Stellar navigation to Satellite navigation

Dr Carlo Kopp

Navigating over large distances has always been one of the greatest challenges for naval and air forces in the modern era, and the scale of the investment in contemporary Global Navigation Satellite Systems (GNSS) such as GPS is enormous. What is less appreciated is that the GNSS model has its origins in an almost ancient navigation technique, stellar navigation.

The earliest forms of stellar navigation involved the use of Eyeball Mk1, some knowledge of the constellations, and a lot of luck. This all changed during the mid 18th Century, with the advent of the modern chronometer, or precision clock, invented by a John Harrison. Using a thermally compensated spiral spring as a timing reference, this design concept remains widely in use.

All precision stellar navigation relies on having a precision tabulated 'almanac', which describes the exact positions of specific stars in time, relative to the earth's orientation, a precision timekeeping device of some kind, and an apparatus which allows the angular position of stars or other celestial bodies to be measured with some accuracy. The accuracy of the position fix then depends on the accuracy of the almanac, the angular measurement apparatus, and the timepiece. Much of the evolution of stellar navigation technique and equipment to date has been about improving the accuracy of the measurement.

Radio navigation aids did not appear until the late 1930s, and did not mature until the 1940s, being used initially for landing aids, and then as bombing aids. The attractiveness of radio navigation aids was that they were independent of weather and could be used in cloud, an advantage especially for instrument flying. Cloud that prevents sighting a star prevents stellar navigation from being used. The drawback of ground based radio navigation aids was their limited range from a beacon location. Highly accurate fixes could only be achieved where a direct or near direct line of sight was available. As a result stellar navigation remains in use to this very day.

The first generation of stellar navigation systems used in military aircraft comprised a suitably trained navigator, equipped with a sextant, an almanac and a clock. The difficulty in taking readings in a slipstream soon led to the innovation of the astrodome, a hemispherical perspex bubble above a navigator's station which allowed the use of an astrocompass, without the unwanted annoyance of slipstream. Astrodomes were a distinct feature of the RAF Lancaster and Halifax, and the US B-17, B-24 and B-29 bombers – heavy bombers, which needed to cover large distances, needed this capability.

The arrangement in the B-24 series is illustrative. The A-1 astrograph was a miniature handheld light table, which allowed the navigator to view star charts in the dark. The handheld Mk II Astrocompass, equipped with bubble levels to align it before use, had bearing and declination scales for angular measurement. The navigator would use these to effect an angular measurement on a known star.

A Mark II Astrocompass, used by navigators in US Army Air Corps bombers such as the B-17, B-24 and B-29.

The astrodome was provided so a navigator could take position fixes from stars.

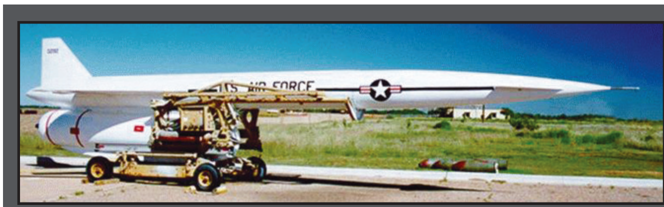
Knowing the exact bearing and elevation of two or more stars, for a given time against the almanac, provided good position fix. Getting an accurate measurement in a vibrating and bouncing bomber was an issue in its own right.

With the shift from piston engine bombers to turbojets, the much increased cruise speed of the aircraft and higher operating altitudes made accuracy in timing more important, yet this generation of aircraft made it increasingly difficult to have a navigator crawl his way to an astrodome to perform a measurement.

