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# Ground and Maritime Moving Target Indicator Radar

NCW 101 part 8

Since the advent of air warfare, inclement weather has provided the principal opportunity for ground force movements, as optical sensors are unable to penetrate an overcast. Ground mapping radars, using real beam or later Synthetic Aperture Radar (SAR) technology, provided a robust means of locating and attacking fixed surface targets, with increasing precision over time. Slow moving targets however remained elusive, and it was not until the advent of Ground Moving Target Indicator (GMTI) radars that this sanctuary was removed.

An excellent example was observed during the 2003 invasion of Iraq, when large sandstorms blown in from the Western desert region brought most operations to a standstill, for days. Seeing this as an opportunity, Saddam's militia units sought to redeploy south in large road convoys, confident that the sandstorms would provide a cloak to conceal them from marauding coalition strike aircraft. An orbiting E-8C JSTARS, sweeping the area with its APY-3 radar in GMTI mode, tracked these convoys. Soon they were annihilated under a barrage of GPS guided JDAMs and smart submunition dispensing Sensor Fused Weapons. The APY-3 penetrated the sandstorms with ease and provided precision targeting data for incoming waves of bombers.

Over a year later, the US Air Force conducted an important trial during the Resultant Fury exercise in the Pacific. An E-8 JSTARS tracked a series of maritime targets using its APY-3 surveillance radar in MMTI mode, including barges simulating amphibious landing craft, and relayed precision realtime tracking data via a modified JTIDS network, to modified GBU-31 JDAM inertially guided bombs in flight, which subsequently annihilated these moving surface targets.

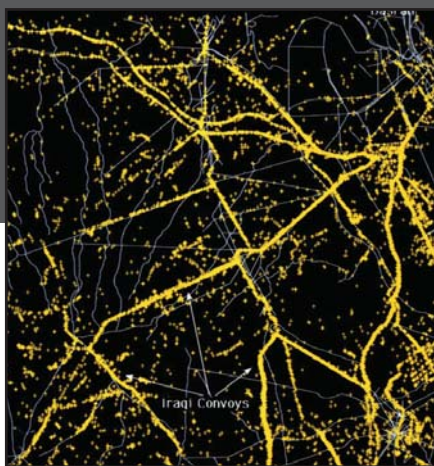
Until the advent of precision GMTI radar technology, both of these strikes would not have been possible.



clockwise from left:  
The E-8C JSTARS equipped with the APY-3 GMTI/SAR X-band radar is the most capable ground surveillance system deployed to date (USAF).

JSTARS imagery of UK countryside (USAF).

The 'Mother of All Retreats' JSTARS imagery of retreating Iraqi troops in 1991 (USAF).



## How GMTI evolved

Moving ground targets and slow moving maritime targets, especially smaller vessels, present serious challenges for legacy radar technologies. These problems arise as a result of the geometries and relative speeds, and radar signatures of such targets, when viewed from an aircraft. The faint energy backscattered from such targets is buried in the enormous reflection from the surface of the earth, termed 'clutter'.

The problem of tracking low flying aircraft and cruise missiles was solved during the 1960s, with the advent of Air Moving Target Indicator (AMTI) and pulse Doppler radar technologies, and supporting Kalman tracking filter technology. These technologies allowed the radar signal and

data processing software and hardware to sift through the jumble of reflected radar signals, and separate the reflections belonging to aircraft from the much stronger clutter reflections from terrain. In pulse Doppler surveillance and air intercept radars this was achieved by discriminating between the Doppler shift in the reflected radar signals. Doppler shift is an increase or decrease in the frequency of a reflected radar signal, which is proportional to the relative velocity between the radar and the target. Increasing frequency is produced by closing targets, decreasing frequency by receding targets. For relatively fast moving aerial targets, the Doppler shifts of these targets are quite different from the Doppler shift of the terrain clutter produced by the motion of the aircraft carrying the radar. Therefore it is feasible to use filtering techniques to separate the targets from the terrain clutter. This is the principle underpinning all 'look-down shoot-down' fighter radars.

