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Autonomy in Satellite Navigation Systems: The Indian Programme

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India is developing an Indian Regional Navigation Satellite System (IRNSS) to provide itself and neighbouring countries with the Position Navigation and Timing (PNT) service. This project is likely to become operational by 2015. Initially, the system will have seven satellites, and the number will later go up to 11.[1] IRNSS will be an independent 7 satellite constellation, built and operated by India with indigenous capability: three in GSO and 4 in non-GSO (inclined 29 degrees with equatorial plane).[2] India has already launched three satellites of their constellation and one thereafter, thus making the initial phase of this system operational.

The IRNSS will provide an absolute position accuracy of approximately 20 metres throughout India, and within a 2,000 km region around it.[3] The system is expected to provide two types of services: one for civilian use, and another as a restricted encrypted service for specific users.

India has also developed the GPS-Aided Geo Augmented Navigation (GAGAN) system. GAGAN is interoperable with GPS, and provides greater reliability than GPS alone. GAGAN has been designed primarily for civil aviation purposes and, when it becomes fully operational, it will be useful in aircraft landing where accuracy of six meters is desirable.[4] The IRNSS is expected to cater for the presence of GAGAN. It will be designed to maintain interoperability between GAGAN and other regional augmentations to the GPS for global navigation.[5] The first GAGAN navigation payload was launched on 21 May 2011 on board the GSAT-8 communications satellite. With this satellite now in position, the process of certification has begun for India's Satellite-Based Augmentation System (SBAS).[6] During January 2014, the Director General of Civil Aviation (DGCA) certified the GAGAN system to RNP0.1 (Required Navigation Performance 0.1 Nautical Mile) service level.[7]

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Background

It is an established fact that primitive tribes used the sky as a guide for path finding. Medieval humans mostly used various star position based techniques for track detection and location identifications. Broadly, such direction finding techniques are commonly known as navigational techniques. In the modern world, navigation involves monitoring and controlling vehicles on land, in water, or in air/space. Navigation can also be viewed as an instrument or mechanism to fix the position and direction of an object. These techniques are based on trigonometry, and owe their origin to the science of astronomy which is probably the oldest of all the sciences to demonstrate the finding of location by using the positions of the stars in the sky. Since then, the techniques for navigation have evolved significantly and, for some years now, satellite based navigation is in use.

This essay analyses the politico-strategic significance of various existing and futuristic space navigation systems. The essay has three major sections: the first section presents an account of global space navigation systems; the second discusses the socio-economic aspects of these systems; and the last section debates the strategic relevance of space navigation.

The Navigation Narrative

The initial investments in designing and developing satellite based navigational systems were made in the early 1960s by the then two superpowers. The first such system came into being during the mid-1960s. Transit, a naval navigation satellite system, was deployed by the US military in the 1960s, and was operational till 31 December 1996. This system was based on the principle of the frequency shift. By monitoring the shift in frequency over a period of time, the system used to identify the location. A minimum of four operational satellites were required for this purpose.[8]

Transit began operating in 1964, with five satellites that broadcast two different tones in a polar orbit. The use of two tones allowed the system to compensate for variable signal delays that occurred in the ionosphere. One satellite became oriented upside down, its antenna pointing away from Earth and, due to the limitations of its stabilization system, could not be re-oriented. However, the remaining satellites were adequate. It took submarines six to 10 minutes to get a fix, which was accurate to within 25 meters.[9]

It is important to note that the basic efforts towards the development of navigational systems during 1960s/70s had a nuclear backdrop. It was the era of the nuclear stalemate, and investments in space were mostly viewed from the point of view of possible advantages such investments could give to add 'teeth' to the nuclear arsenal. The first satellite-based radio navigation system developed by the erstwhile USSR was the Tsiklon.[10] This system had thirty one satellites which were launched between 1967 and 1978. The basic aim behind developing this system was to provide positioning facilities to ballistic missile submarines.

The Tsiklon series was followed by the fully operational 'Tsyklon-B' or the 'Parus' system. This system was formally inducted into service in 1976; however, the full 22 satellite constellation did not become operational until 1980. The Parus series satellites continued to be launched until April 2010, and it is believed that now these satellites are being exclusively used for military communications. The Parus was followed by the Tsikada – a simplified system for civilian use. In fact, the Parus is sometimes referred to as the 'Tsikada Military' or 'Tsikada-M'. The Tsikada system was put into service in 1979, and acquired its full complement of satellites (ten in number) by 1986. The Tsikada was largely used by the Soviet merchant marine.[11]

The present generation satellite navigational systems are more direct. The satellite broadcasts a signal, with the exact time of transmission and the position of the satellite.

