Model of a Monopulse Radar Tracking System for Student Laboratory

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Abstract. *Development, construction and testing of a student laboratory model of the radar system that can be used for monopulse tracking is described. The laboratory model is simple and can be assembled from the existing equipment while the missing parts can be manufactured in a basically equipped RF electronics workshop. The laboratory model is used for student laboratory exercises as a part of a basic course on radar systems. The system is based on a Σ-Δ hybrid for processing signals obtained from two antennas. The composition of the model is described. Student exercises and measurements on the model are proposed. Alternative instruments which can be used in the model are considered. Possible improvements of the model are discussed.*

Keywords

Education, radar, monopulse radar, tracking.

1. Introduction

Modern radar systems, used in many areas from civil air traffic control to various military applications, use monopulse techniques [1], [2]. Improved angle sensing, resolution and angular accuracy offered by monopulse radars are their main advantage over classic radar systems.

Monopulse radar systems are complex, high-cost equipment that can rarely be seen by engineering students. However, basic monopulse techniques are relatively simple and can be made more comprehensible to students through laboratory exercises. The described laboratory model of a radar system that can be used for monopulse angle measurement and tracking is used in student laboratory exercises as a part of a basic course on radar systems at the Faculty of Electrical Engineering and Computing in Zagreb. Its purpose is to demonstrate the basic principles of how the RF part of the radar system is operating and how the angle measurement accuracy can be improved by using techniques employed in monopulse radar systems.

2. Monopulse Radar

The monopulse radar system is mainly used for target angle measurement and tracking. The information on the target angular position is determined by comparison of signals received in two or more simultaneous beams. The term "monopulse" comes from the ability of this system to extract the angular position from only one pulse. However, in practice the angular position of the target is obtained from multiple pulses in order to improve target detection probability and further improve angle measurement accuracy.

The main advantage of a monopulse system in comparison to standard angle measurement methods is that it is not affected by amplitude fluctuations of the target echo because the angle information is acquired by comparing signals received by several simultaneous beams and produced by a single echo pulse. If the echo amplitude changes, it changes in the same way in all receiver channels.

There are three main monopulse techniques for angle-sensing. These techniques are: amplitude-comparison, phase-comparison and the combination of the amplitude and phase comparison [1], [2]. The applied monopulse technique determines the nature of information in the received signal prior to any processing. This means that the choice of a certain monopulse technique will determine the construction of the radar antenna system.

Angle measurement in a monopulse radar system is performed by an angle discriminator. If the angle discriminator is non-coherent and the angle-sensing response is produced only by amplitude relations, it is called amplitude discriminator. Angle discriminators responding only to phase relations are called phase angle discriminators, while angle discriminators responding to both amplitude and phase relations are called sum-and-difference angle discriminators. The type of angle discriminator determines the nature of the processing used to extract the angle information from the received signals.

Any kind of angle-sensing can be combined with any type of angle discriminator [2]. In this paper, a model of an amplitude-comparison monopulse system with sum-and-difference angle discriminator is described.

The amplitude-comparison monopulse system should have two equal antennas with overlapping patterns and their main beam directions squinted at certain angle θ_s (Fig. 1).

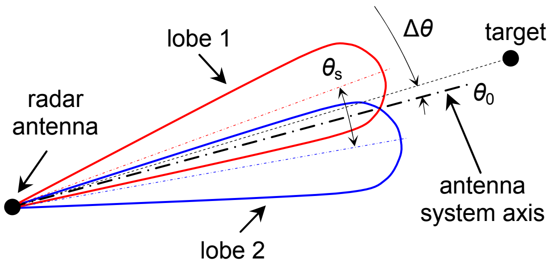

Fig. 1. Partial antenna patterns for amplitude sum-and-difference monopulse system.

Two resulting patterns (sum and difference) are obtained by adding and subtracting the signals from the two antennas. Only the sum pattern is used in transmission, while both patterns are used in reception. Therefore, the radar transmitter is connected in the sum channel with a T/R switch (Fig. 2). The same T/R switch (marked as circulator in Fig. 2) is usually placed also in the difference channel in order to maintain the same phase relationship in both receiver channels (Fig. 2).

