survey, and that most of the inventors of GPS Met were based in U.S. universities, but is more than one decade behind Europe. Characteristically, China's investments in GNSS Meteorology now dwarf those of the USA.

with differing specialties and goals are all driving investments in research, training and geodetic infrastructure. Such a diverse approach would require national coordination (e.g., on shared geodetic infrastructure), but given that different agencies are interested in different areas of geodesy, having most of them involved in funding decisions will help research in every important branch of geodesy become adequately funded.

The problem, of course, is *getting from here to there*. Even if the DOD and other government agencies wanted to quadruple the number of geodesists they employ within a year, they would find that there are not enough geodesists available, because America's graduate research and education programs have been starved of resources for decades, and our national training capacity is now absurdly small. It follows that one of the highest priorities, especially at the beginning of the renaissance, should be to grow national training capacity as quickly as possible, and here revitalized academic geodesy programs must do the heaviest lifting (though summer internships in government and industry would help). As we explain below, graduate training in geodesy and basic research in geodesy are intrinsically coupled. There must be a major and sustained increase of basic and applied research in geodesy in the U.S. to drive innovation in our geospatial agencies and industries. Such research programs will provide the training grounds for most future geodesists.

Recovery mechanism 1: Greatly expanded training and recruitment

We believe that to reverse the U.S. collapse in geodetic capacity it will be necessary to engage in three distinct modes of training[12], and to succeed at them all.

Mode 1: A general education, outreach and mass recruitment effort aimed at thousands (eventually tens of thousands) of mostly young people, that provides free, self-paced and useful instruction in the various branches of geodesy via the internet (using a YouTube channel for example), supplemented by occasional 'inspirational' videos in which geodesists and other geospatial specialists from the NGA, NGS, different branches of industry, and academic research groups describe the fascinations of our discipline, the adventures of geodetic fieldwork, and the career opportunities available to suitably-trained individuals. The hope is that a significant fraction of these trainees would eventually enter one of the geospatial professions, including geodesy. The objectives of Mode 1 training include

• Mass recruitment of young STEM talent into geodesy—in grad school, the NGS, the NGA, the DOD, the USGS, the geospatial industry, the defense industry, high tech companies, the space industry, etc.

• Basic or supplemental training in geodesy for the people already working in the other geospatial sciences, geospatial engineering, etc., that currently lack the geodetic skills that they need[5] .

• Basic training (via the entry level courses) for managers and administrators who need at least a passing familiarity with the concepts, language and techniques of geodesy, and an understanding of the relevance of geodesy to other geospatial sciences, geospatial technology, geospatial services and applications, i.e., across the entire spectrum of what some now call the 4th industrial revolution.

• Increasing the 'visibility' of geodesy in other STEM disciplines

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[12] This theme is developed at greater length in a white paper by M. Bevis (2021) *"Can the USA train itself out of the capacity crisis in geodesy and geospatial technology?"*, available on request (mbevis@gmail.com).

To maximize the scale of Mode 1 activity it is essential to eliminate *all* barriers to entry, which means no tuition, no requirements, no exams, no schedules, no imposed rate of learning, etc. Therefore Mode 1 training is learning for its own sake, and delivers no grades, certificates or degrees. However, it can be used to prepare people (at their own pace) for formal modes of education that do provide credentials, should they so wish.

All U.S. academics understand that one of the biggest challenges of teaching the present generation is that it has a much shorter attention span than had students 25 years ago. This means that the video training courses must be of very high quality, unusually compelling, up-to-date and relevant.

Mode 2: In-house training (basic and supplemental) of the existing employees of the government's geospatial organizations, via remote-access to university courses, by enrolling part-time in local universities, or providing employees with leave to obtain certificates or an M.S. degree from a full-time graduate program anywhere in the country, at the geospatial organization's expense. Without Mode 2 training, organizations like NGA cannot help their own employees adapt to the evolving technical requirements of their missions, or the constant reinvention of the geodetic sciences and technologies[5], and it will also be difficult for these employees to grow their technical competencies from one geospatial discipline into an adjacent one.

Mode 3: Advanced academic training for young researchers. The purpose of teaching or training is to disseminate or propagate existing knowledge, whereas the purpose of research is to discover or create new knowledge. Young scientists learn to do research by working with already accomplished researchers on important and difficult research problems. In practice, academic research projects both produce new knowledge *and* train the next generation of researchers. Each generation of researchers, at their peak, will create the future of their science, and they will train the next generation of researchers.

