Antenna Subsystem for Small Missile

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Abstract

The purpose of this project is to propose a conceptual design of an antenna subsystem suitable for installation on a small missile or a smart bomb of Thailand's Defence Technology Institute (Public Organization) or DTI. The antenna is planned to be used for ground-to-ground or air-to-ground communication, together with other subsystems such as missile processing unit, sensors, GPS receiver, power distribution, and small fins for missile/bomb direction control.

This project consists of a design of a 1.575 GHz GPS receiving antenna and a 2.4 GHz Telemetry transmitting antenna. The project starts from the study of System Requirements, followed by System Architecture and System Sizing. Then, subsystem components including antenna, feeding network, and/or splitter/combiner are designed, simulated, built, and tested with related discussion and recommendation.

Keywords-Small Missile; Series-fed Rectangular Patch Array;

1. Introduction

This research project is a part of Control and Communication Laboratory (OCC) roadmap towards a development of high-performance guided short-range missile, following the success of our unguided missile. Result of the research can also be used for accuracy improvement of other ground-to-ground and air-to-ground bombs.

In general, in its ready-to-use state, these missile/bomb will be able to work autonomously, using position data from onboard GPS receiver and/or Inertial Navigation System (INS). The reason for using 2.4 GHz telemetry signal for communicating with the ground or the aircraft is not only because it is a compromise between the lower 900 MHz and the higher 5.8 GHz frequency bands, but also because it can be realized onto a missile/bomb easily using a simple FR-4 substrate. However, other frequency such as 1.2 GHz, which is already popular for analogue video transmission, can also be used if there is sufficient surface area on the missile.

In term of use, the operational ranges of these missile/bomb can be found up to a few hundreds of kilometers and with up to supersonic muzzle velocity. On leaving the launcher, both rotating and non-rotating types can be found, with the latter be easier to control. The rotating missiles are normally controlled by means of pulser while the non-rotating ones are controlled by fins.

Normally the control & guidance section/adapter of a missile/bomb is made as a small section, easily attached to the missile/bomb with minimal modification, mostly be means of special strap or harness that can withstand high tensile force and axial acceleration. Any electronic equipment attached to the missile in this manner also needs to withstand vibration from chemical combustion and plume effect as well as aerodynamic perturbation. External antenna may also subject to instantaneous temperature of many hundreds Celsius especially in the case of a longer-range missile, in which case phenolic resin or ceramic will be used to coat its surface.

The extra antenna (apart from the GPS one) can serve many purposes. It can be used when the main guidance is not yet fully developed or when GPS is automatically cut-off at any cruise speed over 1.5 mach. It can also be used for sending various missile parameter and monitoring data to the ground control station or sending video signal (from a camera attached at the head of the missile) to the ground for visual guidance purposes.

The scope of this project focuses on the context of a small missile, such as the 122mm missile, with 10-20 km range. It is assumed that the missile is launched from a launcher in a ground-to-ground fashion and there is a need for the missile to communicate with the ground tracking station for most of the flight.

2. System Requirement and System Design

2.1. System Requirement

Missile test configuration shall be most resemble to real configuration and if still not finalized, worst case analysis must be used. During the test, the missile will be launched into the sea, far away from habitant area. The communication can take place between the missile and the command post which may situate near the launcher or by the side of trajectory path. Here, the latter is chosen as shown in Fig.1 as it would be more economical and only 1 ground tracking station would be required (2 or more tracking stations with separate data link and time synchronization would be needed for longer range).

The wrap-around antenna onboard the missile is designed to have Horizontal Polarization (HP) while cruising parallel to the earth surface. The rotation of the missile will turn HP into Circular Polarization (CP) automatically, however it is decided that normal HP is to be used at the ground tracking station and 3dB loss is allocated for Polarization Loss. The orientation on the missile motor and its polarization is shown in Fig. 1.

