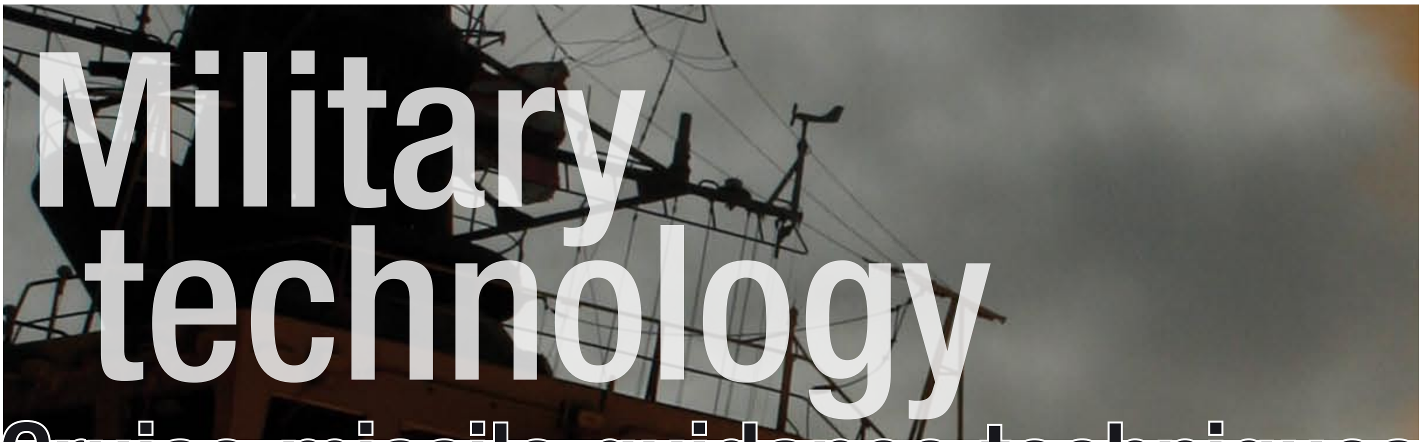

Cruise missile guidance techniques

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With an operational pedigree covering six and half decades, cruise missiles can be regarded as mature and well established technology. There has been significant evolution in the technologies used to construct cruise missiles, spanning airframes, propulsion, penetration aids and guidance systems.

In airframe technology, designs have become progressively more compact, to accommodate internal and external carriage by aircraft, launch tubes on warships or torpedo tubes in submarines. Propulsion has evolved from simple pulse jets, through turbojets and liquid propellant rockets or ramjets to the current mix of: turbojets for subsonic tactical cruise missiles, turbofans for subsonic strategic cruise missiles; and ramjets or mixed turbojet/rocket designs for supersonic tactical cruise missiles.

Penetration aids emerged during the 1960s as air defence systems evolved to greater potency, with low altitude terrain following or sea skimming flight profiles to hide missiles from radars and, increasingly, stealth shaping and materials to deny acquisition and tracking by air defence radars. Some Soviet cruise missiles were also equipped with track-breaking defensive jammers to defeat interception by air defence missiles.

Finally, cruise missile guidance has evolved and strongly diversified over this period.

Late model Block IV Tactical Tomahawk and F-15E chase plane during trials.

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The Cruise Missile Guidance Problem

The basic idea behind all cruise missiles is that of a weapon that can be launched at a target from outside an enemy's air defence system, to avoid exposing the launch platform to enemy attack. This presents important design challenges, the first of which is getting the cruise missile to reliably navigate its way across distances of up to thousands of miles to the proximity of an intended target – and once in proximity to the target, ensuring the warhead can be guided to the aimpoint with sufficient precision to produce military effect.

The first operational cruise missile was the German FZG-76/V-1, of which more than 8,000 were launched, mostly against targets in the UK. Its guidance system was by modern standards primitive: a gyroscope based autopilot to maintain heading, and an anemometer driven distance measuring device. The weapon was aligned to the intended heading and distance before launch, and once the odometer setting on the distance measuring device said the weapon was over the target, the autopilot would drive it into a steep nosedive. While inaccurate to the tune of miles of error, this sufficed for the area bombardment of large urban targets like London. The principal aim of the bombardment was to terrorise the civilian population and divert military effort in the UK away from offensive operations and towards air defence.