> The receiver compares the time of the broadcast encoded in the transmission with the time of the reception measured by an internal clock, thereby measuring the time-of-flight to the satellite. Several such measurements can be made at the same time to different satellites, allowing a continual fix to be generated in real time.[12]

The system overcomes various technical limitations – like problems arising due to fast moving receivers, etc. Errors are reduced by various filtering techniques.

It could be argued that the revolution in space navigation happened with the approval of the GPS (global positioning satellite network). For many years, this single US system has become synonymous with satellite navigation. During 1970s, and under the direction of Bradford W. Parkinson (a US Air Force colonel then, and subsequently Professor of Aeronautics and Astronautics at Stanford University) was instrumental in developing a military satellite navigation system called the Global Positioning System/NAVSTAR. Its first 'Phase 1 bird' was launched in February 1978 and, when the system was up and running, it provided positions accurate to within 10 meters. The signal was specially encoded so that civilian users were only able to obtain locations with an accuracy of about 50 meters. Subsequently, a constellation of 25 GPS satellites was developed.[13]

During last few decades, the GPS has been responsible for bringing about significant changes in military tactics, and has also created various new applications for civilian use. Presently, the GPS could be viewed as an application that covers almost every discipline of life. The GPS could become the next utility – like electricity, running water, and the telephone – in the near future. The applications of this high-tech capability are limited only by the human imagination. GPS based products could even fuel the next economic expansion of the free world.[14] In 1983, US President Roland Reagan offered the GPS civil services to the world free of direct charges in the aftermath of the loss of the KAL 007.[15]

The GPS is owned and operated by the US Government as a national resource. Their Department of Defense (DoD) is the steward of the GPS, and is required by law to keep it operational and available on a continuous, worldwide basis. The DoD is also expected to ensure that no hostile usage of GPS takes place. Presently, there are 31 GPS satellites in orbit, and over the years, the US administration has ensured that the GPS remains a dynamic system with periodic upgrades. On 25 February 2010, the US Air Force has awarded a contract[16] to a private company to develop the GPS Next Generation Operational Control System (OCX) to increase both the accuracy and the availability of GPS navigation signals, as also serve as a critical part of GPS modernization. The development process is currently in progress.

Apart from the GPS, another operational system with a global footprint is Russia's GLONASS constellation. The GLONASS went on to the drawing board in the mid-1970s during the Soviet era, while the launching of satellites began in 1980s. There were 12 functional satellites when the USSR disintegrated in 1991. This constellation has witnessed various ups and downs, mainly because of the Russia's financial constraints. However, with improvement in its economic conditions post 2000, Russia's investments in its space programme in general, and GLONASS in particular, started increasing. Technically, the complete GLONASS grouping should have 24 operational and 2-3 reserve satellites to have global coverage.[17]

The Russian government realised that the satellite navigation system should become top priority, both for military and civilian purposes, and its Decree No. 587 of 20 August 2001 approved a Federal Task Programme on the Global Navigation System (GNS). This GNS programme aims at improving both space, ground-based and user equipment segments of the GLONASS system. The basic aim has been to ensure that GLONASS performances are similar to those of GPS. By 2010, GLONASS reached full coverage in Russian territory, and in 2011 full operational capability with the full orbital constellation of 24 satellites. GLONASS had a US$ 11.81 budget approved through 2020, by which time the system is scheduled to have all satellites transmitting both the new CDMA and legacy FDMA signals.[18] Presently, the third generation GLONASS–K programme is underway. The first satellite of the third generation, GLONASS-K1, was launched on 26 February 2011. GLONASS-K1 satellites have a 10-year design life. A completely new design, GLONASS-K2, will start launching after 2014 – probably around 2016.