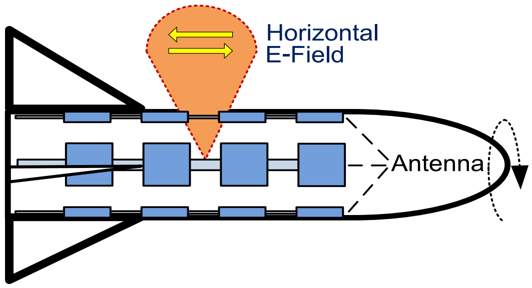

Figure 1. Horizontal E-filed of the radiation pattern when viewed from the ground tracking station.

2.2. System Architecture

From the link budget of the 2.4 telemetry signal calculated at a range of 20 km between airborne transmitter and the ground receiver, 10dB airborne wrap-around antenna gain is required. The link budget for the 1.575GHz GPS signal reception is not of our concern as the gain and sensitivity of an active GPS antenna and GPS receiver are relatively high and is therefore more than sufficient (most GPS antennae have been designed to receive GPS signals very well even for the passive types (with no amplification). The reliability and efficiency is even higher with an active configuration.

3. Equipment Design and Development

In this project, "Altium Designer" has been used for PCB design, "Antenna Magus" for cylindrical array antenna design and simulation, "Tx-Line" for microstrip line dimension calculation, and ZVH-8 R&S Antenna and Cable Analyzer (with Spectrum Analyzer and Vector Analyzer functions) for most of measurements and analysis.

3.1. Onboard GPS Antenna

In case the missile is not rotating, only 1 GPS antenna facing to the sky is needed. However, 2-4 equally spaced GPS antennae would be required around the missile circumference if it is rotating. Whatever the configuration, the antennae should be embedded into the missile surface, leaving only the surface of the patch facing outwards with non-metal cover and temperature insulation. Anything protruding from the surface will introduce unwanted aerodynamic drag.

In the past, some experiment has been made on RHCP microstrip patch antenna as well as Quadrifilar Helix for receiving the GPS signal. The latter may be suitable for amateur rocket but not a tactical missile because 1) special fiberglass radome capable of withstanding high temperature is needed 2) the radiation pattern will be altered due to such radome, and 3) it is difficult to build a Quadrifilar Helix with high gain in every direction. Therefore COTS active GPS antenna will be a good candidate. The high gain characteristic of such antenna can compensate other drawbacks which may exist if any. However, a low-profile and moderate size patches, which can withstand high 'g' force and vibration will be preferable. An example of COTS GPS antenna used in the laboratory is shown in Fig.3.

Figure 3. Active GPS antenna with 28dB gain (cable loss not included)

Fig. 4 shows general configuration of fixed fins and controllable fins as well as various antennae and how they fit into the nose cone of missile/bomb in the form of nose adapter. The design also depends on levels of reliability and precision of the system and types of the missile whether it is rotating or not.

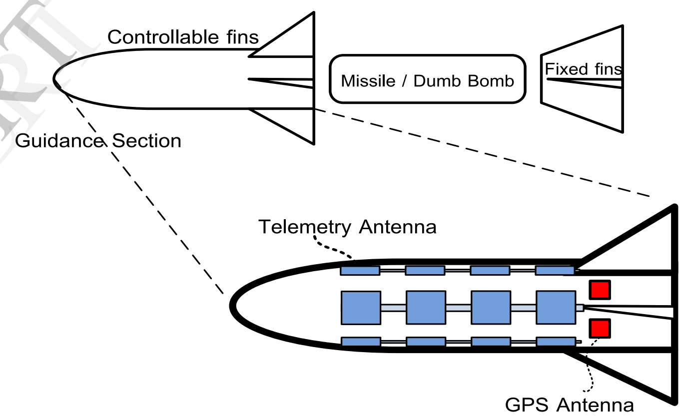

Figure 4. Fixed-fin and controllable-fin adapters, together with GPS and telemetry antennae

Four telemetry antennae placing 90° apart around the missile could be used, or only one antenna facing to the ground would be sufficient if the missile is not rotating. Not only does four-antenna configuration help the communication with the ground, it also helps improve system availability in case the missile is to be maneuvered. A splitter/combiner designed at specified frequency is normally used for combining signals from many antennae. It is used where overall gain of the system is not too critical as some power loss has to be sacrificed due to nature of this type of power combiner (e.g. a minimum of 6 dB would be lost for the 4-way splitter/combiner).