Difficulties arise however, when the target is slow moving, since its Doppler shift differs little from the Doppler shift produced by the motion of the radar relative to the terrain. Unfortunately, moving ground vehicles like trucks, 4WDs, tanks, cars and other such targets fall precisely into this category. As powerful as pulse Doppler techniques may be they are simply unsuitable for this category of target.

Historically, the problem of tracking opposing ground forces became acute during the Cold War period, as the Soviets deployed increasing numbers of tanks and armoured vehicles in Eastern Europe. Given the poor weather prevalent through much of the year, and complex forested and mountainous terrain in many areas of interest, the US were especially concerned about their ability to divine and understand Soviet ground force movements. The Red Army juggernaut was not to be trifled with. While NATO had an overwhelming advantage in superior air power, which could annihilate massed formations of tanks, air power can only be used with effect where the location of the target is known. This problem became of increasing concern to US strategic planners during the 1960s and 1970s. The result was robust investment in research to find a way of tracking ground vehicles effectively.

The approach first pursued was adaptation of existing Airborne Moving Target Indicator (AMTI) radar, at that time being introduced in AEW&C radars to provide overland capability. All MTI radars are based on the idea of subtracting radar returns from consecutive pulses sent out by the radar. Signals from moving targets will differ slightly, due to their motion, more so than the ground clutter the radar sees. When the two returns are subtracted, the targets appear as differences. This technique is easy to implement in a static ground based or shipboard radar, but harder to do for airborne radars, and techniques were required to compensate the Doppler shift of the terrain clutter. An MTI mode of this ilk was introduced on the Motorola AN/APS-94 Side Looking Airborne Radar carried in the OV-1 Mohawk, during the late 1960s. It had limited capability, but was a step in the right direction.

The next breakthrough was the US Army's SOTAS (Stand Off Target Acquisition System) demonstrator, which installed a rotating AN/APS-94 antenna under a UH-1 Huey helicopter, to provide continual MTI surveillance through a circular arc. The APS-94 and SOTAS were feasible since the Mohawk and UH-1 were very slow moving vehicles, as a result of which the Doppler shifts in the radar clutter were quite small. For a faster platform, like an aircraft, where Doppler shifts in the clutter were much larger, this technique was no longer viable.

A completely new approach to this problem was needed, and this led to the genesis of the modern GMTI radar. In 1969 the US Air Force entered the game, by funding the MIT Lincoln Laboratory to develop the Multi-Lateration Radar Surveillance and Strike System or MLRS, using a pair of MTI radars. This effort led to the discovery of a technique termed Displaced Phase Center Antenna (DPCA), which is the basis of all modern GMTI and MMTI radars.

DPCA in its simplest form splits a sidelooking radar antenna into two halves. A radar pulse is transmitted, reflects off terrain and moving targets, and travels back to the aircraft. Because the aircraft has forward motion, and the antenna is

split into halves, the half of the antenna nearer to the tail will be in the physical location occupied fractions of a second earlier, by the half of the antenna nearer to the nose. Therefore, the motion of the aircraft is compensated for, and the clutter disappears. This is a very simple but also very powerful idea, as it allowed clutter to be removed from the radar signal by a clever arrangement of antennas, rather than complex signal and data processing. In such simple DPCA systems, the Pulse Repetition Frequency (PRF) of the radar is adjusted to match the forward velocity of the aircraft, and the range at which targets are searched for, so that pulses transmitted arrive at the right instant in time to reject the clutter.

Further research led to improved signal processing, which reduced the sensitivity of DPCA to aircraft velocity.

Such simple DPCA systems were capable of detecting ground vehicles moving at much lower speeds than any previous technique could. They still had the limitation of poor angular accuracy when tracking ground targets, critical for targeting applications.

Subsequently, a further discovery was that by splitting the antenna into three rather than two segments, it was possible to not only reject the clutter, but also perform a very precise angle measurement against a moving ground target. This was the breakthrough which was needed to produce operationally effective GMTI radars.

Armed with this research, the US Air Force and Army, with DARPA support, launched the Pave Mover demonstration program, which was intended to develop the radar technology needed to defeat massed Soviet armoured attacks in all weather.