The European Union (EU) has a major ambition to develop its own satellite navigational system, and they are developing a system called Galileo. This system is being developed by the European Space Agency (ESA). The process of developing this constellation began in 2003. However, owing mainly to financial problems, the process has been very slow. This system was conceived as civilian systeminter-operable, with GPS and Glonass. However, it has military utility too. During 2011–12, four satellites have been launched to validate the Galileo concept in both space and on earth. This In-Orbit Validation (IOV) phase is presently being followed by additional satellite launches to reach Initial Operational Capability (IOC) around 2015. The fully deployed Galileo system should consist of 30 satellites (27 operational +3 active spares), positioned in three circular Medium Earth Orbit (MEO).[19]

The European Commission has proposed the new framework for the financing and governance of the two European satellite navigation programmes Galileo and EGNOS[20] (European Geostationary Navigation Overlay Service) for the period 2014–2020. The Commission proposes to earmark US$ 9.5 billion to guarantee the completion of the EU satellite navigation infrastructure, and to ensure the exploitation of the systems until 2020.[21]

Major space-faring Asian states too are showing interest in owning their individual satellite navigational systems. China is investing in a Global Navigation Satellite System (GNSS), while India and Japan are developing the Regional Navigation Satellite System (RNSS).

China's interest in satellite navigation technology dates back to the late 1960s. However, owing to various technical difficulties and the lack of funding – particularly during the Cold War era – China had not made much of a progress towards developing such a system. Based on 'Twin-Star' regional navigation theory, they tested satellite positioning system on two DFH-2A communications satellites in 1989. This test showed that the precision of the Twin-Star system was comparable to the publicly available signals of the United States Global Positioning System (GPS).[22] Following this, government approval for the development of the satellite navigational system was granted during 1993–94. China's first regional navigational system was called BeiDou/BeiDou-1, and was developed by the China Academy of Space Technology (CAST). The system is capable of providing all-weather, two-dimensional positioning data for both military and civilian purposes. It can also undertake communication functions. The first two satellites for this system were launched during 2000, and the system began providing navigational support in late 2001. The third satellite (backup) was launched during 2003, and the network has been made available to civilian users since April 2004. China is only the third country in the world to possess an operational space-based navigational network. The fourth satellite in this constellation was launched during 2007, and the system works at with 20m accuracy.[23]

After making BeiDou-1 operational, China has begun working on its more ambitious project of developing a navigational system with a global footprint. This system is known as Compass (Beidou-2), and has 35 satellites – of which 5 are proposed to be placed in geostationary orbit, and 30 in Medium Earth Orbit (MEO).[24] The entire system is expected to become operational by 2020. As of December 2011, the BeiDou system was officially announced to provide Initial Operational Service providing initial passive positioning navigation and timing services for the whole Asia-Pacific region, with a constellation of 10 satellites (5 GEO satellites and 5 IGSO satellites). During 2012, 5 additional satellites (1 GEO satellites and 4 MEO satellites) were launched, increasing to 14 the number of satellites of the constellation.[25]

China has also developed another less known regional navigation satellite system called CAPS (Chinese Area Positioning System). This project was initiated in 2002. It is a passive one-way system in which satellites broadcast navigation messages, and receivers are the 'listeners.'[26] This concept is different from conventional navigational systems. In this system, all navigation-related facilities are located on the ground from where the messages are generated. These messages are sent to the communication satellites which only act as transponders. The CAPS constellation is not specifically launched for navigational purposes but works on bandwidth rented on commercial communications satellites. It consists of commercial geostationary (GEO) communication satellites, and inclined geo-synchronous orbit (IGSO) communication satellites. China took three years to develop a validation system for CAPS, and uses four commercial GEO communication satellites.[27] Such a constellation cannot provide 3D positioning because all satellites are located in orbit over the equator. The height estimate can be provided by incorporating a barometer into the receivers.[28]

Japan has a two pronged approach to satellite navigation. First, to make use of the globally available US GPS System by incorporating additional features to make it more accurate, and applicable to their areas of interest. Secondly, to develop a regional network consisting of a Tsiklon of navigational satellites which can cover gaps in GPS signals. This is because sometimes the GPS underperforms in Japan because of different topographical features.