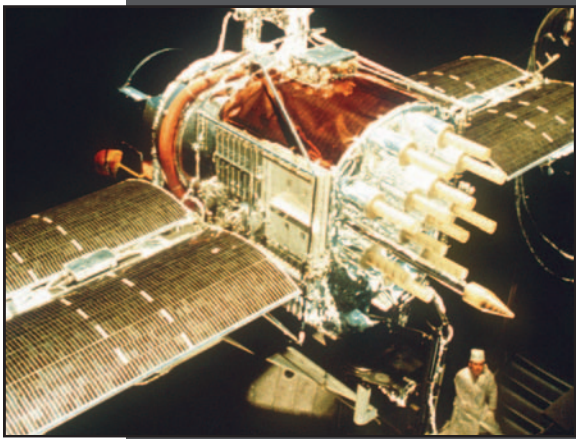
This resulted in the introduction of first-generation analogue electronic automatic astrocompasses, such as the Kollsman Instruments MD-1 used in the Strategic Air Command B-52C/D/E/F/G aircraft. This complex and difficult to maintain design essentially provided an automated replacement for the navigator taking celestial readings, using a photomultiplier tube (instead of a human eyeball) and servo-driven gimbal and analogue computers to perform the sighting task and angle measurements. For the B-52, tasked with nuclear strikes flown over the polar region, such hardware was essential to provide accurate long haul navigation. The 500 nautical mile range NAA AGM-28A Hound Dog standoff missile, carried by the B-52, also used an astrotracker, the Kollsman Instruments KS-140, to provide navigational updates for the inertial autopilot. The later B-52H and RC-135 were fitted with the AN/AJN-11 Astro-Automatic Compass Set.

The next step was further automation seen in the SAC Convair B-58 Hustler bomber equipped with the Kollsman Instruments KS-39 astro-tracker. The device would be locked by the bombardier-navigator on to a specific star, which it would then continuously track in elevation and azimuth. The last astro-tracker to be introduced on a SAC bomber was the Litton AN/ASQ-119 fitted to the FB-111A, in the distinctive upper nose 'hump'. These were later removed during conversion to the F-111G configuration.

Automatic astrotrackers could achieve very high accuracy but were expensive to build and expensive to maintain, with very high demands on calibration accuracy. The advent of satellite navigation systems saw the decline of these devices. They are not yet extinct; in fact, the most recent upgrade to the RC-135V/W Rivet Joint electronic intelligence gathering aircraft is a Northrop-Grumman LN-120G, which is a GPS-augmented stellar inertial navigation system capable of tracking stars day and night. The LN-120G uses a stellar angular fix to further enhance the accuracy of the GPS aided inertial navigation system. Northrop Grumman boasts an angular accuracy of 20 arc-seconds. Thirty of these systems are to be fitted to the Rivet Joint fleet to provide exceptionally high, and undisclosed, positioning accuracy.



The AGM-128A Hound Dog standoff missile used the KS-140 astro-tracker.



left: An early Navstar GPS satellite, in 1981.

The SAC FB-111A used the Litton ASQ-119 astro-tracker to improve inertial system accuracy.

The drawback inherent in astro-trackers is they require an unobstructed view of one or more stars. This is feasible for a high-flying aircraft, but not feasible for one penetrating adverse weather, especially at lower altitudes.

The advent of the earliest satellites sparked interest in using them as navigational aids, exploiting existing ideas in radio navigation aids. Several key technologies emerged during that period. One was the atomic clock, capable of producing extremely accurate and stable timing data, the other was the evolution of radio-rangefinding techniques using pseudo-random codes and correlation techniques.

The first studies exploring the idea of navigation by satellite were the US Air Force Project 621 in 1962 and the US Naval research Lab TIMATION project in 1963.

Satellite navigation using a microwave radio signal offers two huge advantages over stellar navigation, the first being genuine all weather day night operation, the other being the absence of expensive to build and maintain optical tracking hardware. However, satellite navigation also requires cheap and compact digital computers for the end user navigation equipment, a technology that did not emerge until the microprocessor became viable during the late 1970s.

The big cost difference in satellite navigation systems arises from the use of precision rangefinding techniques as the primary measurement, rather than precision angular measurement. Whether an angular measurement is performed in the radio or optical bands, it is always more expensive to perform than a rangefinding measurement.