Hughes and Grumman/Norden were contracted to develop two DPCA based Pave Mover radar demonstrators, which flew during the early 1980s to support the Assault Breaker smart anti armour munition demonstrations. The Pave Mover radars were carried in the weapon bay of an F-111E. The target tracking information produced by these radars was then relayed over a microwave datalink to a ground station, which processed the data for distribution to missile batteries, which would then fire submunition dispensing ballistic missiles at approaching armoured columns (refer <http://www.ausairpower.net/TE-Assault-Breaker.html> for details).



US Army UH-1 fitted with the SOTAS MTI radar, deployed in Germany during the Cold War (via <http://www.usarmygermany.com>).

The Pave Mover trials were a resounding success, and provided the proof of concept for the E-8 JSTARS and its massive APY-3 phased array radar. The APY-3 remains the largest DPCA GMTI radar ever built, using a 24 foot long phased array antenna, mechanically stabilised in roll. The system is so large, that a Boeing 707-320 airframe is required to carry it.

The APY-3, like most GMTI radars, operates in the centimetric X-band, the remainder typically operating in the even shorter Ku-band. The choice of radar wavelength for these applications is not arbitrary, as these bands were found to be best for detecting ground targets. Tanks, trucks, 4WDs, artillery pieces and other such targets are of the size where most of their radar signature is produced by detail features, so a centimetric band radar performs best in detecting such targets.

Another important performance aspect of GMTI radars is their effective range. The ugly reality is that to achieve good range in such radars, given the often low signatures of the targets involved, considerable power and a large antenna aperture are required (this is not unlike the problem faced by Soviet designers when they built the massive X-band Uspekh maritime targeting radar carried by the Bear D maritime reconnaissance and targeting aircraft). Building large centimetric band high power radars is not easy, which is why so few such systems exist.

With JSTARS in development, other applications were sought for this technology. Norden, a key player via prior Pave Mover experience, sought to introduce this capability into an upgrade for the US Navy's A-6 Intruder via a new Norden AN/APQ-173 radar, and into the new phased array Westinghouse AN/APQ-183 radar in the A-12A, intended to replace the A-6. Both programs were cancelled. The technology was subsequently introduced into the AN/APG-76, a large Ku band attack radar designed for an Israeli F-4E upgrade.

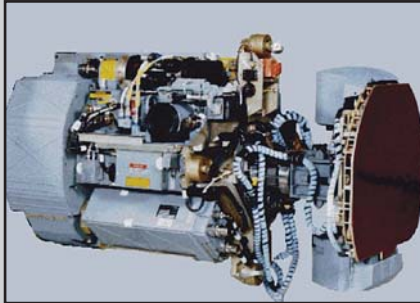
The large APG-76 was designed with five receiver channels, and could simultaneously perform high resolution SAR imaging and DPCA GMTI tracking and targeting. This superb but large Ku band radar used a conventional planar antenna, supplemented by three lower auxiliary antennas for three segment DPCA GMTI modes, which provided it with the most accurate GMTI capability in any fighter radar during the 1990s.

The Grumman/Norden and Hughes Pave Mover demonstrators proved the concept of highly accurate DPCA GMTI radar. Both were carried in the weapon bay on an F-111E (Norden).





The Norden APG-76 MMRS was the first fighter radar to employ DPCA GMTI capability, providing exceptional tracking accuracy. (Northrop-Grumman)