In the immediate post war period the US and Soviets reverse engineered the V-1 and initiated development of their own unique cruise missile designs. The first generation of theatre or tactical weapons – exemplified by the US Navy Regulus series, the US Air Force Mace/Matador series, and the Soviet KS-1 Kometa and Kh-20 Kangaroo series – further evolved guidance technology. All missiles employed initially accurate gyro based autopilots, but radio command links permitted adjustment of the weapon flightpath so that the nuclear warhead could be positioned as precisely as possible. An error of hundreds of yards could be enough to reduce the overpressure produced by a nuclear warhead below the lethality threshold for hardened targets. During the 1950s the first conventionally armed post-war tactical cruise missiles emerged, primarily as anti-shipping weapons. While midcourse guidance continued to be gyro-based and sometimes supplemented by midcourse radio link updates, terminal accuracy was provided by a compact short range radar seeker, semi-active in

Northrop SM-62 Snark intercontinental cruise missile.

Martin Matador ground launched cruise missile.

Boeing AGM-86 CALCM.

AGM-158 JASSM cruise missile.

the earliest designs but soon supplanted by active radar designs. This generation of weapons typically flew at medium to high altitudes, diving to attack their aimpoint.

The next important advance in cruise missile guidance came with the massive ground-launched Northrop SM-62 Snark intercontinental cruise missile, intended to autonomously fly over the polar regions to attack targets in the Soviet Union with a large nuclear warhead. The intercontinental distances presented a new challenge for designers – ensuring that the missile could hit a target over a distance of the order of ten times greater than that covered with any earlier cruise missile design.

The Snark introduced a proper inertial navigation system, which used a gyro stabilised platform and precision accelerometers to measure the vehicle's motion in space, with an analogue computer system used to accumulate measurements and locate the vehicle's position. The problem soon observed was that drift in the inertial system was too great for operational use, as inertial system positioning errors are cumulative – so many miles of positioning error accumulate with every hour of flight.

The solution to this problem was to introduce another device to perform precision measurements of the vehicle's geographical position along its flightpath, so as to correct or 'bound' the error produced in the inertial system. This was a fundamental idea and one which remains central to modern guided weapons design today. Periodically, the accumulated inertial system error would be reduced to the error in the position measuring device.

The technology for this purpose was the stellar navigation system, or star tracker, an automated optical device which performed angular measurements against known star positions and used these to calculate the vehicle's position in space. Stellar systems proved remarkably accurate but were also expensive to build and difficult to maintain. They also required that the vehicle carrying them flew at a high altitude to ensure that cloud would not block the line of sight to the stars to be tracked.

What is less well known is that the success of the stellar systems provided the impetus for the development of now ubiquitous satellite navigation systems, such as GPS and Glonass. Satellite navigation is based upon a similar concept to stellar navigation, but replaces stars with polar orbit satellites, natural light with man-made microwave signals, and uses pseudo-range measurements rather than angle measurements, these features drove down costs and permitted position measurements at all altitudes under all weather conditions. Satellite navigation technology, although initiated during the early 1960s, did not become operationally used until the 1980s.

In the 1960s progressive improvements in inertial system accuracy, but also increasing costs in such equipment, resulted in conflicting demands for accuracy versus cost. This led to the next major advance in cruise missile guidance technology, based on terrain contour mapping. This technology entered operational use in US cruise missiles during the 1970s, and Soviet missiles during the 1980s. The technology of TERCOM (TERrain COntour Matching) was used, like stellar systems, to null out cumulative inertial system errors.

The idea behind TERCOM is relatively simple in concept, albeit complex in detail. A cruise missile flying over a piece of terrain continuously measures the terrain elevation under its flightpath, by using a radar altimeter and comparing the measured results with a barometric altimeter elevation. The TERCOM navigator also carries a stored digital elevation map of the terrain it is intended to fly over. The elevation curve of the terrain flown over is then compared, by computer software, with the stored digital elevation map, to find the best possible match. Once the profile is matched to the mapping data, the position can be found within the digital map with good accuracy, and used to correct the inertial system error.

TERCOM was a huge advance against stellar systems since it was: compatible with low altitude flight by a cruise missile, intended to evade enemy defences, was relatively cheap to manufacture, and potentially highly accurate, down to tens of metres. More than accurate enough for a 220 kilotonne nuclear warhead, and accurate enough for a 500 kg class conventional warhead, against many target types.

TERCOM was not free of problems. The missile had to be flown over terrain that was sufficiently hilly to produce a unique and prominent elevation profile to match against the stored map, the latter introducing the challenge of generating and maintaining precise elevation mapping data of hostile nation geographies. TERCOM is ineffective over water, over seasonally shifting terrain like sand dunes, and terrain with varying seasonal radar reflectivity, like Siberian tundra and taiga where snowfalls could alter elevation or conceal terrain features. Limited memory capacity in the missile made it often difficult to store enough mapping data.