Nearly all truly *major* innovations in any science, including geodesy, are made by just the top few percent of the professional research scientists in that field, and nearly all of these were trained in the context of high-level research projects, mostly in strong and established graduate programs[13]. The greater the number of researchers in a given science, the greater the rate of major breakthroughs. Therefore, a significant fraction of the most talented and hardworking (and mostly young) scientists that can be encouraged to enter a strategically important field, such as geodesy, should become full-time graduate students engaged in serious research in a top-flight program. One reason we need Mode 1 training is to attract a lot of young people into a very big basic training and selection funnel[14].

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[13] Think about the physicists who built the atomic bomb in Los Alamos. They were either leading academic physicists of the day, like Fermi, Bethe, Oppenheimer, and Wigner, or they were graduate students in, or recent graduates of top physics programs, like Richard Feynman.

[14] Continuing with the physics analogy, if one or two thousand students enter the physics funnel as undergrads, many hundreds go on to grad school, many dozens or perhaps one hundred become professional Ph.D. level researchers, and while nearly all of those scientists will play very useful roles, probably less than five of them will make truly ground-breaking discoveries or innovations. Presumably this is one motivation for the great size of China's geodetic training apparatus.

Recovery mechanism 2: Greatly expanded research and technical development

Basic research drives applied research and technology forward[15]. Basic research fills the reservoir of new principles, facts and opportunities that supply and power technological innovation. If a nation's capacity for basic research shrivels, its downstream technologies will surely follow. The history of science makes it clear that it is impossible to predict if a given basic research project will lead to a major discovery. Most truly transformative discoveries are accidents that occur in front of well-prepared minds. The way to increase the probability of major scientific advances, is to have larger numbers of research groups poking around at the boundaries between the known and the unknown in the areas of interest.

China is pursuing a nearly optimal strategy. If one examines the acknowledgements sections of China's peer-reviewed scientific publications in pure and applied geodesy, one notices two patterns: (i) most research groups, even not particularly accomplished ones (as yet), are citing support from anywhere between 3 and 8 research grants or contracts, and (ii) Chinese government funding agencies often fund 5-10 research groups to work simultaneously in the same area of geodetic research. In most cases these overlapping investigations are largely independent efforts, though most cite the major findings of the others. This redundant or duplicated tasking increases the probability of success. Chinese industry certainly takes advantage of these discoveries, and it also absorbs a significant fraction of the research students who cut their teeth on fundamental research projects.

In the last year or two, increasing numbers of China's geodetic research papers are being published in Chinese. This change must reflect a reversal in government policy. While the Chinese research community, mostly fluent in English, can assimilate the West's publications, that advantage is asymmetric. Presumably, the shift in publication policy reflects the Chinese government's conviction that soon, if not now, the West will have more to learn from Chinese research in geodesy than vice-versa.

Unless there is a major expansion of both basic and applied research in geodesy in the U.S.—soon—we believe that it is inevitable that China will surpass both the U.S. and Europe, not just in these disciplines, but in most of the technologies and applications they support. While our *basic* research should be concentrated in academia (though not exclusively so), applied research should be pursued in academia and our geospatial industries and the geospatial agencies of the government and the DOD. Industry, government agencies and the military would also tend to lead most 'operational' applications.

While China has learned from America's traditional approach to the funding of science and technology, at this point we need to learn from theirs. There should be a concerted effort to fund multiple geodesy research projects in each academic geodesy program, ensuring that these contracts and grants allow for the expansion of the geodetic faculty and their Ph.D. staff scientists and technicians, and provide the necessary funds for many more American graduate students as well. More than one research group should be funded to investigate any technically difficult and potentially crucial topic. As the community of U.S. geodesists expands, so should the level of funding, to keep this growth on track. There should be regular

[15] There is a positive feedback: new technologies provide new tools for basic research, extending its reach into the unknown. The relationship between science and technology is like that of a double helix, with each helix climbing up the back of the other.

encounters between academic geodesists, their students, government geodesists and industry, not only to seek synergies in R&D, but so that recent M.S. and Ph.D. graduates are quickly and optimally placed.

Concluding remarks

The DOD began to withdraw its support for academic geodesy around the time that it fully realized its original conception of the Global Positioning System (GPS) and established itself as the world's only geodetic superpower. This disinvestment was not an isolated event: the DOD also closed down its own geodetic research group in Hanscom AFB, for example. In retrospect, we can see that it was GPS rather than earlier developments in satellite geodesy that really launched the geospatial revolution and what is now a vast geospatial economy. GPS drove an explosion of scientific and technological creativity that extended far beyond the original conception of 'positioning, navigation and timing'.

