# Precision Munitions and the Systems in Which They Are Embedded—GPS, Mapping, High-Resolution Radar, and Non-Lethal Weapons

by
Richard L. Garwin
Council on Foreign Relations
rgarwin@cfr.org
www.fas.org/rlg and www.cfr.org

Presented at the XV Amaldi Conference
Helsinki, September 25-27, 2003

I am glad to be here to tell you about this vast field of precision munitions and how they are used. A precision munition is of no use at all unless you have directed and delivered it; important tools for this are the Global Positioning System, mapping to find out where the potential targets are, and high resolution radar, for its contribution to mapping and to observation of the targets.

A nation may sometimes resort to combat to achieve its goals, so the planning and conduct of war are important and typically costly national activities. Warfare may have the purpose of repelling enemy forces or allowing the advance of one's own forces into occupied territory. It may also have the quite different purpose of deterrence or compellence—to operate on the judgment and will of the national authorities to order cessation of hostilities, compliance with the requests of the opponent, or surrender of authority and of the state.

History is replete with examples of precision munitions: expert archers, sharpshooters with rifles, and even poison administered to a commander or head of state. In contrast to these are weapons of wide effect: the intentional spread of disease, fire bombing, mass bombing with explosives or even nuclear weapons, and the exploitation of societal vulnerabilities in the form of dams, food supply, and the like.

Precision munitions have to find their place in this spectrum. They could, in fact, be used for mass effect, as when a single torpedo is delivered by aircraft in the water upstream of a dam to provoke massive flooding, or to eliminate a substantial source of hydroelectric power necessary for war production.

This is largely a technical presentation. I leave it to others to debate the political significance of precision weapons and move now to discuss their status in the current U.S. armory, as displayed in the 2003 war in Iraq. Although these weapons were employed by a largely American military force, they might also be involved in the support of some future UN mandate.

First, the weapons themselves, of which here are a few:

- **Laser-guided bombs** First used in the Vietnam War in 1969, 25 000 laser-guided bombs had been dropped by the U.S. Air Force in Vietnam by 1974. The Navy was not yet able to use these bombs because they did not allow wires in their pylons, a precaution taken to avoid any possibility that the powerful shipboard radars might detonate one of the bombs on the aircraft carrier deck. Naval aircraft have now overcome this hazard.

- **JDAM—Joint Direct Attack Munition** This is “bombing by navigation.” The weapon steers itself to the target, not by laser or television guidance, but by seeking the co-ordinates of the target as defined by some universal navigation system, in this case the Global Positioning System. The weapons are designated as joint, because they are used by both the Air Force and the Navy

- **RPG—Rocket-Propelled Grenade** Most weapons used at short enough range are precision weapons._ Among these are rocket-propelled grenades; the RPG-7 is an old Soviet weapon and all armed forces have had such weapons for at least forty years.

- **Wire-, Laser-, or Radio-Guided Missiles** These are line-of-sight direct-fired. They are either steered manually by the person who is observing the target—the tank—or they are steered automatically to move them to the cross-hairs in the sight, a method which makes a lot more sense.

- **UAVs** A notable example among these vehicles is General Atomics’ Predator aircraft, which operates in the intermediate altitude range of 10 km or so. These aircraft have recently been armed with small missiles, anti-tank missiles, and laser-guided bombs. They can fly also at much lower altitudes, where they could be armed with a powerful sniper rifle that could destroy the engine in a vehicle without causing other damage.

- **ARM—Anti-Radiation Missile** This is rather confusingly named, as the “radiation” it is countering is electromagnetic, in the form of radar emissions. The weapon homes in on the antenna of the radar, thus making it hazardous to turn on the air defense radars, because once they are active they are subject to destruction by these Anti Radiation Missiles that can be launched from aircraft in the neighborhood. The result is severe degradation of the air defense system, either from the radar’s destruction or from its silence. In modern warfare, a stationary radar might be accurately located by its emissions and targeted for destruction by JDAM, even at a time when the radar is not operating.

- **Mines or Command-Detonated Munitions** These may be anything from a few kg to 1000 kg of explosive, which could be buried in a roadway or path or erected next to the road, as in Iraq, or in Sicily at times, and detonated as the vehicle is passing.

On the following page you will find a general description of the JDAM, which can also be found at the U.S. Air Force site at
http://www.af.mil/factsheets/factsheet_print.asp?fsID=108&page=1.