While good enough for the nuclear armed Navy RGM-109A Tomahawk and Air Force AGM-86 ALCM, TERCOM was not good enough to hit individual buildings or structures with a conventional warhead. The US Navy therefore supplemented TERCOM in its RGM-109C/D Tomahawk Land Attack Missile with an additional system based on what is termed scene matching correlator technology. This technology was also used in the 1980s Pershing II ballistic missile, the Russian KAB-500/1500Kr and US DAMASK/JDAM smart bombs, and the recent Chinese guided anti-ship ballistic missile system intended to sink aircraft carriers.

Scene matching correlators use a camera to image the terrain beneath the weapon, and then digitally compare the image with a stored image produced by satellite or aerial reconnaissance. By measuring the rotation and translation required to exactly align the two images, the device can measure the position error of the vehicle very accurately, and use this to correct the inertial and TERCOM errors. The DSMAC (Digital Scene Matching Area Correlator) used in several blocks of the Tomahawk was indeed accurate, but produced operational side effects not unlike TERCOM, which was the need to program the missiles to fly over terrain with easily matched features in proximity to the target. During the 1991 Desert Storm campaign, this resulted in a number of Baghdad freeway intersections being used as such references, which allowed Saddam's air defence troops to set up gun batteries and shoot down a number of Tomahawks. Scene matching correlator technology is, like TERCOM, sensitive to seasonal variations in terrain contrast. Tomahawks equipped with DSMAC also carried flashlamps to illuminate the terrain when imaged at night.

RGM-109C TLAM hitting a semi-hardened test target.

By the 1980s the first GPS receivers were being integrated into US cruise missiles. GPS was attractive since it allowed the missile to continuously correct its inertial error, regardless of terrain and weather conditions, and worked as well over water as land.

These advantages were offset by problems with vulnerability to jamming, as the GPS signal is inherently very faint, susceptibility to 'multipath' effects where GPS signals are reflected from terrain or buildings, and accuracy variations resulting from how many satellites are visible at any given time, and how they are spread across the sky.

All US cruise missiles are now equipped with a GPS and inertial guidance package, with mechanical inertial technology replaced by cheaper and more accurate Ring Laser Gyro technology during the late 1980s and 1990s.

Problems with the basic accuracy of GPS have been progressively addressed by the introduction of Wide Area Differential GPS techniques, where correction signals valid for a given geographical are broadcast by a radio link to the GPS receiver, in the instance of US missiles using the WAGE (Wide Area GPS Enhancement), this being embedded in encrypted pages within the GPS navigation message broadcast by later model satellites. The most accurate technology of this kind developed in the US during the 1990s can correct GPS errors down to several inches in three dimensions – accurate enough to put a weapon into the open hatch of an armoured vehicle.

Problems with susceptibility to jamming and multipath have proven more difficult to deal with. They have resulted in the introduction of smart antenna technology, typically based on 'digital beam-forming' in software. The idea behind this technology is again simple in concept but complex in detail. The most basic GPS antenna will see the whole hemisphere above the missile, and thus collects signals from GPS satellites, as well as hostile jammers. So called Controlled Reception Pattern Antennas (CRPA) will synthesise in software narrow beams which are pointed in space in the direction where the GPS almanac predicts a satellite will be, making the antenna effectively blind in all other directions. The most sophisticated designs of this type will produce so called 'nulls' in the antenna pattern which are pointed at jammers to further suppress their effect.

Much of the widely publicised problems in early production AGM-158 JASSM cruise missiles were a result of software problems in this kind of GPS receiver, causing the missile to lose track of GPS satellites and lose its way.

Advanced GPS receivers provide precision levels of accuracy, and good resistance to surface based GPS jammers. They are less effective against sophisticated opponents who might deploy GPS jammers on satellites, UAVs or balloons.

The latest generation of US cruise missiles uses GPS/inertial guidance, but supplements it with a nose mounted digital thermal imaging device, the intent being to provide a DSMAC-like capability against fixed targets – and with suitable software, and automatic recognition capability against a mobile target like a radar or missile battery. Datalinks, typically derived from the JTIDS/Link-16 technology, are being introduced to provide a capability to retarget the weapon if a mobile target has moved while the missile is enroute – this facility depending critically on the user having the reconnaissance and surveillance capability to detect such movements.

The longer term trends in cruise missile guidance will be more intelligence, more autonomy, more diversity in sensors, better reliability and lower costs.