Based on his wartime experiences, Vannevar Bush[16] published in 1945 his highly influential report "Science, The Endless Frontier" in which he argued that basic research was the "the pacemaker of technological progress" and explained that "new products and new processes do not appear full-grown" but are "founded on new principles and new conceptions, which in turn are painstakingly developed by research in the purest realms of science!" Europe, and especially China, were deeply impressed by the strategic, technological and economic advantages that accrued to the U.S. as a result of its enormous investments in science in the aftermath of WWII ("the physicist's war"). They still believe this formula to be valid, while the DOD seems to have lost that conviction, at least when it comes to geodesy.

Perhaps the DOD felt in the early 1990's that it could leave all basic geodetic research to the NSF and NASA. However, while NSF has funded many scientific *applications* of geodesy (in tectonics, seismology, glaciology, climate change, etc.), it has rarely funded the development of geodesy itself. NASA has supported basic research in geodesy, but its funding of external academic research in geodesy, especially basic research, has declined in relative terms, and now amounts to a very small fraction of the investments being made in basic geodetic research and training by the Chinese government.

One of us recalls the DOD geodesist Owen 'Obie' Williams telling him that he had just attended a Pentagon meeting where he was told by a group of generals and admirals that there was no "military requirement" for geodetic positioning with an accuracy better than 1 meter. This was around the time that the DOD began to withdraw funding from its own geodesists, and those in academia and industry. The traditional criticism of generals is that they are always preparing for the last war. In this case, these military leaders were fixated on the applications of geodesy that they could then identify then, based on past experience, with little interest in what might lie just beyond the "endless frontier".

China seeks to eclipse the U.S. in many strategic sciences, but we assert that it is in the field of geodesy that this goal is closest to being *fully* realized. It is not too late for the U.S. to reverse course, but only if it

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[16] Bush was an engineer by training, a prolific inventor, a public intellectual, and arguably the greatest scientific administrator of the 20th century. During World War II he chaired the National Defense Research Committee, and later the Office of Scientific Research and Development that coordinated nearly all wartime R&D. After the war he was, in effect, the first presidential science advisor.

starts to do so very soon. If the necessary corrective action is delayed for several more years, the U.S. will have to send most of its future geodesists to Europe or China to obtain the necessary training. It is also important for the U.S. government to realize that governments, including the military, have *always* been the main funders of geodesy research and training, and that this is still the case now over most of the developed world. It certainly is in Europe, Japan and China. The recently established geodetic/geospatial partnership involving academia, government and industry in Australia provides another case in point.

The American geodetic community bears some of the blame for its own decline. It has been far too passive as it has watched its government and increasingly 'corporate' university administrations undermine the nation's research and training capacity in one of the most technologically productive and strategically important of all the sciences. We must do better than that.

Awareness of the U.S. geospatial capacity crisis, and the central role that geodesy plays in that crisis, has become more widespread than it was just 2-3 years ago. Even so, we remain very concerned that the national response could easily prove to be 'too little, too late'. Gearing up an adequate response at this late date will require a wider and deeper appreciation of the problem in government and the DOD, a shared commitment to overcome it, a coordination of vision and effort across academia, industry and all relevant civilian government and military agencies and services, and large and sustained investments. We believe that much can be learned from China's human and capital investments in geodesy and the adjacent disciplines and technologies, including their use of parallel or redundant tasking in the pursuit of its key goals, so as to ensure that its overall strategy is much less vulnerable to sequential 'weakest link' failures.

APPENDIX

Mechanisms that blocked and may still limit institutional and national awareness of the U.S. capacity crisis in geodesy and some adjacent geospatial disciplines

What were (and are) the mechanisms that created and sustain such a costly awareness gap between the U.S. and China? We are not experts in organizational dynamics, but we can offer the following ideas:

• *Broken lines of communication* in top-down systems of policy making and implementation, that block 'upward' transmission of information from the technical experts who best understand a given problem (and the possible avenues of redress) to those with the power and resources to drive the necessary change[17]. This is a particularly potent mechanism in any organization that strongly adheres to 'narrow' chains of command. Even one or two people in the middle of a communication channel one person wide can block vital information from reaching the leaders (who really need to know) for years at a time.

• *Divisional conflicts of interest*. The term 'conflict of interest' is widely used, usually in a highly negative context, but we use it in a rather more general sense. By divisions we mean the sequential embedding of smaller organizational units in larger ones, as in NGS-NOS-NOAA, or Office of Geomatics-NGA-DOD, and, in some cases, we refer to conflicts between organizational units that are placed at the same level in the organizational chart of their owner, for example, different colleges within a university. The conflicts of interest may be hidden or obscure, but more often they are not, and they may include differences in priority that make sense at the divisional level, but do not serve the interests of the parent organization, or, in this case, the national interest.

