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A Novel Planar Antenna Array for a Ground-Based Synthetic Aperture Radar

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Abstract: A MIMO GB-SAR system called MELISSA was put in place to monitor landslides in Italy and the sinking of the Costa Concordia cruise liner in France. It comprises 12 pyramidal horn antennas placed in a linear geometry for transmission, and these are used in the detection of the motion of a target (for example a landslide or other terrestrial deformation). The low half power beam width (19.76° at θ = 90°) of the transmitting radiation pattern of MELISSA results in low coverage area of the target. This paper proposes two alternative types of horn antenna for the current transmitter module of MELISSA, namely the cantenna and coaxial cavity horn antenna, for installation in a 2×6 planar antenna array. A higher value of the 3 dB beamwidth is observed using these arrays (38.320 at θ = 90° and 104.80 at φ = 0° for the cantenna array and 410 at θ = 90° and 140.40 at φ = 0° for the coaxial cavity horn antenna array). The overall gain of the proposed systems is around 10 dBi, and the efficiencies are between 85% and 90%. Using the Dolph Chebyshev beamforming technique on the proposed antenna arrays yields a zero sidelobe level, which improves the overall peak sidelobe ratio of the system and in turn the quality of the images obtained. Our proposed design for the transmitting section of the MELISSA system has applications terrestrial deformation monitoring with higher area coverage.

Keywords: Cantenna, Coaxial cavity horn, Dolph Chebyshev beamforming, GB-SAR, Isolation, MELISSA, Mutual coupling.

1 Introduction

The Mimo Enhanced LInear Short SAR (MELISSA) system was used to monitor the fatal shipwreck of the Costa Concordia, an Italian cruise ship that capsized and sank in January 2012, leading to the loss of 32 lives [1]. MELISSA was first designed and used to enhance the LInear Synthetic Aperture Radar System (LISA) [2, 3] which was introduced by the Joint Research Centre of the European Union for landslide monitoring in Italy. Other GB-SAR systems have also been employed in the monitoring of terrestrial

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deformations, such as IBIS-L [4], In-GB-SAR [5] and MMW-GB-SAR [6]. A comparison of their features and construction is given in **Table 1**.

Table 1
Analysis of the architectures of GB-SARs.

GB-SAR system	Axis length [m]	Centre freq. [GHz]	Antenna type	No. of antennas	Azimuth resol. [m]	Range resol. [m]	Bandwidth [Hz]	Distance [m]
LISA	5	5.83	Horn	2	6	2.5	60 M	1000–2900
IBIS-L	2	17.2	Horn	2	4.4	0.75	200 M	4000
In-GB-SAR	NA	2–8.4	Horn	1	3.5	5	100 M	5
MMW-GB-SAR	1	32–36	Horn	2	3.75	3	26.5–40 G	3

MELISSA makes use of the Multiple Input Multiple Output (MIMO) technique to transmit and receive waveforms, using a linear antenna array of 12 pyramidal horn antennas in the transmitting module and another 12 Vivaldi antennas in the receiving module. There is huge scope for improvement in the structure of the transmitter and receiver antenna arrays in the MELISSA system [3]. A 2×6 planar antenna array of pyramidal horns was proven in our earlier work to have a higher half power beam width (HPBW), better directivity and lower peak sidelobe ratio (PSLR) than the linear antenna array configuration of the MELISSA transmitter [7]. The next step in the enhancement of the transmitter module of MELISSA is to choose the best type of horn antenna for higher coverage. A comparative analysis has been carried out of the performance of 18 individual horn antenna elements in a 2×6 planar antenna array configuration [8]; these horn antennas were compared based on the performance metrics of HPBW and gain, and it was observed that all of the horns surveyed provided a higher HPBW than conventional pyramidal horns in the 2×6 planar antenna array configuration [8]. In addition to higher HPBW and significant gain, low mutual coupling and high isolation are critical factors in the performance of any MIMO system. A detailed analysis of the existing isolation schemes used in MIMO systems is presented below.

Interaction between the antennas in a MIMO antenna array leads to undesirable effects in the radiation pattern of any designed system. The nullification of mutual coupling leads to an increase in isolation and hence the information-carrying capacity of the MIMO system.

The parameter of mutual coupling was explored in [9], in which the authors connected a lossless network between two monopole antennas with orthogonal power and demonstrated a reduction in the mutual coupling. In [10], the authors investigated the creation of a multiport decoupling network in which the mutual coupling between the modes of radiation of the antennas in the array was cancelled. These results were validated using quarter-wave dipoles with 0.1λ spacing. Simultaneous integral equations were explored in [11] to perform an analysis of the mutual coupling between two dipole antennas involving exact kernels with finite gap feeds. Using their proposed method, the authors of [11] demonstrated the strong correlation between the distance of the antennas and the amount of mutual coupling.