3.2. Power Spliter/ Combiner for GPS Antennae

In case of rotating missiles, such as the 122mm or the 130mm missile, GPS antennae should be installed around missile nose cone above the fuze area. As radiation pattern of a GPS rectangular patch would come out of the patch in a perpendicular direction, the final pattern will be the sum of the radiations from all patches for a planar array. The resultant vector could be both constructive and destructive. In case of conformal antenna, such as cylindrical array, such phenomenon will not be too critical as all patches are in different planes. Here, Nyquist Sampling Theorem can be used to find optimum number of patches required. It is noted that antenna patches could also be installed on the warhead which has bigger area and therefore should be easier. However, in many cases it is found that there are high risk of possible scratches from launch tube or launch rack.

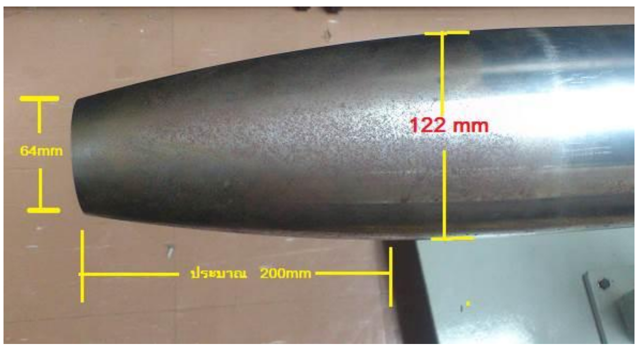

Figure 5. Typical nose cone of a small missile

According to Nyquist Sampling Theorem, any signal with frequency f can be reconstructed effectively by sampling it at sampling frequency $\geq 2f$. Conversely, it can be concluded that the installation of n antennae patches around the missile will produce more or less like a 4-petal radiation pattern when looking into the cross-sectional area of the nose cone if $n \geq (2\pi R)/(\lambda/2)$ or ≥ 2.1 around ϕ64mm. However, it is found that $n \geq 4.0$ when calculated around ϕ122 mm (GPS frequency is 1.575 GHz).

It is obvious that the installation of GPS antennae around the area between the nose cone and the warhead (at ϕ122 mm in Fig.5) is easier as available area is bigger. It also depends on the designer's judgment whether to use 4 or 6 antenna patches (odd numbers can also be used but is difficult to realize in general). As installation area is limited, the 2.4GHz telemetry signal therefore is prevalent here as there can be many GPS satellites in different directions in the sky but there is only one tracking station on the ground. Other factors to be considered include sizes and gains of the patch antennae to be used. The bigger the patch, the higher the gain. Also, bad sensitivity gives rise to too high GPS Time-To-First-Fix (TTFF).

Figure 6. Measurement of S21 radiation pattern using R&S ZVH-8

An experimentation has been made with 4 GPS antennae installed around a foil-wrapped PVC tube. Signals from the antennae are routed into a 4-way 1.575GHz splitter/combiner built in the laboratory (with an SMT inductor to pass DC supply to the antennae at the input junction of the splitter/combiner). The measured radiation pattern around the tube is very similar to the simulated result using Antenna Magus as shown in Fig.6-8.