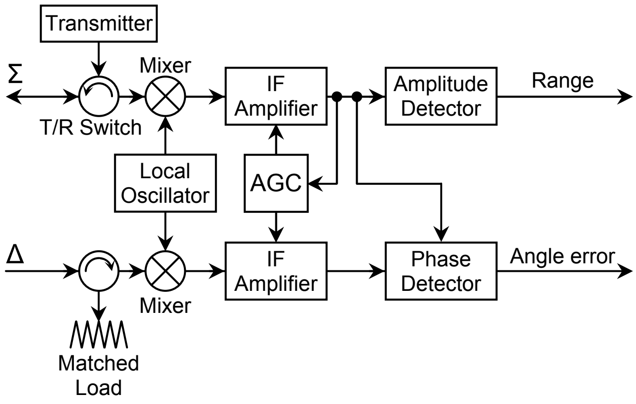

Fig. 2. Block diagram of the monopulse radar system.

The received sum signal is used for target detection, range measurement, and as phase reference for determining the sign of angle error measurement. The magnitude of the angle error $\Delta\theta$ is determined from the difference signal. The angle error is measured in reference to the antenna system axis θ_0 (Fig. 1). The described antenna system of two antennas (Fig. 1) must exist for every angular coordinate which the radar system is measuring (e.g. for simultaneous measurement in azimuth and elevation the system should have two pairs of antennas). In that case also another similar receiver chain for the difference (Δ) signal producing the angle error for the other angle coordinate should be added to the block diagram in Fig. 2.

3. Laboratory Model

The purpose of the laboratory model is to clearly demonstrate the advantage of a monopulse tracking system to engineering students attending the basic radar course. The laboratory model had to be composed of the existing laboratory equipment with minimal additional costs and investments. Therefore, the frequency band around 2 GHz was selected for operation. Of course, any other frequency, depending on the availability of the needed equipment, can be used.

3.1 Antenna System

The emphasis is given to a model of the antenna system generating simultaneous sum and difference radiation patterns. Any type of antenna or antenna array can be used. It is only important that the two antennas are identical, i.e. that they have equal radiation patterns which are then positioned symmetrically with respect to the antenna system axis (Fig. 1). The antennas must also have reasonably high gain (~ 10 dB) because this affects the overall system performance. The effect of improving angle measurement accuracy, which we wish to demonstrate, will be more pronounced if the gain of the single antenna is higher [2].

The antenna system used in our laboratory model consists of two identical horn antennas. Each antenna has 12.9 dB gain at the specified operating frequency. The antenna phase centers are spaced 1.43 λ_0 apart, where λ_0 is the free space wavelength of the signal. The squint angle is ~4°.

The signals at the antenna outputs are coherently added and subtracted by using a π-hybrid. When the π-hybrid is used for adding and subtracting two signals it is often called Σ-Δ hybrid.

3.2 Design of the π-Hybrid

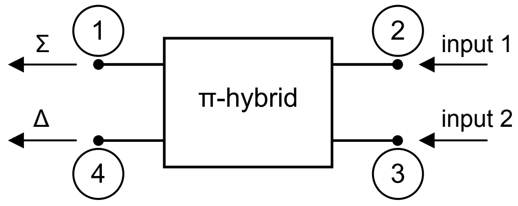

Fig. 3. Symbol of the π-hybrid.

The π-hybrid is the main component for simultaneously obtaining two radiation patters. Its symbol, with port numbering, is shown in Fig. 3. Following the convention of port numbering in Fig. 3, the π-hybrid is described by its scattering matrix [3], [4]:

$$[S]=\frac{1}{\sqrt{2}}\begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & -1 \\ 1 & 0 & 0 & 1 \\ 0 & -1 & 1 & 0 \end{bmatrix} . \qquad (1)$$

This matrix can be obtained by various technical realizations like magic-T or ring hybrid [1], [3], [4].

As this part was missing for completion of our system, to reduce the overall cost and complexity, it was decided to manufacture the π-hybrid in the form of ring hybrid in microstrip technology. The π-hybrid was designed by using the ADS electromagnetic simulator package from Agilent [5]. It was manufactured on Taconic PTFE substrate with thickness of 1.576 mm, relative dielectric constant of 2.55 and loss tangent of 0.0018. The manufactured π-hybrid is shown in Fig. 4. Calculated and measured results are compared in Figs 5 – 8.