To augment the strength of the GPS, Japan has developed the MSAS (MTSAT[29] Satellite based Augmentation System). It is essentially an overlay system for increasing the accuracy of GPS navigation by transmitting differential information.[30] This system was conceived during the 1990s, and the first satellite was launched in 1999. The MTSAT system is designed to consist of one or two satellites. The end of MTSATs life is in 2015 and 2016. The major beneficiaries of the MSAS are aircraft operating on routes across the Pacific. This satellite also provides weather related inputs.[31]

Japan's regional navigation satellite system is known as the Quasi-Zenith Satellite System (QZSS), and the development of this system was authorized by the Japanese government in 2002. Actually, the overall (conceptualised) proposal is to develop a programme in a two-phase build-up of quasi-zenith (QZO), then another quasi-zenith and geostationary orbiting satellites (QZO and GEO). Phase one will have three satellites in Quasi-Zenith Orbit, and the second will have four satellites in QZO and GEO.[32] It appears that currently Japan is concentrating on phase one, and developing QZSS. The first of the QZSS satellites (known as Michibiki) was successfully launched in September 2010, while aiming at a final 7-satellite constellation in the future. Later, on March 2013, the Japanese Cabinet Office formally announced a US$ 540 million contract award with Mitsubishi to build one geostationary satellite and two additional quasi-zenith satellites (QZSs). The three satellites are scheduled to be launched before the end of 2017.[33] Japan has a cooperative agreement with the US since 1998 for the use of the GPS for civilian purposes. This was reviewed on 13 January 2011. Japan's policy appears to be to develop its own regional system, and depend on the US system for its other requirements.

Tool for Socio-economic Development

Since 1994, when the GPS became globally available, it has emerged as a major global navigation system. It has been observed that its civilian use is clearly dominating its use by the military. The system has proved to be of immense utility for providing correct navigation to the airlines, the shipping industry, and for other civilian needs. The few inherent disadvantages of the GPS (blind zones, difficulties owing to terrain problems, etc.) are being dealt with by using the spread of differential GPS. Differential GPS uses GPS receivers and satellites in conjunction with a ground station – or a pseudo-satellite – at a known position, to provide high-precision tracking in specific locations.[34] Many states are found making effective use of the GPS facilities by using new technologies to upgrade some of these services to cater for their specific usages.

Today, both developed and developing countries are found using global navigational systems for the purposes addressing various social challenges. The management of available natural resources is an important issue for modern states while devising various growth models. They appreciate the need for undertaking various developmental works which could meet the requirements of the present without harming the interests of future generations. They are always on the lookout for technological support for undertaking 'sustainable development', and have found space technology as one of the important tools for such purposes. Over the years, a few states are acquiring and developing various space technologies, and satellite navigation is one amongst them. In particular combinations, the GPS and the geographic information system (GIS) is being successfully used for geospatial analysis in a multiplicity of situations, ranging from agriculture, public health, disaster management, environmental resource management, and ecological monitoring.

The monopoly of the GPS continues even today because many other systems are yet to mature fully. GPS equipment is also found being used in various consumer applications. There are various rapidly expanding areas for GPS usage, and personal usage is mainly towards using location-based services (LBS). Present generation land-based system users include automobile drivers; rail trains; fleet managers of trucks, delivery vehicles and public transportation; emergency responders like fire fighting vehicles, ambulances, and the police. Also, these services are useful for recreational activities like hiking, hunting, skiing, biking, and golfing.[35]

Overall GPS service management involves various public and private agencies. The market for GPS or GPS derived products is showing a significant increase. This includes GPS technology and the use of the GPS signals. Presently, the business share of GPS is much more in the private sector than in the defence sector. Also, there are no strict US governmental restrictions on the sale of most GPS products and services. The industry could supply GPS products to firms that use GPS products to enhance the competitiveness of their products (e.g., luxury car builders); firms that use such products to meet the needs of their customers (e.g., surveyors); to service providers (e.g., ambulance operators); and to firms that benefit from the improvements in the public sector brought about by GPS (e.g., commercial airlines and long-distance communication firms). Interestingly, the growth of commercial GPS firms has also provided benefits back to the US government. In the Persian Gulf War (1991), commercial suppliers were able to meet the higher-than-expected demand for GPS receivers, even when suppliers or GPS receivers could not meet all military specifications.[36]

Today, many countries are involved in using various GPS products, and there are multiple commercial agencies involved in GPS related business. Hence, it would be difficult to present an exact numerical value to indicate the volume and profits generated out of this business. Some idea about the extent of GPS reach and popularity can be made based on the sales value of this system. For instance, Garmin is a producer of consumer and professional (aviation, marine) grade GPS receivers. As of May 2014, Garmin has sold over 126 million GPS devices. Garmin operates in more than 100 countries in the world. They have products like Handheld GPS, Marine GPS, Automotive GPS, Laptop GPS, and Mobile Apps, etc. Most of these devices can display the current location on a map too.[37]