• *Monetary distraction*, by which we refer to people and institutions being so fixated on the big money/ large scale applications end of the geospatial spectrum, they do not perceive a rolling collapse propagating from the opposite (scientific) end of the spectrum. Picture an inverted geospatial pyramid [18] which grows upwards from its narrow scientific tip, geodesy, through geospatial technology, large-scale geospatial engineering and services, to governmental, military, space and business applications. The present global economic value of that pyramid is roughly $ 1 trillion per year. Nearly all that money is concentrated in the top third of the inverted pyramid. Mission-oriented entities like the military naturally tend to focus on applications, and on very-big-money programs as well. They have been staring at the top of the inverted pyramid, while its tip or base is crumbling, threatening the technical and economic integrity of the entire edifice.

• *Self-reinforcing trends*. That is, positive feedback mechanisms that amplify original forcings. Geodesists often joke that geodesy has become an 'invisible science' [19]. One of the problems of a shrinking pool of experts, is that there are fewer encounters between those technical experts and senior organizational

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[17] As in the punchline of a military joke, "General, we need some PWAKS". People Who Actually Know Something.

[18] The inverted geospatial pyramid is discussed in greater detail in "*The Case for a DOD University-Affiliated Research Center (UARC) focused on Geodesy and Geospatial Technology*" by M. Bevis, R. Salman, D. Caccamise and C. Sanford (2020), available from the NGA Office of Geomatics.

[19] This is rather ironic, since about 3.5 billion people worldwide, knowingly or unknowingly, utilize one or more Global Navigation Satellite Systems (GNSS), including the Global Positioning System (GPS), via their smartphones, every day.

administrators, so the technical misconceptions or wishful thinking of the latter are much less likely to be corrected. If and when corrective measures are finally adopted, they may be so detached from technical feedback and reality, that they have very little prospect of success. The numerical decline in the number of representatives of a particular technical discipline will often lower their political clout, and even suggest to some non-technical administrators that, by association, their discipline is unimportant, and unworthy of administrative concern.

• *The Geospatial Tower of Babel*. Here we refer to confusion driven by ambiguous or misunderstood terminology that the disciplines of geodesy, the other geospatial sciences, and geodetic/geospatial engineering, have used to describe themselves or each other. We address here the most worrying of these confusions.

The term 'geomatics' was created in the 1980s and emphasized in the 1990s and 2000s. Some agencies and universities changed their program names to include the word geomatics. The term geomatics was based on the concept that the increasing potential of electronic computing was revolutionizing surveys and representation sciences: "Geomatics is defined as a systemic, multidisciplinary, integrated approach to selecting the instruments and the appropriate techniques for collecting, storing, integrating, modeling, analyzing, retrieving at will, transforming, displaying, and distributing spatially georeferenced data from different sources with well-defined accuracy characteristics and continuity in a digital format."[20] It does state the following: "Erected on the scientific framework of geodesy, it uses terrestrial, marine, airborne, and satellite-based sensors to acquire spatial and other data". But, geodesy has, in effect, been eliminated from the definition of geomatics used by most people today. In academia, geodesy is usually considered to be distinct from geomatics. But this understanding is not universal.

This ambiguity as to what geomatics really means, and, even more importantly, what it depends on, has led some individuals to believe that investments in geodetic research are not necessary for innovation in geospatial technology. Nothing could be further from the truth. Advances in geospatial technology often depend on advances in geodesy. Furthermore, optimal utilization of a geospatial technology often requires a sophisticated understanding of geodesy.

• *The Tragedy of the Commons* refers to a situation in which people (but also organizations and governments) with access to a shared resource (*i.e.*, the commons) pursue their narrow self-interests to the extent that they collectively deplete or destroy that resource. In this case, each of the many geospatial funding agencies, civilian or military, that rely on geodesy, focuses its investments on geospatial applications of greatest interest to them (be it climate change or satellite technology), and leaves all the other agencies to support the infrastructural science that underpins the common good. As a result, that resource is not nurtured or renewed at all, but relentlessly declines, which ultimately damages *every* entity engaged in such 'selfish' or myopic behavior.

We invite you to write to us with additional mechanisms that can explain a major strategic blunder that took at least 25 years to unfold, and did so in plain sight, apparently undetected.

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[20] for example, Appl Geomat (2010) 2:137–146, Basics of geomatics, Mario A. Gomarasca, Published online: 27 July 2010, National Research Council of Italy.