**JDAM: General Characteristics**

**Primary Function:** Guided air-to-surface weapon
**Contractor:** Boeing Corp.
**Length:** (JDAM and warhead) GBU-31 (v) 1/B: 152.7 inches (387.9 centimeters); GBU-31 (v) 3/B: 148.6 inches (377.4 centimeters); GBU-32 (v) 1/B: 119.5 inches (303.5 centimeters)
**Launch Weight:** (JDAM and warhead) GBU-31 (v) 1/B: 2,036 pounds (925.4 kilograms); GBU-31 (v) 3/B: 2,115 pounds (961.4 kilograms); GBU-32 (v) 1/B: 1,013 pounds (460.5 kilograms)
**Wingspan:** GBU-31: 25 inches (63.5 centimeters); GBU-32: 19.6 ins. (49.8 centimeters)
**Range:** Up to 15 miles (25 kilometers)
**Ceiling:** 45,000-plus feet (13,677 meters)
**Guidance System:** GPS/INS
**Unit cost:** Approximately $21,000 per tailkit (FY 01 dollars)
**Date Deployed:** 1999
**Inventory:** The tailkit is in full-rate production. Projected inventory is 158,000 for the Air Force and 82,000 for the U.S. Navy

Such a weapon can be equipped with folding wings so that it will easily fly from the aircraft to 100 km from its launch point.

Some of these weapons have perhaps unforeseen characteristics. Well known is the JDAM's precision, on the order of 5 meters accuracy with 90% probability, not only in two dimensions, i.e., in x and y (latitude and longitude), but in three dimensions. But these weapons can even be flown so that they approach the target on a pre-defined trajectory, even horizontal, so that they can fly into a window or down an air shaft. This is not only a 3-dimensional guidance problem; it is at least 5- and maybe 6-dimensional, because at times one may want to delay the arrival until a precise instant in time. These weapons are very cheap—about 20 000 dollars, 15 000 euros, per kit—and they are applied to so called "dumb bombs," of which there are millions in inventory. About 90 000 of these weapons are to be produced at present under the current contract, for a total stockpile ("inventory") of 240 000 bombs.

At http://www.uav.com/products/predator.html is a picture of the Predator, the UAV made by General Atomics. It is equipped with an infrared video still camera and radar sensors, has a time-on-station of about 20 hours, and is a rather slow aircraft—100 km/hr.

According to Anthony Abbott of the Aerospace Corporation:

> GPS/INS-guided weapons are very effective against stationary targets, but many adversaries have adopted defensive strategies that involve constant movement. This challenge is being addressed by numerous studies, which have shown that GPS/INS delivery techniques can still work if some adjustments are made—specifically in terms of calculating the revised target coordinates and transmitting them to the weapon in flight. (see Abbott, Anthony, "GPS/Inertial Navigation for Precise Weapon Delivery," *Crosslink* (Summer 2002); also at http://www.aero.org/publications/crosslink/summer2002/05.html).

How these updates are generated is a matter of detail. They could come from a radar system observing the terrain while the weapon is falling; they could come from an observer on the ground who has some kind of input device which might simply trace the trajectory on a map; or they could come from a more automated system in which a laser, for instance, is used, not to guide the bomb itself, but to determine, by means of sensors, the co-ordinates of the target.

Abbot notes that future conflicts will probably rely on smaller munitions to minimize collateral damage. If the job is to destroy a tank, for instance, and 50 kg of high explosive is sufficient, why use a 1 000 kg weapon that will cause a lot more damage in the neighborhood? However, as the weapons are reduced in explosive yield, the accuracy must become even better. Such improvements in accuracy, as Abbot notes, mean that with these more modern weapons defensive strategies that involve constant movement are no longer proof against attack.

We have to recall that other precision munitions are available and have been for a long time. Such weapons include knives, hand guns, suicide explosive vests, and belts. They may be non-discriminating, but so are the precision munitions. When the United States bombed the Chinese Embassy in Belgrade, that was not a fault in the guidance system, it was a fault in the target selection process.

Non-lethal weapons (NLW) can also be considered precision weapons. These include strong nets for stopping cars and trucks, and Tasers—hand-held weapons that shoot electric darts to disable people by stimulating an involuntary, but temporary, contraction of the muscles. Tasers use a very high voltage but limited power. I know many people who have volunteered to be temporarily disabled by a Taser. All of these people were helpless in defending against it, but they recovered fully within a few minutes. It is not clear, however, what would happen to people with pacemakers or other problems. Further information on such weapons can be found in the reports of several Council on Foreign Relations-sponsored Task Forces on NLW (see *NonLethal Technologies: Military Options and Implications*, (Council on Foreign Relations, 1995) and *NonLethal Technologies: Progress and Prospects*, (New York: Council on Foreign Relations, 1999); also at http://www.cfr.org/publication.php?id=3326).