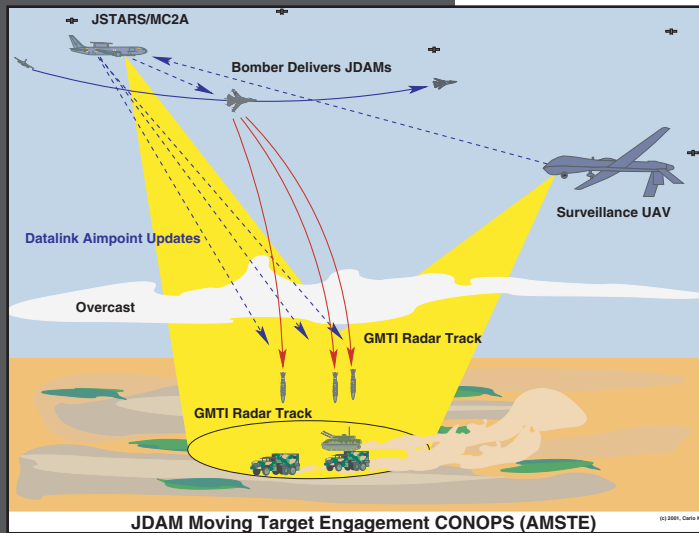


Other manufacturers of multimode X-band fighter radars soon sought to emulate what Norden did by providing DPCA GMTI capabilities in existing fighter radar designs. Invariably they exploited the fact that most of these radars had antennas which were segmented into four quadrants, which permitted monopulse angle tracking for air to air engagements.

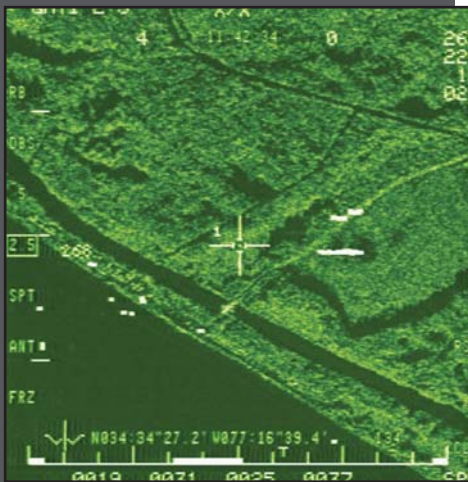
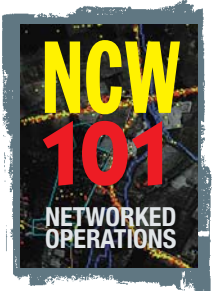
Whether the radar antennas were segmented in an 'X' or a '+' pattern determined whether the highly accurate three segment DPCA or less accurate two segment DPCA technique could be used. To date none of the manufacturers have disclosed this, as it would no doubt have an adverse effect on marketing if customers knew that only basic two segment DPCA could be used.

Having a 3 segment DPCA GMTI capability is valuable in radars used on aircraft which are to perform battlefield interdiction role, as this allows blind all weather attacks with GPS guided weapons like the GBU-31 JDAM or GBU-39/40 Small Diameter Bomb, on moving columns of ground vehicles or surface shipping. The drawback of GMTI capability on such radars is that the useful footprint is limited by the modest power output and small antenna size on these radars, which results in them having a very small footprint compared to specialised Intelligence Surveillance Reconnaissance radars like the APY-3 or the equivalent but smaller European SOSTAR-X system.

In the Australian public defence debate, fighter radars with GMTI capability are often touted as equivalent somehow to large multi-segment DPCA GMTI radars in the JSTARS category. This is from a technical and operational perspective pure nonsense, as the fighter radars not only cannot match the useful range and footprint of the larger radars, but due to smaller antenna sizes cannot even come close to competing in angular accuracy and thus achievable precision when used for targeting or ISR purposes. Never let facts get in the way of a good yarn!



JDAM Moving Target Engagement CONOPS (AMSTE)



APG-76 GMTI/SAR imagery, convoy crossing bridge and beachhead assault. (Northrop-Grumman)

## The future of GMTI/MMTI

DPCA GMTI radars are tremendously useful, whether used for battlefield surveillance, reconnaissance or targeting, or in maritime operations.

The latter is especially interesting, since conventional pulsed maritime radars are designed primarily for the detection of full size shipping in blue water operations. That is an environment where the ocean surface clutter is well understood, and targets are both very large and usually highly reflective to radar.

The reality of much of contemporary maritime surveillance is that it takes place in littoral waters, or archipelagic waters, where targets often exploit landmass clutter to evade radars designed for blue water operations. Another factor is that in such environments, many targets of interest are often very small, be they landing craft, barges, fishing boats, launches, yachts, speedboats, dhows and other small traffic. As a result targets of relatively low radar signature are operating in a complex maritime clutter environment.