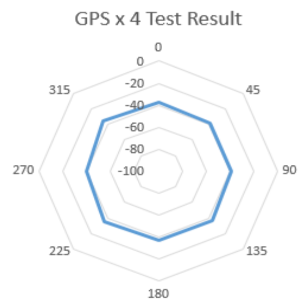

Figure 7. MS Excel plot of S21 every 45° around the PVC tube

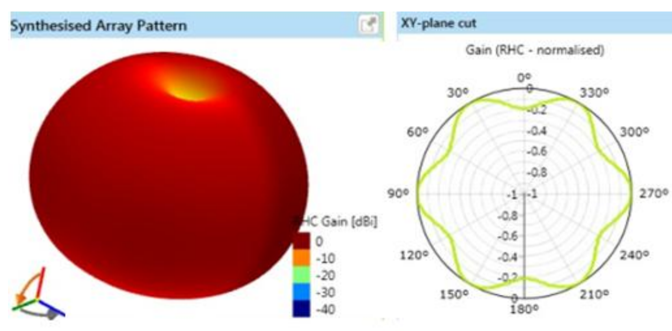

Figure 8. The simulated radiation pattern from Antenna Magus

3.3. The 2.4GHz Telemetry Wrap-Around Antenna

A study of how to effectively roll FR-4 substrate has been carried out. Both FR-4 of 1.6mm and 0.8mm thick have been baked at the temperature of 170-200°C using convection oven,

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then immediately roll-formed using metal-sheet roll forming machine. As 2.4GHz is relatively low for patch array realization, the patch size is quite big and is difficult to roll or bend into cylindrical shape and therefore is only suitable for a big missile with diameter of 400mm or more. FR-4 has been used as it is cheap, easy to find and its losses at 2.4GHz is still not too high. However, it is also possible to shift the frequency up to make the patch size smaller, e.g. to C-band or 5.8GHz ISM band, to make it easier to bend or roll the antenna but this will be at the expense of more complex and expensive equipment and tools such as a special RT-Duroid substrate. Apart from this, it is still found that thinner substrate, e.g. 0.8mm, can be bent more easily and also at a bigger curvature. However, the thinner the substrate, the higher the frequency it supports. Some examples of bent substrate are shown in Fig.9.

Figure 9. FR-4 substrate no.1 and no.2 of 1.6mm thick with their maximum curvatures, and the easier-to-bend substrate no.3 of 0.8mm thick

Some experiment has also been made on blade antenna but it is found that it is not suitable for a tactical missile as the protruding blade can be incompatible with the launcher. Also it is quite difficult to produce uniform radiation pattern around the rocket motor.

One of the solutions for effective bending of patch array antenna is to use a paper substrate. Here, A4 paper has been experimented, together with top and bottom copper sheet covers. However, as the thinnest available copper sheet is 3oz or 0.109mm thick, or 3oz copper sheet is available, there are some difficulties in engraving it into patches and feeding network of precise and consistent dimensions. It is found also that the antenna gain achieved using paper substrate is far less than that from FR-4 substrate even though it can be made to conform to wide variety of shapes including cylinder. The measured gain is also lower than the simulated gain. The solution to this problem includes adding a connectorized power amplifier to the transmitting chain, reducing splitter/combiner loss, and using a special wraparound antenna with more than 1 dimension, e.g. 2x4, 2x6, etc. The blade and paper-substrate wrap-around antennae made are shown in Fig.10.

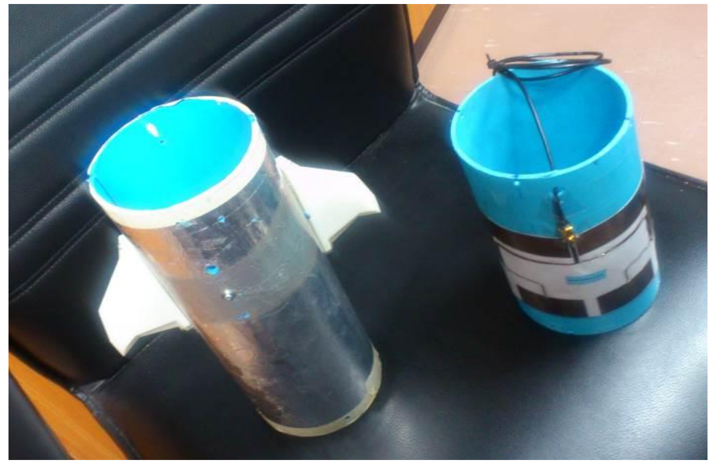

Figure 10. Blade antenna and 1x4 corporate wrap-around Antenna

Paper substrate presents a great deal of design flexibility. Its dielectric permittivity, ε_r , varies between 2.7 and 3.0 in general condition, and can be adapted on different types of platforms. However, the value can change easily due to environmental atmosphere, i.e. dry, damp, wet, etc., as well as whenever the paper substrate is being bent around. Care therefore must be taken by properly sealing the antenna against moisture and heat.