In any of these systems there are important parameters, not only on the weapons, but also on the overall system, for accuracy, timeliness, and environmental conditions, i.e., whether the system works in darkness, under cloud, or through smoke. For instance, while the laser-guided weapon can be highly accurate, the laser must be designating the target for basically the entire time that the weapon is falling—on the order of one minute from high altitude. If either the laser path or the sight-line from the falling bomb is interrupted by cloud or smoke or dust from previous explosions, the weapon will not strike the intended target. From that point of view, the GPS-guided weapon is far more flexible, since it is not vulnerable to smoke, camouflage netting (if you know the target is there), or dust from previous explosions.

Some of these weapons are autonomous, in that they and their operator provide the information, identification, location, and firing authority, as in the case of a Predator armed with an anti-tank weapon. Nevertheless, one still needs specific "rules of engagement" regarding their use. A responsible military will not send such weapons out just to strike anything that moves. All too often, especially in the heat of battle, mistakes are made, though one hopes that would happen less often in the case of these unmanned vehicles, where no lives are at risk and self-defense is not a justification for a hasty reaction.

Other precision weapons and their delivery vehicles may be launched and fired by command from a "network-centric" system of systems. Specifically, there is an observation system, a data analysis system, a strike system, an evaluation system, and a communication system. These include the mapping of terrain and the "cultural features," e.g. roads, buildings, missile silos, target locations, as well the obstructions to those targets. Sometimes these obstructions may be advantageous in providing protection from air defense or observed prematurely. Sometimes, however, the obstructions need to be countered in some way, such as when one encounters a protective berm in front of a tunnel entrance, and the weapon needs to maneuver to avoid the earth mound and strike the entrance itself.

Still other subsystems navigate via the Global Positioning System. These systems are often supplemented by Inertial Navigation, since GPS signals are very weak and easily overcome in the target area. Even if it does not acquire GPS signal, though, a weapon like the JDAM still has an accuracy on the order of 30 m.

The need for situational awareness is another important parameter for precision weapons. A military meeting room might make an excellent target, but only if it is occupied by military personnel at the time of strike. They could equally well meet in a tent. To mitigate that uncertainty, accurate intelligence is essential.

Intelligence acquisition can take many forms. One can, for instance use signal intelligence (SIGINT) and its subset, communications intelligence (COMINT). Inadvertent signals that are radiated by equipment can be very informative, and may also be supplemented by information on radars—their frequency, their scanning, and their direction of look at any particular time. Added to that is the information that the human eye can interpret—imagery intelligence (IMINT)—in the visible and infrared spectra. Such information is supplemented by radar mapping and imagery. There is also a network of spies and informants, collectively known as human intelligence (HUMINT), and a lot of "open source" intelligence such as newspapers, public radio broadcasts. We need a database of friendly and opposing forces; no military wants to destroy its own forces and they want to know the importance of the target and where are the key targets to be found.

In any military activity one does not want to waste limited resources, so the ability to evaluate a potential move or strike is crucial. As in a game of Chess or Go, one would like to know which of the possible moves it is best. One needs to locate and understand the capabilities of enemy defenses and then reduce or destroy them. Deceiving the enemy or jamming their communications is another option to consider. Stealth technology is one way to protect the offensive side, and tactics such as flying at very low level outside of radar view and of most countermeasures, then popping up at the last moment for delivery of a weapon, are also effective. Of course, the enemy might also be considering these options, so it is also important to understand the other side's capability to interfere with communication or navigation systems and to disguise or hide militarily significant targets.

Communication capabilities to and from friendly forces are also essential, as are spotters on the ground, overall intelligence for assessing the situation, and appropriately formatted, detailed maps to provide to people on the ground and in the air. Unmanned aerial vehicles and pilots receive such maps, sometimes even in flight, in order to see the appropriate approach route and co-ordinate his or her activity with that of other people. Additionally, pre-distorted views of the target and surrounding area can enhance a pilot's awareness and targeting ability, whether that pilot is man or machine. Even a television guidance system on a weapon can point out in advance that the weapon should strike a particular column supporting a structure or a particular corner of a window. As the accuracy available from GPS is exhausted, the smoke and haze will have cleared because one is so close and one can go over to visual automatic guidance for the weapon.

While images of the target can be useful, there are limitations. Although radar images of cities look just like an ordinary picture, the images are not instantaneous; the images do not capture moving vehicles, and they do not normally provide continuous coverage.

These high resolution radar images, taken from aircraft in the theater or, e.g., from Canadian and European radar satellites, are "synthetic aperture radar" (SAR). These are capable of resolution in both directions. If the vehicle carrying the SAR is moving from south to north, by having a wide bandwidth, i.e., a very short pulse, a radar signal sent out and returned can locate the target accurately in east-west position and give a picture resolution depending on the bandwidth. A 600 MHz bandwidth corresponds to about 30 cm of resolution, for two-way travel.