A method of improving the isolation of closely packed patch antennas was investigated in [12], using a decoupling metamaterial configuration. The authors observed higher isolation between the transmitting and receiving antennas when using their novel isolation technique. In [13], the authors were able to achieve a suppression of more than 10 dB using a 2D metasurface wall with microstrip patch antennas. A reduction in the isolation of an airborne SAR system was explored in [14] using a simplified composite right-/left-handed transmission line (SCRLH-TL). The antenna array designed in [14] is used for wideband applications in the UHF, L, C and S bands, and also finds applications in UAVs. The use of a monofilar Archimedean spiral and rectangular slots was proposed in [15] for scanning applications in passive radar systems. The proposed design can scan a wide angle from −25° to +45°, and has applications in FM radio, GPS and other fields involving wideband usage. A reduction in the mutual coupling of a planar array of tightly packed patch antennas using a metamaterial substrate was presented in [16], and a coupling suppression of around 5 dB was achieved using the novel technique proposed by the authors. Increased isolation was achieved in [17] using mutually coupled U-shaped transmission lines for a 2×3 planar antenna array. This antenna finds application in SAR operations working in the X and Ku bands. A full duplex application is investigated in the design proposed in [18], in which the authors used a metamaterial EB gap to achieve isolation of greater than 30 dB for an antenna array of three microstrip patches.

This article presents a study and exploration of two specific horn antennas, the pin-fed circular waveguide antenna (popularly known as the cantenna) and the coaxial cavity horn antenna, in terms of their suitability to replace the pyramidal horn antenna in the conventional linear array in the transmitter module of the MELISSA system. The novelty of our work can be summarised as follows:

– The existing transmitting linear antenna array of pyramidal horns results in a low HPBW (29.80° at $\theta = 90°$ and 41.81° at $\varphi = 0°$) which leads to lower area coverage for monitoring.
– Our proposed 2×6 cantenna and 2×6 coaxial cavity horn antenna arrays give comparable gain to that of MELISSA (around 10 dBi) and higher HPBW (38.25° at $\theta = 90°$ and 106.4° at $\varphi = 0°$ for the cantenna array and 41° at $\theta = 90°$ and 140.4° at $\varphi = 0°$ for the coaxial cavity horn antenna array).
– The application of Dolph Chebyshev beamforming to our proposed transmitting antenna system results in no sidelobes and complete concentration of the transmitted radiation onto the imaging of the terrestrial deformation.

Section 2 of this article throws some light on the currently available MELISSA system and our earlier work on providing an alternate antenna array geometry for the transmitter module of MELISSA. Section 3 describes the design of a 2×6 planar array using cantennas as the individual elements, while Section 4 describes the design of an array using coaxial cavity horns. Section 5 gives a mathematical proof and explanation for the improvement in the HPBW of the radiation patterns of the 2×6 antenna arrays obtained in Sections 3 and 4. Section 6 concludes the article.

2 Related Work: Replacement of the Transmitter Module of the MELISSA System

MELISSA [1, 3] is designed to make use of the MIMO technique, in which 12 pyramidal horn antennas placed in a linear antenna array geometry transmit mutually orthogonal waveforms. Twelve Vivaldi antennas are placed in a linear configuration to serve as the receiving module. The radiation pattern was simulated for 12 pyramidal horn antennas using a linear antenna array geometry, and the HPBW and the total gain are illustrated in Fig.1. Fig. 2 shows the MELISSA system, with the transmitting and receiving antennas placed next to each other.

In our previous work, an exhaustive study was carried out using Matlab simulations of an alternate antenna array geometry to replace the existing linear array of 12 horn antennas in MELISSA's transmitter module. The results revealed the feasibility of a 2×6 planar antenna array geometry (with 12 horn antennas), with a maximum value of HPBW of 113.5° [7]. This value of HPBW is comparable to that of the existing LISA system [2], demonstrating that a 2×6 planar horn antenna array configuration used in MELISSA's transmitter module can provide an area coverage in the range and azimuth directions equivalent to that of LISA. Further calculations were carried out to determine the PSLR for each of the alternate, linear and planar array configurations under study, and it was found that the 2×6 configuration yielded the lowest PSLR value of −12 dB [7]. This is a core requirement for efficient image processing in radar systems. It was therefore concluded that the linear antenna array of 12 pyramidal horn antennas could be replaced by a 2×6 planar antenna geometry of pyramidal horn antennas, as illustrated in Fig. 3.