The Navstar GPS (Global Positioning System) program was initiated almost a decade later, through the merger of US Navy and Air Force projects into a single multi-agency program led by the US Air Force. The first experimental GPS satellite, the Navigation Technology Satellite 2 or NTS.2 was launched in 1977.

The fundamental idea behind all current satellite navigation schemes is that of measuring the 'pseudo-range' to four or more satellites, the orbital position of which is known with high precision. This information permits the solution of a system of mathematical equations that yields the geographical position of the receiver.

The ranging measurement is achieved by synchronising the navigation receiver with a master clock broadcast by the satellites, and then measuring the time it takes for a coded navigation signal to travel from the satellite to the receiver.

Geometry being what it is, there are no free lunches and best accuracy is always achieved when satellites are widely spaced within the receiver's field of view. When satellites are bunched together in one part of the sky, accuracy declines rapidly. This effect is called Geometrical Dilution of Precision (GDOP).

During the bombing of Yugoslavia, the US Air Force issued all bomber units with pre-computed graphs of GDOP errors for all sites of interest by day and hour of the day – these depending on where satellites appeared at that time relative to the target areas – to allow preplanned missions to be flown at times when the GDOP error was minimised.

The first GPS receivers introduced during the 1980s were big, cumbersome and expensive, and used a single channel receiver which consecutively locked on to each visible satellite and performed the pseudo-range measurement. By the 1990s, the receivers were multi-channel, typically with five to eight receiver channels, more compact and cheaper.

This was the period when GPS started to migrate from aircraft and ships – large and expensive platforms – to become a ubiquitous navigation system in military platforms, and in guided munitions.

Prior to the advent of GPS, navigation systems were based on expensive inertial platforms, which used additional sensors to improve accuracy. While inertial systems have the wonderful quality of being able to measure the platform's position in space without external references, they also accrue a continuous drift error over time, a fact of life whether the inertial unit uses spinning gyros, spinning beryllium spheres, laser cavities bored into a block of glass, or spools of optical fibre.

The most expensive but accurate navigation systems predating GPS used Doppler equipment to perform precise velocity measurements, and astro-trackers for celestial fixes to bound the drift error accrued in the inertial system. Many airborne systems included additional modes in the radar along with thermal imaging and laser targeting equipment to provide additional navigation fix inputs into the system.

Yet, a single box of GPS receiver hardware, often very much cheaper than the equipment it replaced, could achieve equal or better accuracy. This is why GPS has conquered the world completely.

GPS soon found its way into guided munitions. An interesting observation was that Australia's DSTO was one of the first to propose a GPS guided bomb, but the idea did not sell with the Canberra bureacracy and thus Australia did not see a GPS-aided weapon until the JDAM was acquired.

Munitions applications resulted in the emergence of GPS jammers, and jam resistant GPS receivers. GPS guided bombs forced the development of receivers capable of very fast satellite acquisition. More recently, additional GPS signals were introduced to further improve jam resistance, and improve accuracy.

The whole domain of differential GPS techniques evolved from the 1980s, using a supplementary channel to carry additional correction data, applied to the GPS pseudo-range measurement to correct for atmospheric delays, orbital drift and other sources of error. The most accurate differential GPS systems today have positioning errors of mere inches.

The Soviets realised the potential of GPS very early and played a catch-up game to deploy their equivalent, Glonass. The fall of the Soviet Empire saw an under-populated Glonass constellation in orbit, and Russia has not had the economic might to fully populate it. The Europeans have most recently bought into the game, with the emerging Galileo system.

Where does the future lie? Probably in two dominant satellite navigation systems, with increasing jam resistance and accuracy, as these systems further mature. End user equipment will become better, more accurate and cheaper.

Yet in many respects, satellite navigation systems owe most to stellar navigation systems, with their deep historical roots.

Further Reading:
http://www.ndu.edu/ctnsp/Def_Tech/DTP%2017%20S&T%20Innovation%20Conundrum.pdf