Flexible substrate experimented in the project are the A4 80g office paper and a thicker artwork paper. Art paper comes in many standard sizes starting from 1mm thickness, while many pages of A4 paper have to be used in order to make a thicker substrate. In general, the lower the frequency, the thicker the substrate is needed. It is found that the best way to increase the antenna gain without worrying much about the balance of phases is to use series-fed rectangular patch array. Four or six of them can be put around the missile and connected through a single 4-way or 6-way splitter/combiner in the way similar to that of GPS antennae. Doing so would eliminate the problem with bending an antenna array around small missile circumference. It is also possible to bend each antenna array longitudinally along the nose cone of the missile if needed in order to avoid any possible scratches from the launch tube/rack.

Two main design modes for series-fed rectangular patch array are available, namely the resonant mode and the travelling-wave mode. The former is used here as it gives relatively high gain at boresight with no beam-tilt due to the resonant effect caused by the last patch in the series which is open-circuited. It is found from the simulation that as high as 20dB gain and as narrow as 5° beamwidth can be achieved for a long antenna. Figure 11 shows some examples of resonant series-fed rectangular patch array experimented by the project using FR-4 and flexible substrates.

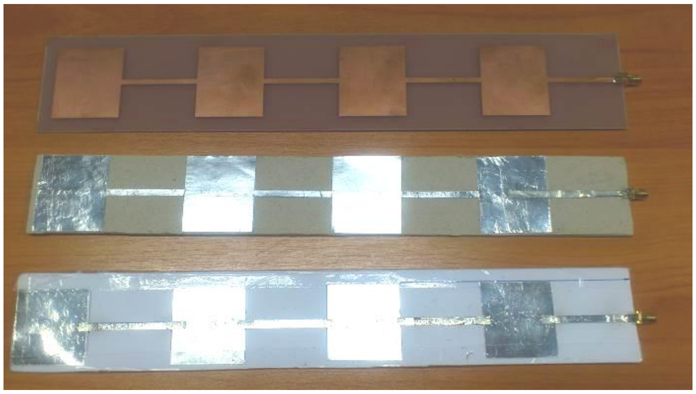

Figure 11. 1x4 series-fed rectangular patch array made by FR-4 substrate (top), art paper (middle) and A4 paper (bottom)

Figure 12 is the S11 (in the form of VSWR) response of the A4-paper substrate series-fed rectangular patch array. The response is low enough to be used as a transmitting antenna and the resonant frequency is as designed, the gain achieved is quite different from the simulated value. The reason could be due to many factors such as correct value of dielectric permittivity, the use of copper foil for making antenna patches also suffers certain discontinuity of impedances at various junctions as well as at the SMA soldering point. These problems can be solved using a bigger copper foil/copper sheet, and tin-plated type is the most helpful.

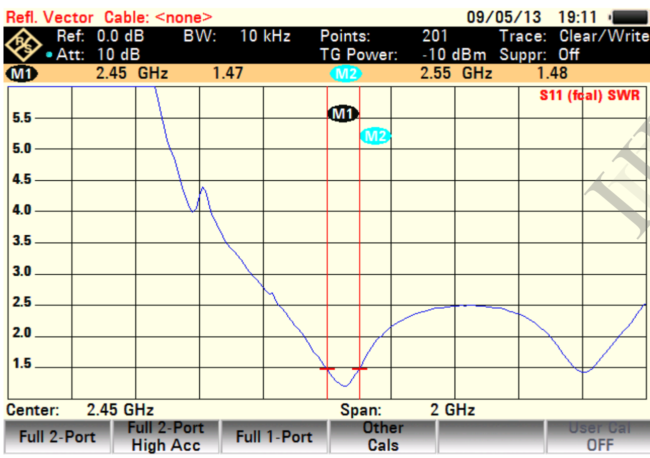

Figure 12. S11 response in the form of VSWR for paper substrate antenna measured using R&S ZVH-8