But the resolution along the path is obtained only from a very large antenna, and to get a wavelength of resolution, one must subtend an angle that is almost the total angle of space at the target. This can be done not with a physical antenna but with a synthetic antenna—synthetic aperture—by adding together, in phase, all of the returns from each possible picture element. At C-band (about 6 GHz), 5 cm wavelength, this resolution is about 5 cm, but it can be obtained only by observation over a very long time.

For an aircraft traveling 500 km/h and at a distance of 200 km from the target area, the observation has to take place over a distance of travel of 400 km or so, and that requires some 30 minutes. For a satellite SAR traveling at almost 8 km/s, a low-earth-orbit satellite speed, it will take about 2 minutes to cover 1 000 km to obtain such good resolution at a range of 600 km. If you have a shorter observation time, e.g., instead of 2 minutes you are limited to 20 seconds, a time shorter by a factor 6, the resolution along the track will be greater, i.e., blurred, by a factor 6, yielding a resolution of about 40 cm rather than 6 cm.

Detecting moving targets on the ground can be done much more rapidly, but these targets are only located precisely when in range of the radar and have much greater location uncertainty perpendicular to the line from the radar to the target. Yet that may be good enough for precision strike if you know that the target is on a road, so that a digital map, together with the range of the observation in particular places, can be used for precision attack.

The big brother of Predator is the Global Hawk, a very large aircraft with a payload of 1 000–2 000 kg, operating at an altitude of 20 km. (Pictures can be found on the web at http://www.is.northropgrumman.com/gallery/usaf/global_hawk.htm). Its wingspan is about 35 m, and because this is a high altitude aircraft it flies at about 500 km/h in order to provide lift in the rarefied air. This is also unmanned and, typically, has a bulbous bow and no windows, as the sensors look out the bottom and out the side. The Integrated Sensor Suite for Global Hawk, built by Raytheon Corporation, is (Information is also available on the web at http://www.raytheon.com/products/globalhawk_iss/)

| **Raytheon Integrated Sensor Suite for Global Hawk** (402 kg) |
|---|
| EO/IR aperture 28 cm, pixel MWIR: 11.4μrad; visible 5.1 μrad<br>WAS: 5750 $km^2$/hr; 1900 2 x 2 km spot/24 hr |
| Radar (X-band); 600 MHz bandwidth; 3.5kW peak.<br>8000 $km^2$/hr 10-km-wide strip at 1-m resolution to 200 km<br>1900 2 x 2 km spots/24 hr at 0.3 m res. |
| Ground Moving Tgt. Indicator radar 15000 $km^2$/min<br>Minimum detectable (radial) velocity 2.1 m/s. |

Of course, accurate mapping requires accurate navigation—the location and direction of the camera or radar is important. This is done with the aid of control points—check points on the ground which have been observed by other means—or by taking a GPS unit there and determining the precise location of some easily recognized landmark in order to extrapolate a little bit to the next intersection. GPS is the system of choice both for locating the imaging system and for navigating the weapon delivery vehicles or the munitions themselves. GPS gives an accuracy of about 5 m in 3-D with a probability of 90%. This accuracy changes with time and place, though, as the 24 active Global Positioning System satellites move on their 12-hour circular orbits around the Earth. With "differential GPS," much better accuracy is possible.

The following box contains some statistics on the Intelligence, Surveillance, and Reconnaissance operations, as well as the use of precision-guided munitions, during Operation Iraqi Freedom (also available at http://www.urbanoperations.com/oifcentaf.pdf):

| **COALITION ISR FACTS** | |
|---|---|
| US and Coalition ISR Aircraft | 80 |
| ISR Sorties | 1 000 |
| Battlefield Images | 42 000 |
| Hours of SIGINT Coverage | 2 400 |
| Hours of Full Motion Video | 3 200 |
| Hours of Moving Target Indicator | 1 700 |
| Guided Munitions Used | 19 948 |
| Unguided Munitions Used | 9 251 |

In the 1991 war almost ten times as many unguided munitions were used, causing a lot more damage. The societal damage in Iraq in 2003 was not caused by the bombing; it was caused after the war because, for one reason or another—lack of planning, lack of capability, or inattention—insufficient security was maintained against sabotage, looting, and destruction of the society.

But finally I leave you with these questions that I have not addressed:

- What does it mean to win a war by precise targeting of military capabilities only?
  During the attack on Baghdad, you would hear on European or American radio broadcasts telephone conversations from friends who where having tea on their terraces or in their swimming-pool while there where bombing attacks across the city, of which they had no fear because of the precision of the bombing.
- How soon will others have net-centric systems like the one I described?
- What will be the outcome of specific counters to this net-centric warfare—jamming, information warfare, deception and concealment?

And of great interest to the people using and opposing warfare:

- Does precision warfare render less discriminating weapons unacceptable?

Constructive use of technology is only possible if political and societal leaders understand these new developments and act in a responsible manner.