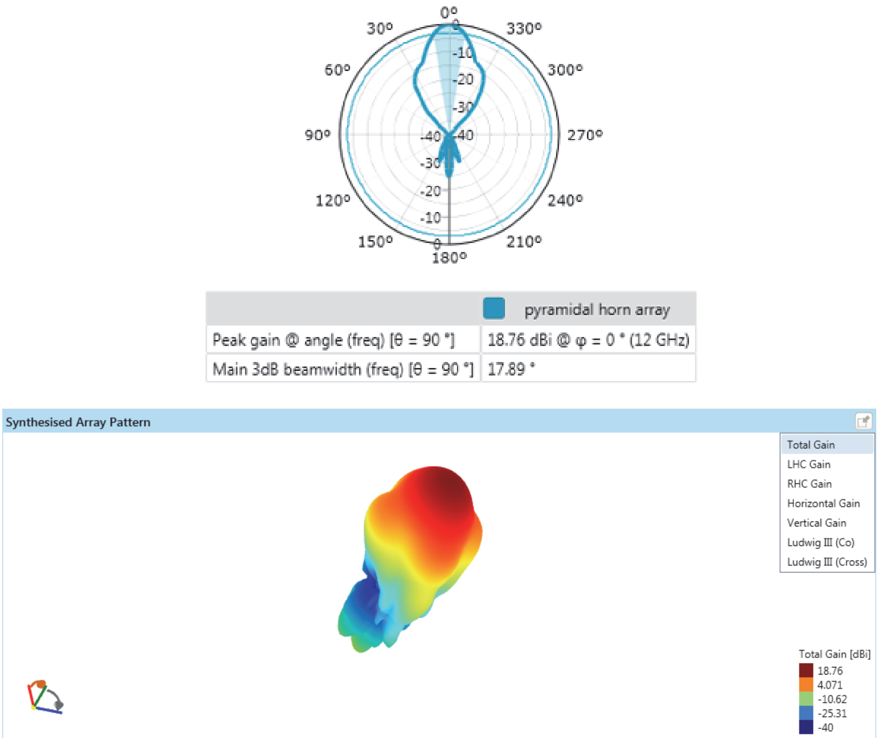


Fig. 1 – *Peak gain and HPBW of 12 linear pyramidal horn antennas in the existing MELISSA [3] system: (a) 2D plot; (b) 3D plot.*

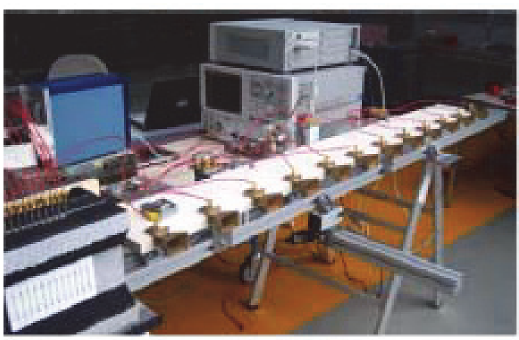


Fig. 2 – *The MELISSA system (adapted from [3]).*

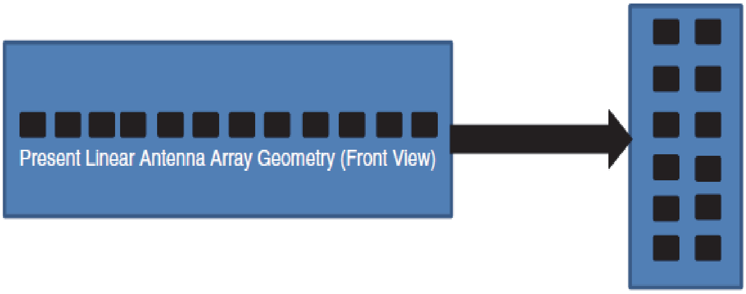


Fig. 3 – *Alternate antenna array architecture for the transmitting module of MELISSA (adapted from [4]).*

3 Design and Testing of a Cantenna for the Transmitter Module of the MELISSA System

The pin-fed circular waveguide antenna, popularly known as the cantenna, is a simple microwave antenna. It is mainly used in applications demanding a low cost, robust antenna in a stand-alone capacity or as a parabolic reflector feed. Its application in a transmitter-receiver pair in a laptop-based radar system was explored using an experimental setup at the MIT Lincoln Laboratory, sponsored by the Air Force under Contract #FA8721-05-C-0002 [19]. This radar system was presented at the MIT Independent Activities Period (IAP) in 2011, and was designed to perform experiments on Doppler frequency shifts, involving a ranging study and a synthetic aperture radar (SAR).

The pin feed of the cantenna causes it to have only linear polarisation. It is the simplest member of the conical horn antenna class, as it represents a conical horn without a flare. A feed pin excites the TE11 waveguide mode causing a coaxial-to-waveguide transition.