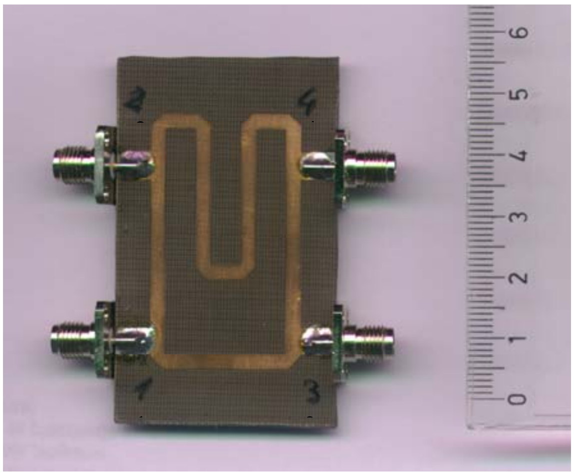

Fig. 4. π-hybrid realized in microstrip technology as ring hybrid.

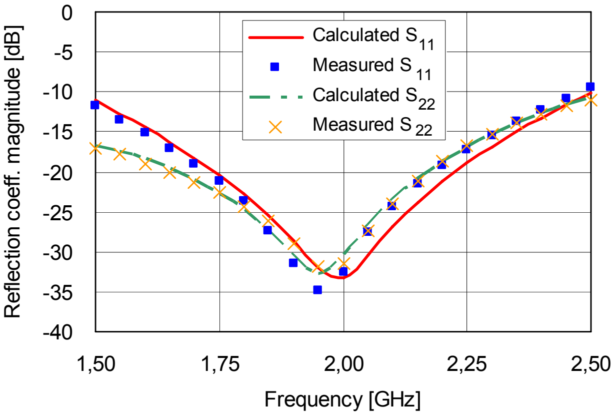

Fig. 5. Calculated and measured S_{11} and S_{22} of the π-hybrid.

Satisfactory impedance matching at all ports of the π-hybrid was obtained at the design frequency of 2 GHz. In Fig. 5 only the results for ports 1 and 2 are shown. Due to the circuit geometrical symmetry (Fig. 4), the results for the ports 3 and 4 are practically the same. Also the isolation between the sum (port 1) and difference (port 4) ports is very good (Fig. 6).

As the signals from the two antennas have to be added and subtracted, the transmission coefficients between the two inputs (ports 2 and 3) and the Σ and Δ outputs (ports 1 and 4) have to be considered. At the center frequency of 2 GHz the measured phase difference between the two channels at the sum output port is 1.3° (desired value 0°), while on the difference port the phase difference is 176.0° (desired value 180°).

At the same frequency the measured amplitude differences between the two signals are less than 0.5 dB for transmission from any input to any output port (Figs 7 and 8). Therefore, satisfactory operation can be expected.

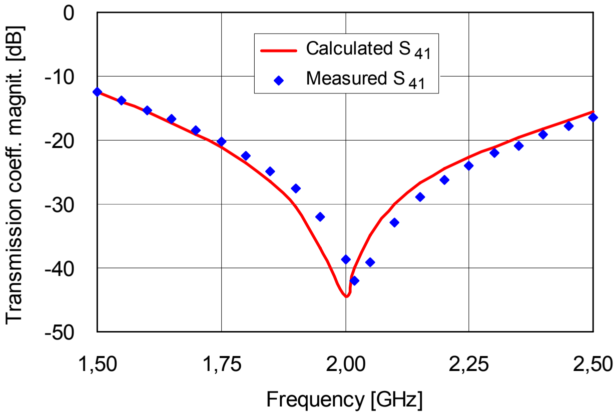

Fig. 6. Calculated and measured S_{41} of the π-hybrid.

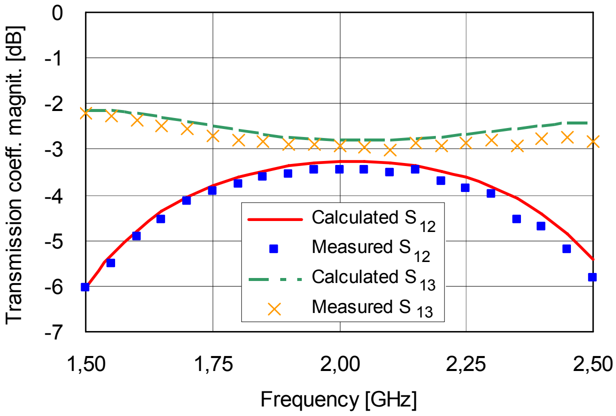

Fig. 7. Calculated and measured S_{12} and S_{13} of the π-hybrid.