Correct thickness of the foil should also be input into the simulation. It is noted that most of the COTS foil will already have thicknesses far beyond those required by Skin Effect criteria. Among all substrates experimented, FR-4 gives closest gain performance to the simulated value with discrepancy of no more than 2dB, while the performance obtained from paper substrates can vary.

The realization of the series-fed rectangular patch arrays onto a small missile with nose cone and warhead length of 200-300 mm may limit number of patches to only 3-4 patches, which results into a bigger radiation beamwidth. Simulated radiation patterns and dimensions for different number of patches is shown in Fig.13.

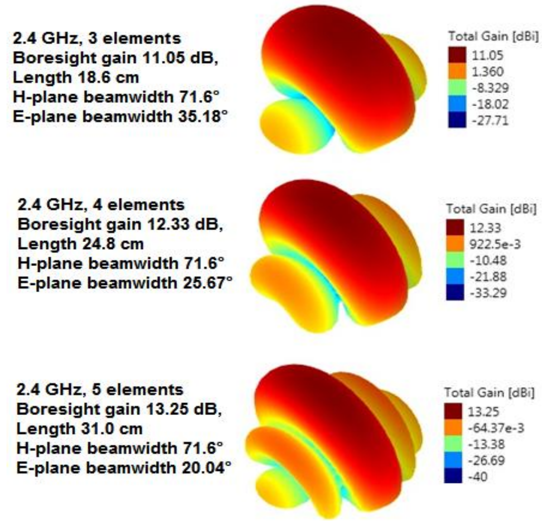

Figure 13. Simulated radiation patterns and dimensions for different number of patches of series-fed rectangular microstrip patch array

3.4. Power Splitter/Combiner for 2.4GHz Telemetry Antenna

4-way power splitter/combiner has been developed in the same way as that for GPS antennae. Corporate feeding network has been used for its design simplicity. As from Nyquist Theorem, number of antenna element, n, should be such that $n \geq (2\pi R)/(\lambda/2)$, where R is roughly about 58 mm (the area around ϕ122mm), and λ is 0.1225m for 2.4GHz.

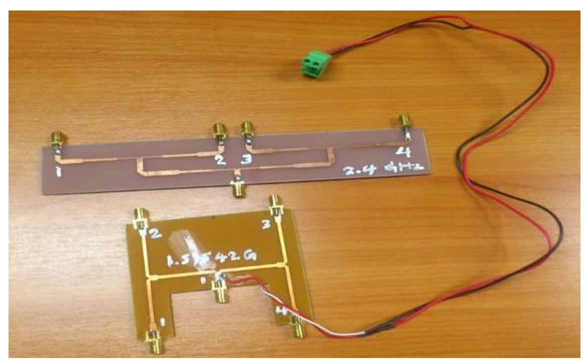

Figure 14. Comparison of the 1x4 feeding networks for the 2.4 GHz and 1.575 GHz antennae

It turns out that $n \geq 5.9$, however only $n = 4$ will be used here due to a concern on space that needs to be shared with GPS antennae. Fig. 14 shows a comparison between the 1.575GHz GPS and 2.4GHz TM splitter/combiners. It is noted that the GPS splitter/combiner has been bent into 'H' shape in order to better fit inside missile compartment. Power supply is also fed into the input junction through an SMT inductor. S21 measured between the output and the input ports of the 2.4GHz feeding network in TABLE 1 shows average value of about -8 dB (theoretical loss for the 1x4 splitter is -6dB) with minor differences among different ports. If perfect balance of phases is to be guaranteed, it is recommended to buy commercial graded component.