Fig. 4 illustrates the cantenna as designed using the Antenna Magus tool Version 4.2.1. Antenna Magus is an antenna analysis and design tool with a database of over 250 antenna topologies that can be explored to give an optimal topology design. It also supports the synthesis of antennas of various sizes and shapes. The dimensions of the cantenna can be calculated using the following equations, based upon the operating wavelength (λ) of the wave:

$$L_g \geq \frac{3}{4}\lambda, \tag{1}$$

$$D_g \geq \frac{1}{2}\lambda, \tag{2}$$

$$L_p \geq \frac{1}{4}\lambda , \tag{3}$$

$$S \approx \frac{1}{4}\lambda , \tag{4}$$

where L_g is the length of the cantenna, D_g is the diameter of the cantenna, L_p is the length of the pin feed and S is the spacing of the pin feed from the base.

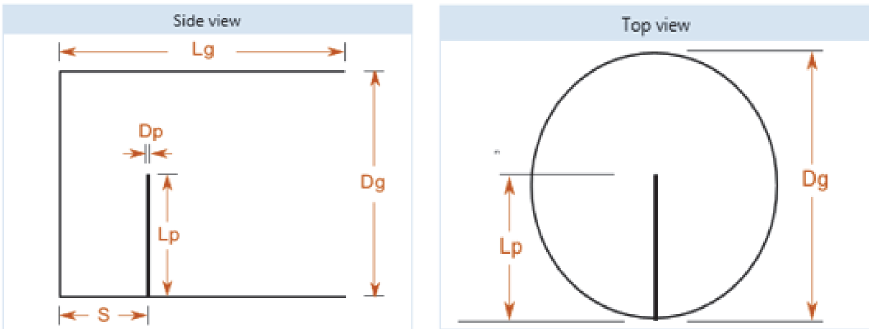


Fig. 4 – *The cantenna: (a) side view; (b) top view (adapted from [21]).*

Since the MELISSA system works at 12 GHz in the X band frequency range, a 2×6 planar array using cantennas was also designed for the same frequency using Antenna Magus Version 4.2.1. This design yielded the following values for the individual cantenna elements:

$L_g = 37.60\,[\text{mm}]$, $D_g = 16.89\,[\text{mm}]$, $L_p = 6.121\,[\text{mm}]$ and $S = 11.87\,[\text{mm}]$.

The radiation pattern of the 2×6 planar array using cantennas is shown in Fig. 5. This shows a HPBW of 26.21° at $\theta = 90°$ and 106.4° at $\varphi = 0°$.

From Fig. 5b, it is evident that 12 cantennas placed in a 2×6 planar configuration provide an HPBW greater than 100°, which is a key requirement for maximum area coverage in applications such as landslide monitoring [4]. The above results show that the 2×6 planar antenna array configuration consisting of individual cantenna elements can be used to replace the existing transmitter module of the MELISSA system for landslide monitoring applications. Fig. 6 illustrates the peak gain and efficiency graph for this 2×6 cantenna array.

The next section of this article describes the design of yet another 2×6 planar antenna array using the individual elements of coaxial cavity horn antennas and their related results.