Over the years, various states have used GPS technologies innovatively for multiple purposes. In conjunction with GIS, cartographic mapping, and other technologies, GPS has been used for the purposes of disaster relief and recovery efforts. This use of GPS by emergency responders always saves time, and hence also saves lives and property. The GPS also has utility in the medical field, including public health systems. In India (for example, in the West Bengal region) the GPS was very effectively used during February 2003 to monitor polio eradication. The GPS also helps to monitor (and reduce) crime. When out on parole, many hardened criminals are sometimes found strapped with the GPS ankle bracelets.[38]

The Global Navigation Satellite System (GNSS) market comprises of products (receivers and devices) and services using GNSS-based positioning as a significant enabler. Market segments include Location-Based Services (LBS), road, rail, aviation, maritime, agriculture, and surveying services. The

Global GNSS market size was approximately US$ 260 billion during 2013–14. The forecast is that Global enabled GNSS markets will grow to approximately US$ 340 billion per annum by 2022. Core revenues are expected to reach US$ 140 billion in 2019.[39] Presently, more than 70 per cent of the market belongs to GPS, and a similar trend is expected to continue for a few more years. Most of navigational systems under development today are expected to be GPS compatible. It needs to be understood that the approach behind developing new systems should not be to challenge the GPS but to supplement it.

Presently, the navigational market is not only restricted towards the sale of data and receivers but also involves the development of various custom-made and general purpose software modules. In addition, since the majority of new systems (like Galileo, etc.) are still in the early phase of development, various satellites are required to be launched in future. Thus, at least for the coming few years, there will be a market involving satellite/sensors development and manufacture, and the providing of launching facilities. States like India and China – which are making inroads in the global satellite launch market – are keen to have such orders.

In 2006, the United Nations General Assembly has set up an International Committee on Global Navigation Satellite Systems as an informal body to promote cooperation on matters of mutual interest related to civilian satellite-based positioning, navigation, timing, and value-added services. The committee also addresses the issues related to the compatibility and interoperability of global navigation satellite systems. One of the main purposes of this forum is to promote the use of this system, and to support sustainable development, particularly in developing countries.[40]

Strategic Relevance of Space Navigation

The evolution of space navigation has a military 'DNA'. A few decades ago, the US Department of defence (DoD) supported the concept of highly accurate, space-based PNT (Positioning, Navigation, and Timing) system and went ahead towards developing a GPS system for military use in limited war environments. A seminal Navigation Satellite Study briefing (prepared in August 1966 by Aerospace Corporation engineers James Woodford and Hideyoshi Nakamura), identified tactical air strikes by high-speed, manoeuvring aircraft as the main example of how a space-based PNT system might benefit military operations. The engineers explained specifically how a future system like the GPS could contribute to all six phases of a tactical air strike: target identification and coordinate determination; aircraft navigation to the vicinity of the target;

target acquisition by aircraft; determination of bomb release point; aircraft navigation back to base; and damage assessment. They concluded that a navigation system suitable for use by high speed manoeuvring aircraft will also serve a wide variety of other users. Among other uses, they envisioned missile terminal guidance; air delivery of stores; air traffic control; rescue; positioning guns or other equipment on land or sea; aerial mapping; ship missile launch; and satellite tracking.[41] The same logic applies to other operational systems as also still under development. It is important to appreciate that modern day threats are both conventional as well as asymmetric in nature. Owing to issues concerning environmental worries as well as human rights related apprehensions, collateral damage is becoming an unacceptable phenomenon. Hence, 'precision targeting' has emerged as a crucial feature in the modern day warfare. Naturally, the GPS offers the best solution for all such challenges.

Historically, it has been observed that there has always been a connection between technology and geopolitics; and same is true with the space technologies. Satellite navigational technology has a unique character. This technology offers civilian, military, and commercial benefits. This could be a classic case which demonstrates the dual-use nature of space technologies. It is the technology both of the present and of the future. In the 21st century, its commercial utility is found to be outshining military utility. However, most countries are essentially making investments in developing their individual navigational networks owing mainly to military reasons. Broadly, the GPS and the augmented GPS network together could be viewed as 'adequate' in catering to global navigational needs. However, this system provides 'degraded' accuracy, and has no utility in catering for the military needs of nation states. Naturally, to secure their strategic interests, some nation states are making investments in developing their own navigational systems. At first, some nation states – understanding both the cost and the multiple technological challenges – were of the opinion that they should develop a multi-stakeholder navigational network. In particular, there were talks about states like India and China partnering with the EU's Galileo programme. Both these countries had even promised more than US$ 275 million individually to this project. However, the ESA made it clear that these countries would not get any preferential rights to use the system for military purposes. As a result, both countries are now concentrating on developing their own systems. It may be noted that Israel has signed an agreement with the EU which offers Israeli researchers and companies access to various projects associated with the Galileo programme.