Radars designed around DPCA GMTI capabilities are well suited for this regime of operations, since they can much more effectively reject the clutter environment, but also do a better job of separating low signature targets from the background. This is operationally highly valuable. Another application which has emerged for DPCA GMTI radars is cruise missile defence. Cruise missiles are very small low flying targets which hide in clutter, and often have very low radar signatures head on, but larger signatures from abeam. Conventional AWACS and AEW&C radars often have difficulty tracking cruise missiles effectively, since their designs typically assume aircraft sized targets with larger radar signatures. X-band DPCA GMTI radars are generally considered more effective against cruise missiles,

since they are able to extract small targets with lesser Doppler shifts from clutter more effectively, but also because the X-band radar signature of many cruise missiles is higher than their signature in the lower radar bands.

The longer term outlook is that we will see more specialised DPCA GMTI/MMTI radars on specialised ISR platforms, and some kind of DPCA GMTI/MMTI capability in all new fighter radars. How effective the latter will be will depend primarily on the design of the radar antenna segmentation, and especially the power aperture performance of the radar.

The US some years ago launched the MP-RTIP (Multi-Platform Radar Technology Insertion Program) which is a family of modular X-band active phased array (AESA) radars designed for ISR applications, especially DPCA GMTI/MMTI. The MP-RTIP program aims to design not only individual phased array TR modules, but also larger 'tiles' comprising multiple modules, allowing specific antenna configurations to be built up from standard components, to match specific applications.

Three applications have already been announced for MP-RTIP modules. The first is an antenna upgrade for the APY-3 in the E-8C JSTARS, to increase range and sensitivity. The second is an adaptation of the APY-3 upgrade package to the planned, but currently suspended, E-10A MC2A ISR aircraft, intended as a replacement for the E-8C. The third is a new DPCA GMTI/MMTI radar payload for the second generation RQ-4B Global Hawk, intended to replace the U-2's ASARS package in strategic ISR roles.

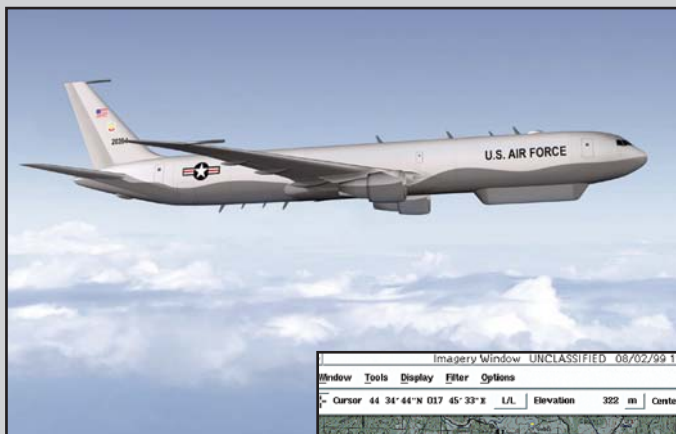
Another application since canvassed by Raytheon is the planned US Navy P-3C replacement, the P-8A MMA, which would carry a shorter variant of the APY-3 MP-RTIP radar, to be used in cruise missile defence, littoral maritime surveillance, and in providing GMTI ISR support for amphibious operations and battlefield interdiction from aircraft carriers.

Networked environments have tremendous potential for high tempo operations, given the ability of a well designed network to distribute targeting data very quickly to large numbers of platforms. Current US Air Force thinking is to extend that network down to munitions like the JDAM and SDB, in flight, and ultimately down to smart submunitions where appropriate.

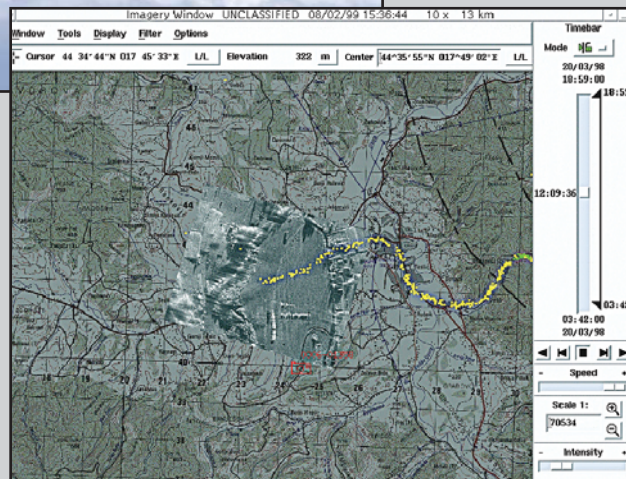
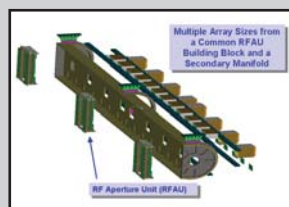
The intent, long term, is to gain the capability for massed precision attacks against moving targets, such as an invasion force landing on a beach, or a massed armoured attack. Current US operational capabilities permit individual attacks on moving targets, or massed attacks on fixed targets.