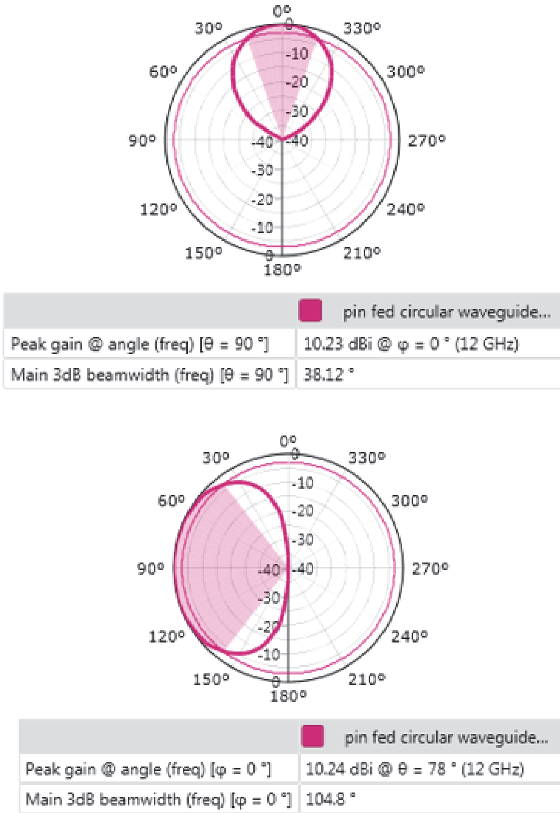


Fig. 5 – *Radiation pattern of a cantenna: (a) XY cut; (b) XZ-cut.*

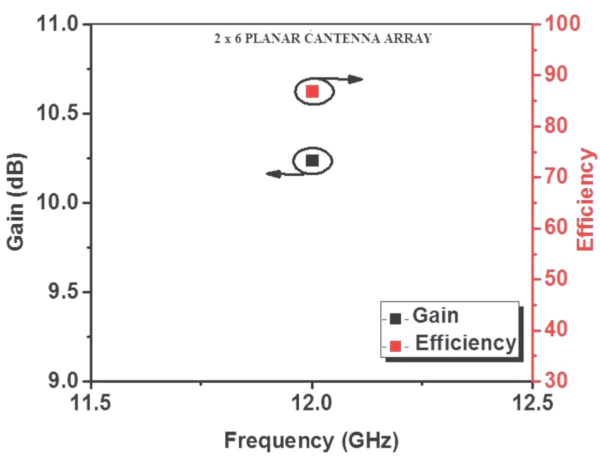


Fig. 6 – *Peak gain and efficiency of a 2×6 cantenna array.*

4 Design and Testing of a Coaxial Cavity Horn Antenna for the Transmitting Module of the MELISSA System

The coaxial cavity horn antenna was designed in [20] to provide optimum output for high aperture efficiency and low cross-polarisation. Fig. 7 presents front and side views of the coaxial cavity horn antenna, designed using the Antenna Magus 4.2.1 tool.

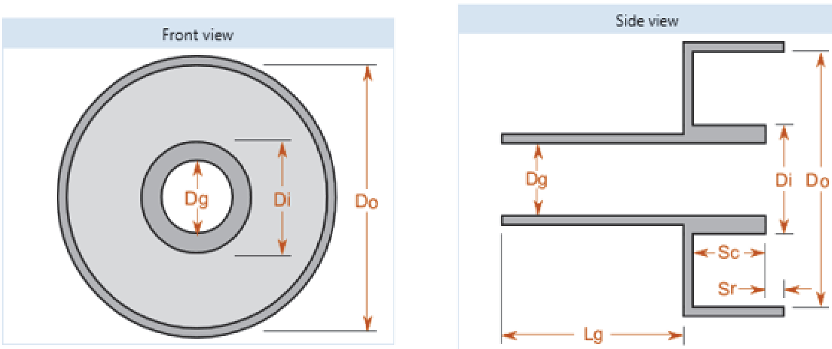


Fig. 7 – Coaxial *cavity horn antenna: (a) front view; (b) side view (adapted from [21]).*

The dimensions of the coaxial cavity horn antenna can be calculated using the following equations based upon the operating wavelength (λ) at an operating frequency of 12 GHz, as in the previous case.

$$D_0 = 1.906\lambda\,, \tag{5}$$

$$D_i \cong 0.8\lambda\,, \tag{6}$$

$$D_g = 0.7\lambda\,, \tag{7}$$

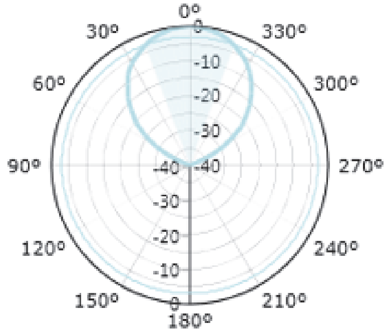
$$S_c = 0.57\lambda\,, \tag{8}$$

$$S_r = 0.1\lambda\,, \tag{9}$$

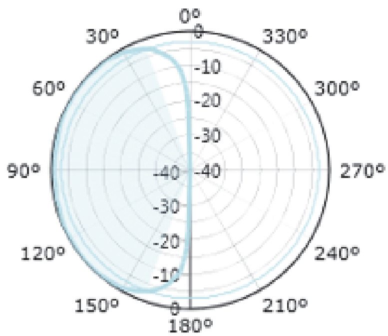
$$L_g = 0.9\lambda\,, \tag{10}$$

where: D_0 is the diameter of the outer cavity; D_g is the diameter of the inner wall of the inner cavity; D_i is the diameter of the outer wall of the inner cavity and (L_g+S_c+S_r) is the total length of the coaxial cavity horn antenna.