All major powers making investments in developing their individual navigational systems have interests in the political, military and economic dimensions of this technology. They are interested in making their systems accessible to other countries, both at a cost or otherwise. It appears that, in some cases, these countries are probably using this technology as a tool in their foreign policy agenda. Recently, the Indian Prime Minister has suggested that India could make this 'product' available to other South Asian countries which have teamed up as a grouping for political and economic collaboration under the rubric of the South Asian Association for Regional Cooperation (SAARC). Thus, China is providing complete access to their Compass (BeiDou-2) to the Pakistan military, probably as a part of their military collaboration.

China's Compass constellation is also predicated on serving a purpose beyond navigation. It can be used for detecting nuclear explosions, or for electronic or signals intelligence. It has been argued by some that the Compass satellites will have so much extra power on board that they could be used as space-based jammers, and could even target Galileo apart from the GPS.[42] For China, the military utility of Compass is undisputed; however, the Chinese are also expected to use it for economic gains, and more so an as instrument to 'project' its soft power.

The satellite navigation system has emerged as an essential component of military architecture for various nation states. The indispensability of systems like the GPS puts it into the 'bracket' of critical infrastructure. Today, the GPS is also being viewed as an important target which opponents would no doubt wish to neutralise in order to reduce the effectiveness of the US military. The most conceivable option for any adversary could be to jam the satellite(s), either temporarily or permanently. There have been efforts underway towards developing GPS protection technology (anti-jamming technology). Also, many countries are working towards developing various satellite hardening technologies. All navigational systems presently under development need to factor in such future realities, and take preventive measures.

Conclusion

The USA introduced GPS technologies to the rest of the world during the mid-1980s, and also made those available free of cost for use. Space navigation has also emerged as an extremely important constituent of Network Centric Warfare, and countries with modern militaries rely on it significantly. However since, as a policy, the US GPS does not provide military quality signals, a few countries have started developing their own space navigational systems.

Broadly, the present global approach of major nation states towards using space navigational systems appears twofold: one, develop self-sufficiency for strategic needs; and two, for non-military usage depending on the requirement, availability, and utility use of the GPS and/or various other available systems.

Notes

1 T. Ramakrishnan, 'ISRO to Implement Regional Navigation Satellite System', *The Hindu*, 05 January 2011.

2 D. Gowrisankar and S.V. Kibe (was Director Satellite Navigation, ISRO) in a paper presented titled 'India's Satellite Navigation Programme', in Hanoi, Vietnam, 10 December 2008, and available at www.aprsaf.org/data/aprsaf15_data/csawg/CSAWG_6b.pdf, accessed on 15 April 2011.

3 http://www.defence.pk/forums/india-defence/68197-indian-regional-navigational-satellite-system-irnss.html.

4 www.derm.qld.gov.au/gnss/systems.html, accessed on 24 April 2011.

5 Gowrisankar and Kibe, n. 2.

6 http://www.insidegnss.com/node/2665, accessed on 15 April 2011.

7 S. Anil Radhakrishnan, 'GAGAN System Ready for Operations', *The Hindu*, 11 January 2014.

8 http://www.fas.org/spp/military/program/nav/transit.html, accessed on 10 July 2014 and http://www.experiencefestival.com/a/Satellite_navigation_system_-_History_and_theory/id/1793498, accessed on 24 May 2013.

9 http://news.stanford.edu/pr/95/950613Arc5183.html, accessed on 15 July 2014.

10 http://www.astronautix.com/craft/tsiklon.htm, accessed on 28 June 2014.

11 www.vectorsite.net/ttgps_2.html, accessed on 30 April 2014 and http://fas.org/spp/guide/russia/nav/tsikada.htm, accessed on 24 July 2014.

12 http://www.experiencefestival.com/a/Satellite_navigation_system_-_History_and_theory/id/1793498, accessed on 24 March 2011 and https://woodshole. er.usgs.gov/operations/sfmapping/navigation.htm, accessed on 20 June 2014.