The P-8A MMA has been proposed as a platform for carriage of the MP-RTIP radar, for maritime surveillance, cruise missile defence, and ground surveillance tasks (Boeing)



The E-10A MC2A is intended to replace the JSTARS, but has been put on hold due to a funds shortages. It will use the MP-RTIP AESA GMTI/SAR radar.



Whether the attacker is an F-22A dropping eight SDBs or a B-2A dropping 320 SDBs, these systems are currently limited to fixed aimpoints, even if these are loaded into the bombs seconds before release, using the onboard radars for targeting. High precision large DPCA GMTI or MMTI radars are as much the enabling technology for this, as are the radio networks used to communicate with the bombs.

The Affordable Moving Surface Target Engagement (AMSTE) trials conducted in 2003, sponsored by the DARPA Special Projects Office (SPO) and the Air Force Research Laboratory Information Directorate, intended to fuse established GPS/inertially guided bomb, networking, GMTI and SAR radar technologies, to permit massed blind radar bombing precision attacks on moving surface targets.

The model developed in the AMSTE program is simple. Munitions such as the JDAM or SDB are modified to incorporate a datalink receiver, which permits the bomb's aimpoint to be continuously updated in flight. Weapons with GPS/inertial guidance have to date been limited to fixed targets, since the target location could not be updated once the bomb's cable umbilical to the aircraft was broken. Legacy laser and TV guided weapons did not have this limitation, since the weapon is guided by laser illumination on the target, or a TV contrast lock on the target.

For a GPS/inertial guidance system to be capable of use against a moving target, it must have the capability to accept continuous position updates from an offboard source, whatever that may be. The modifications first trialled during the AMSTE drops provide this capability. Understandably the changes to the internal navigation software of the bomb must be more extensive, since the Kalman tracking filter and autopilot must be able to project the future position of the target from a series of consecutive network updates, to bias the bomb's flightpath so it intercepts the target. This would involve a proportional or lead-pursuit homing

algorithm of the ilk used in air to air missiles.

In an operational environment, a GMTI radar like the APY-3 or MP-RTIP is used to track a formation of surface targets like a convoy, tank squadron on the move, or wave of amphibious assault craft approaching a beachhead. Each target is individually tracked in position and speed.

A bomb delivery aircraft is vectored over the target, and its fire control software, via the network, communicates with the targeting GMTI radar system's software. The GMTI radar system software assigns specific bombs to specific targets, and generates cueing commands to the pilot of the bomber, so he can position optimally to drop the weapons.

Once the assigned bombs have separated from their ejectors, the datalink receivers in the bombs go active and acquire target position updates being broadcast over the radio network via the distant GMTI radar system. As the radar continues generating individual tracks for each target, it broadcasts a stream of position updates to each bomb individually over the network. The bombs each continuously predict the future position of their assigned target and fly to this point, impacting with a distance error determined by the GPS guidance in the bomb, and the accuracy of the targeting coordinates generated by the distant GMTI radar system.

The advent of wide area differential GPS systems such as WAGE or EDGE (refer <http://www.ausairpower.net/TE-GPS-Guided-Weps.html> Part V) indicates that future GPS/inertial errors will be as low as inches in longitude, latitude and elevation. As a result the dominant error in the bombing equation will be that of the GMTI radar providing targeting information.

This is why in the long term, it is so critical that appropriate investment is made into DPCA GMTI/MMTI radars, but also why much care must be put into selecting such systems, to ensure that the basic design can produce very accurate target track.