The same approach was followed for the design of the coaxial cavity horn antenna as for the cantenna described in the previous section. Using Antenna Magus software Version 4.2.1, the coaxial cavity horn was simulated at 12 GHz, and the values of the various parameters were obtained as follows. The radiation pattern of the 2×6 planar array using coaxial cavity horn antennas is shown in Fig. 8. This gives a HPBW of 26.98° at $\theta = 90°$ and 140.4° at $\varphi = 0°$.



	coaxial cavity horn array
Peak gain @ angle (freq) [θ = 90 °]	8.084 dBi @ φ = 0 ° (12 GHz)
Main 3dB beamwidth (freq) [θ = 90 °]	41.00 °



	coaxial cavity horn array
Peak gain @ angle (freq) [φ = 0 °]	9.056 dBi @ θ = 131 ° (12 GHz)
Main 3dB beamwidth (freq) [φ = 0 °]	140.4 °

Fig. 8 – *Radiation pattern of 2×6 planar coaxial cavity horn array: (a) XY plane cut; (b) XZ plane cut.*

Fig. 9 illustrates the peak gain efficiency graph in the proposed 2×6 coaxial cavity horn antenna array.

$$D_o = 51.11\,[\text{mm}],\ D_i \cong 20.99\,[\text{mm}],\ D_g = 17.49\,[\text{mm}],$$

$$S_c = 11.74\,[\text{mm}],\ S_r = 2.498\,[\text{mm}] \text{ and } L_g = 24.98\,[\text{mm}].$$

From the simulation results, it can be inferred that a 2×6 planar array using coaxial cavity horn antennas as single elements provides a higher HPBW than a 2×6 planar array of cantennas.

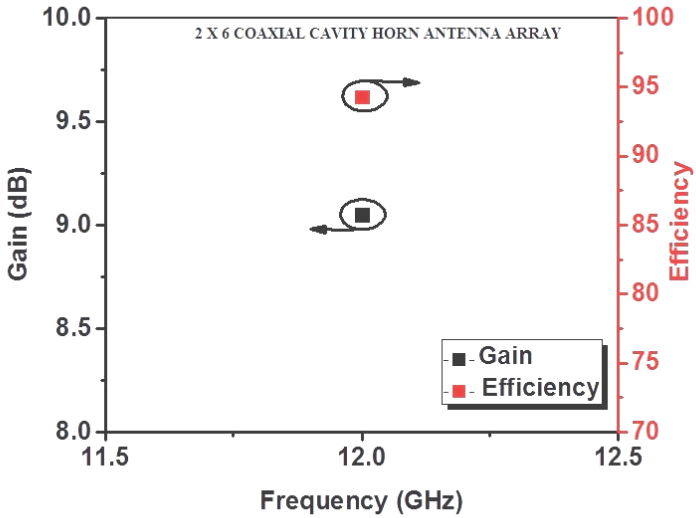


Fig. 9 – *Peak gain and efficiency of 2×6 coaxial cavity horn antenna array.*

5 Enhancement of the Radiation Pattern of MELISSA's Transmitter Module

This section describes the Dolph Chebyshev beamforming technique, which allocates weights to each of the individual antenna elements in the 2×6 planar array and thereby causes a complete reduction in the sidelobe level, increasing the HPBW of the main lobe in the $\theta = 90°$ direction.

The array factor (AF) for a 2×6 planar array which is steered in the broadside direction (i.e. for which the (θ, φ) angles are (0, 0)), would have all weights equal to unity. Here, θ is the display angle of the radiation pattern, measured from the z-axis in the clockwise direction, and φ represents the display angle of the radiation pattern from the *x*-axis in the anti-clockwise direction. Thus, the AF for a 2×6 planar array can be specified as follows:

$$AF = \sum_{b=0}^{1}\sum_{a=0}^{5} \mathrm{e}^{-\mathrm{j}\pi\sin\theta(a\cos\phi + b\sin\phi)} . \tag{11}$$

In (11), *a* is a variable that takes values from 0 to 5, reflecting the design of the six vertical elements, and *b* is another variable that takes the values of 0 or 1, representing the two horizontal elements of the 2×6 planar antenna array.

Figs. 10 and 11 clearly show the disappearance of the sidelobes in both radiation patterns and the increase in the HPBW due to this disappearance. Thus the Dolph Chebyshev beamforming technique reduces the sidelobe level to zero for the 2×6 planar arrays of both cantennas and coaxial cavity horns.

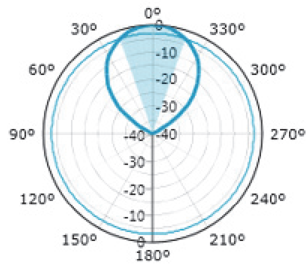


Fig. 10 – *The 2×6 cantenna array:*
(a) before Dolph Chebyshev beamforming;
(b) after Dolph Chebyshev beamforming.