13 http://news.stanford.edu/pr/95/950613Arc5183.html, accessed on 15 July 2014.

14 Sameer Kumar and Kevin B. Moore, 'The Evolution of Global Positioning System (GPS) Technology', *Journal of Science Education and Technology*, vol. 11, no. 1, March 2002, pp. 79-89.

15 Korean Air Lines Flight 007 was shot down by Soviet interceptors on 1 September 1983, killing 269 passengers. The aircraft was shot when it strayed into prohibited Soviet airspace around the time of a planned missile test. Subsequently, it was decided

that the US military would make the GPS available for civilian use so as to avoid any further navigational mishaps in the future.

[16] http://www.losangeles.af.mil/news/story_print.asp?id=123192234, accessed on 16 July 2014.

[17] http://en.ria.ru/russia/20110916/166878748.html accessed on 10 July 2014.

[18] http://www.navipedia.net/index.php/GLONASS_Future_and_Evolutions and http://www.sdcm.ru/index_eng.html, accessed on 16 July 2014.

[19] http://www.spacenews.com/civil/100310-initial-galileo-validation-satellites-delayed.html; http://www.esa.int/Our_Activities/Navigation/The_future_-_Galileo/What_is_Galileo, accessed on 16 July 2014.

[20] Europe's regional augmentation system for GPS signals. It is the precursor to Galileo.

[21] http://ec.europa.eu/enterprise/policies/satnav/galileo/index_en.htm, accessed on 19 July 2014.

[22] 'Beidou1 Experimental Satellite Navigation System', 14 December 2010; http://www.astronautix.com/craft/beidou.htm, accessed on 30 Jun 2014.

[23] http://www.globalsecurity.org/space/world/china/beidou.htm, accessed 12 June 2014; http://www.astronautix.com/craft/beidou.htm, accessed 22 April 2008; ibid; G Yuankai, 'Your Place in the World', *Beijing Review*, 2009, Issue 27, pp. 16-19.

[24] http://en.wikipedia.org/wiki/Beidou_navigation_system, accessed on 11 July 2014.

[25] http://www.navipedia.net/index.php/BeiDou_General_Introduction, accessed on 18 July 2014.

[26] Even though Beidou1 is recognized as a first generation system, like most other navigational systems, it is not a passive system. This constellation is a two way system capable of sending messages to the control center through satellites.

[27] Three satellite receiver ranges are needed for a position fix; a fourth satellite could increase the area of coverage and provide redundant measurements. Also, refer Binghao Li, Shaocheng Zhang, Andrew G. Dempster and Chris Rizos, 'Impact of RNSSs on Positioning in the Asia-Oceania Region', *Journal of Global Positioning Systems* (*2011*), vol. 10, no. 2, pp. 114-124.

[28] Binghao Li and Andrew G. Dempster, 'CAPS-China's Regional Navigation Satellite System', June 2010, pp. 59-63, http://www.insidegnss.com/node/2090, accessed on 24 July 2014.

[29] MTSAT is the Multi-functional Transport Satellite with the dual function of air traffic control (ATC), and navigation and meteorology. Various agencies, like the Ministry of land, infrastructure and transport and the Japan meteorological agency, have stakes in this.

[30] http://dret.net/glossary/msas, accessed on 15 April 2012.

[31] All the inputs on MSAS are based on http://www.insidegnss.com/node/107; http://

www.eurocontrol.int/nexsat/gallery/content/public/Steering%20Group/Meeting10/MTSAT_2009.324NextSAT_MTSAT_Status_ver.2.pdf, accessed on 09 May 2011.

[32] Hideto (Duke) Takahashi, 'Japanese Regional Navigation Satellite System: "The JRANS Concept", *Journal of Global Positioning Systems*, 2004, vol. 3, no. 1-2, pp. 259-264.

[33] http://www.navipedia.net/index.php/QZSS, accessed on 10 July 2014.

[34] http://news.stanford.edu/pr/95/950613Arc5183.html, accessed on 18 July 20014.

[35] Rick W. Sturdevant, 'The Socioeconomic Impact of the NAVSTAR Global Positioning System, 1989-2009', AIAA SPACE 2009 Conference & Exposition, 14-17 September 2009, American Institute of Aeronautics and Astronautics Pasadena, California.

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