TABLE 1. S21 from each output port of the 2.4GHz feeding network

	Port 1	Port 2	Port 3	Port 4
S21 (dB)	-7.38	-8.18	-8.29	-7.16

In order to study resultant radiation pattern of the antennae around rocket motor, basic parameters and geometries of the resonant series-fed microstrip rectangular patch array of the size 1x4, each with fan-beam pattern, is input into Antenna Magus software, together with required distribution matrix. The element pattern is combined with cylindrical array patter and the 3D radiation pattern and the x-y plane cut comes out relatively uniform around the missile as shown in Fig.15.

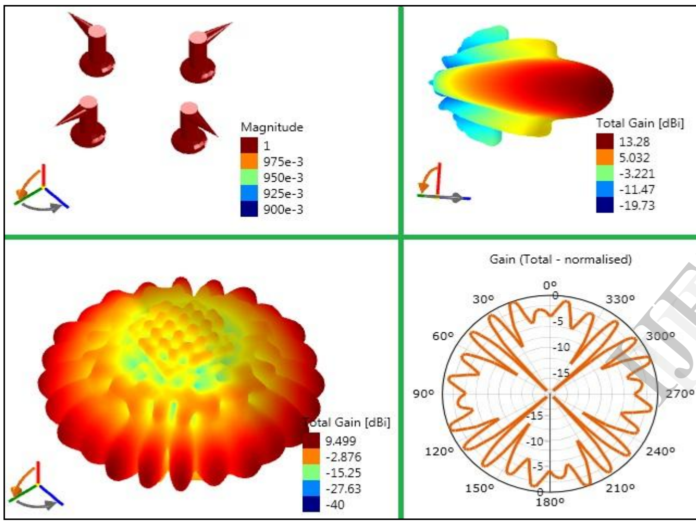

Figure 15. Distribution matrix of 4 antennae around the missile (top-left), fan-beam element pattern (top-right), resulted 3D radiation pattern (bottom-left) and its x-y plane cut pattern (bottom-right)

When compared with the resultant radiation pattern from a typical 1x4 rectangular patch array, the x-y plane cut in Fig. 16 shows significant improvement even though only 4 series-fed patch array are used.

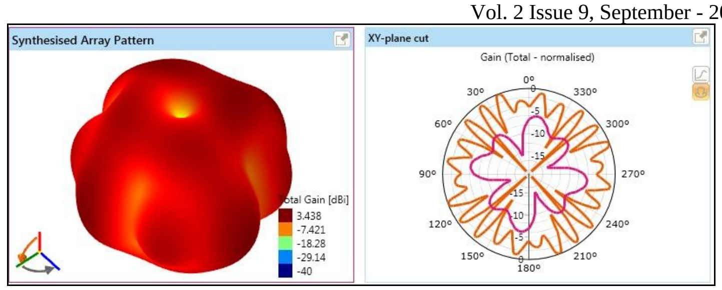

Figure 16. Radiation pattern from a typical 1x4 rectangular patch array and the comparison result with that of 4 x series-fed patch array of 1x4 in x-y plane cut

4. Conclusion

In this project, an overall picture of missile antenna subsystem design process is presented, starting from the studying of CONOP, system parameter and test configuration, followed by the link budget calculation and system sizing before any subsystem design and implementation can take place.

For the component design, it is found that a COTS GPS antenna can be readily used on a missile with some modification. Installation location and required number of antennae have been studied and recommended. Wrap-around antennae for small missile and its feeding network have been discussed. Resonant mode series-fed rectangular patch array has been proposed for use around the missile with some experimentations and discussions. At the end, the resultant radiation pattern from 4 series-fed patch array has been simulated around the missile. The proposed design gives more uniform radiation pattern with higher gain when compared with a typical 1x4 wraparound rectangular patch array and can be easily installed and conformed to the shape of a missile.

5. Acknowledgement

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