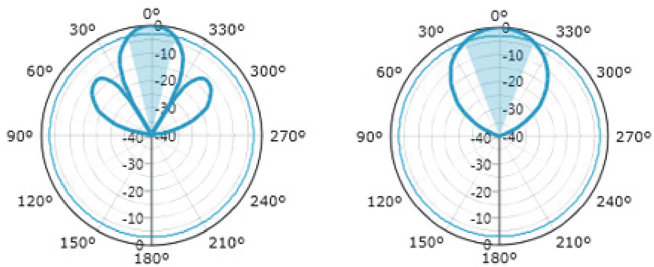


Fig. 11 – *The 2×6 coaxial cavity horn antenna array:*
(a) before Dolph Chebyshev beamforming;
(b) after Dolph Chebyshev beamforming.

Table 2
Comparison of the gain and 3dB beamwidth of the existing MELISSA system and the proposed antenna arrays.

	Linear 12 element pyramidal horn array (existing MELISSA transmitter module)	Proposed 2×6 planar cantenna array	Proposed 2×6 planar coaxial cavity horn antenna array
Gain	18.76	10.24	9.056
Without the Dolph Chebyshev beamforming technique			
3dB BW at θ = 90°	NA	26.21°	26.98°
3 dB BW at φ = 0°	17.89°	104.8°	140.4°
With the Dolph Chebyshev beamforming technique			
3dB BW at θ = 90°	NA	38.32°	41.00°
3 dB BW at φ = 0°	17.89°	104.8°	140.4°

As can be seen from **Table 2** above, the 2×6 coaxial cavity horn antenna array provides the best potential replacement for the existing transmitter module in the MELISSA GB-SAR system, as it provides a wider area of coverage due to its geometrical design, type of antenna element and beamforming technique, all of which have been described and mathematically proven in this article.

7 Conclusion

This article presents simulation and research results for a 2×6 planar antenna array composed of cantennas and another 2×6 array of coaxial cavity horn antennas, which offer feasible options for replacing the linear pyramidal horn antenna array of the transmitting section of MELISSA. The Dolph Chebyshev beamforming technique for the further reduction of sidelobe levels is explained in detail, and the mathematical results obtained show a further increase in the 3 dB beam width in the $\theta = 90°$ direction.

Our proposed designs can give greater area coverage in comparison with the existing MELISSA transmitter design, and hence can provide monitoring of terrestrial deformation over a larger area.

8 References

[1] J. Broussolle, V. Kyovtorov, M. Basso, G. F. Di Silvi E Castiglione, J. Figueiredo Morgado, R. Giuliani, F. Oliveri, P. F. Sammartino, D. Tarchi: MELISSA, A New Class of Ground Based InSAR System. An Example of Application in Support to the Costa Concordia Emergency, ISPRS Journal of Photogrammetry and Remote Sensing, Vol. 91, May 2014, pp. 50 – 58.

[2] D. Tarchi, N. Casagli, R. Fanti, D. D. Leva, G. Luzi, A. Pasuto, M. Pieraccini, S. Silvano: Landslide Monitoring by Using Ground-Based SAR Interferometry: An Example of Application to the Tessina Landslide in Italy, Engineering Geology, Vol. 68, No. 1-2, February 2003, pp. 15 – 30.

[3] D. Tarchi, F. Oliveri, P. F. Sammartino: MIMO Radar and Ground-Based SAR Imaging Systems: Equivalent Approaches for Remote Sensing, IEEE Transactions on Geosciences and Remote Sensing, Vol. 51, No. 1, January 2013, pp. 425 – 435.

[4] M. Crosetto: Ground-Based Synthetic Aperture Radar Deformation Monitoring: Introduction, GeoMonitoring 2011, Clausthal-Zellerfeld, Germany, 3 – 4. March 2011.

[5] M. Sato, Z.- S. Zhou, T. Hamasaki, W.- M. Boerner: Development of a Ground-Based Synthetic Aperture Radar (GB-SAR) System and its Applications to Environment Monitoring and Disaster Prevention, Proceedings of the 2nd International Workshop POLINSAR 2005, Frascati, Italy, January 2005, pp. 20.1 – 20.6.

[6] E. Yigit, S. Demirci, A. Unal, C. Ozdemir, A. Vertiy: Millimeter-Wave Ground-Based Synthetic Aperture Radar Imaging for Foreign Object Debris Detection: Experimental Studies at Short Ranges, Journal of Infrared, Millimeter, and Terahertz Waves, Vol. 33, No. 12, December 2012, pp. 1227 – 1238.

[7] S. Vincent, S. A. J. Francis, E. B. Rajsingh: An Alternate Antenna Array Geometry for a GB-SAR System Used in Landslide Monitoring, Journal of the Indian Society of Remote Sensing, Vol. 43, No. 4, December 2015, pp. 761 – 768.

[8] S. Vincent, S. A. J. Francis, O. P. Kumar, E. B. Rajsingh: A Comparative Study of Horn Antennas Suitable for the Transmitting Antenna Array Module of MELISSA Architecture, Proceedings of the IEEE Distributed Computing, VLSI, Electrical Circuits and Robotics (DISCOVER), Mangalore, India, August 2016, pp. 28 – 34.

[9] J. B. Andersen, H. H. Rasmussen: Decoupling and Descattering Networks for Antennas, IEEE Transactions on Antennas and Propagation, Vol. 24, No. 6, November 1976, pp. 841 – 846.

[10] T.- I. Lee, Y. E. Wang: Mode-Based Beamforming with Closely Spaced Antennas, Proceedings of the IEEE/MTT-S International Microwave Symposium, Honolulu, USA, June 2007, pp. 1723 – 1726.

[11] T. Katagi, H. Ohmine, H. Miyashita, K. Nishimoto: Analysis of Mutual Coupling Between Dipole Antennas Using Simultaneous Integral Equations with Exact Kernels and Finite Gap Feeds, IEEE Transactions on Antennas and Propagation, Vol. 64, No. 5, May 2016, pp. 1979 – 1984.

[12] M. Alibakshikenari, B. S. Virdee, C. H. See, R. Abd-Alhameed, A. Hussein Ali, F. Falcone, E. Limiti: Study on Isolation Improvement Between Closely-Packed Patch Antenna Arrays Based on Fractal Metamaterial Electromagnetic Bandgap Structures, IET Microwaves, Antennas & Propagation, Vol. 12, No. 14, November 2018, pp. 2241 – 2247.

[13] M. Alibakshikenari, B. S. Virdee, P. Shukla, C. H. See, R. Abd-Alhameed, F. Falcone, E. Limiti: Meta-Surface Wall Suppression of Mutual Coupling Between Microstrip Patch Antenna Arrays for THz-Band Applications, Progress In Electromagnetics Research Letters, Vol. 75, May 2018, pp. 105 – 111.

[14] M. Alibakshikenari, B. S. Virdee, E. Limiti: Wideband Planar Array Antenna Based on SCRLH-TL for Airborne Synthetic Aperture Radar Application, Journal of Electromagnetic Waves and Applications, Vol. 32, No. 12, June 2018, pp. 1586 – 1599.

[15] M. Alibakshikenari, B. S. Virdee, A. Ali, E. Limiti: A Novel Monofilar-Archimedean Metamaterial Inspired Leaky-Wave Antenna for Scanning Application for Passive Radar Systems, Microwave Optical Technology Letters, Vol. 60, No. 8, August 2018, pp. 2055 – 2060.

[16] M. Alibakshikenari, A. Salvucci, G. Polli, B. S. Virdee, C. H. See, R. Abd-Alhameed, F. Falcone, A. Andujar, J. Anguera, E. Limiti: Mutual Coupling Reduction Using Metamaterial Supersubstrate for High Performance and Densely Packed Planar Phased Arrays, Proceedings of the 22nd International Microwave and Radar Conference (MIKON 2018), Poznań, Poland, May 2018, pp. 675 – 678.

[17] M. Alibakshikenari, B. S. Virdee, C. H. See, R. Abd-Alhameed, F. Falcone, E. Limiti: Array Antenna for Synthetic Aperture Radar Operating in X and Ku-Bands: A Study to Enhance Isolation Between Radiation Elements, Proceedings of the 12th European Conference on Synthetic Aperture Radar (EUSAR 2018), Aachen, Germany, June 2018, pp. 1083 – 1087.

[18] M. Alibakshikenari, M. Vittori, S. Colangeli, B. S. Virdee, A. Andujar, J. Anguera, E. Limiti: EM Isolation Enhancement Based on Metamaterial Concept in Antenna Array System to Support Full-Duplex Application, Proceedings of the IEEE Asia Pacific Microwave Conference (APMC2017), Kuala Lumpur, Malaysia, November 2017, pp. 740 – 742.

[19] G. L. Charvat: MIT IAP 2011 Laptop Based Radar: Block Diagram, Schematics, Bill of Material, and Fabrication Instructions, Presented at the 2011 MIT Independent Activities Period (IAP), MIT Lincoln Laboratory, January 2011.

[20] A. A. Kishk: Optimum Coaxial Cavity Horn for High Aperture Efficiency and Low Cross-Polarization, Proceedings of the IEEE AP-S, International Symposium, Antennas and Propagation, Syracuse, USA, June 1988, pp. 1278 – 1281.

[21] Antenna Magus- Explore. Design. Deliver., Available on: http://www.antennamagus.com/index.php