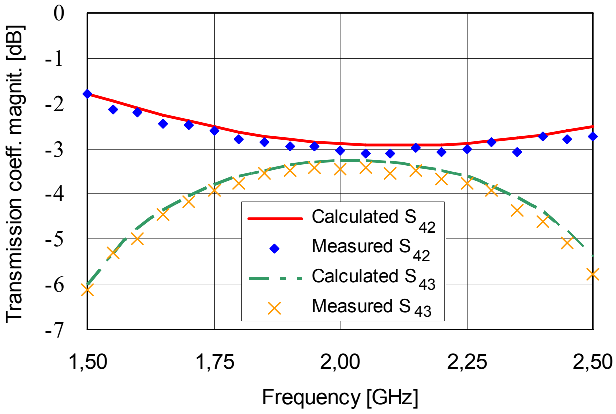

Fig. 8. Calculated and measured S_{42} and S_{43} of the π-hybrid.

Finally, the antenna system consisting of two horns and the π-hybrid is assembled (Fig. 9).

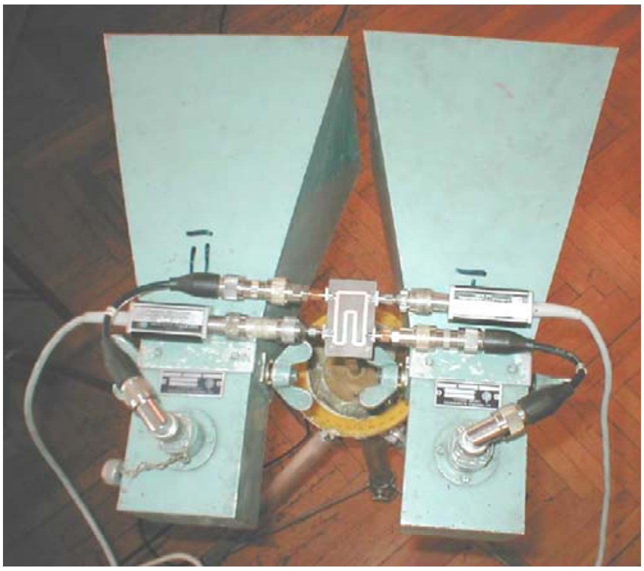

Fig. 9. Two horn antennas with Σ-Δ hybrid.

3.3 Laboratory Model Operation

The main objective of the student laboratory model of the monopulse radar system is to demonstrate how the angular tracking accuracy can be improved with the described antenna system (Fig. 9). All measurements and processing performed by the system shown in Fig. 2 are not necessary for this purpose. Therefore, the range measurement part was omitted. The angle error information is contained in the ratio of the difference and sum signals [2]. Even if only the magnitude of this ratio is measured, significant improvement in angular tracking accuracy can be observed. Such simplified implementation can be realized with two amplitude detectors, instead of the phase detector. In our laboratory model we have used an existing scalar network analyzer, because it allows to measure absolute detected signal values as well as their ratios. The scalar network analyzer is the HP 8755A Swept Amplitude Analyzer. It can measure the R, A and B channels and the ratios A/R and B/R on linear and logarithmic display.

Although the antenna system in a real monopulse radar would be used for transmitting and receiving, in our model it was used only for receiving. The target echo was replaced by a signal generator and a transmitting antenna on the far side of the lab.

To realize a model closer to the real monopulse radar (i.e. a model which would use the antenna for both transmitting and receiving) a circulator with high isolation, acting as T/R switch, should be placed in the sum port branch of the Σ-Δ hybrid to isolate the sum receiver channel from the transmitted signal (in the same way as in Fig. 2). The same circulator should then be added in the difference port branch to maintain equal phase shift and attenuation in both channels as shown in Fig. 2. In addition a target with high RCS (e.g. a corner reflector) should be provided.

The antenna outputs are connected to the ports 2 and 3 of the Σ-Δ hybrid by a pair of phase matched cables. The diode detectors of the scalar network analyzer (channels A and R) are connected to the sum and difference outputs of the hybrid (Fig. 9).

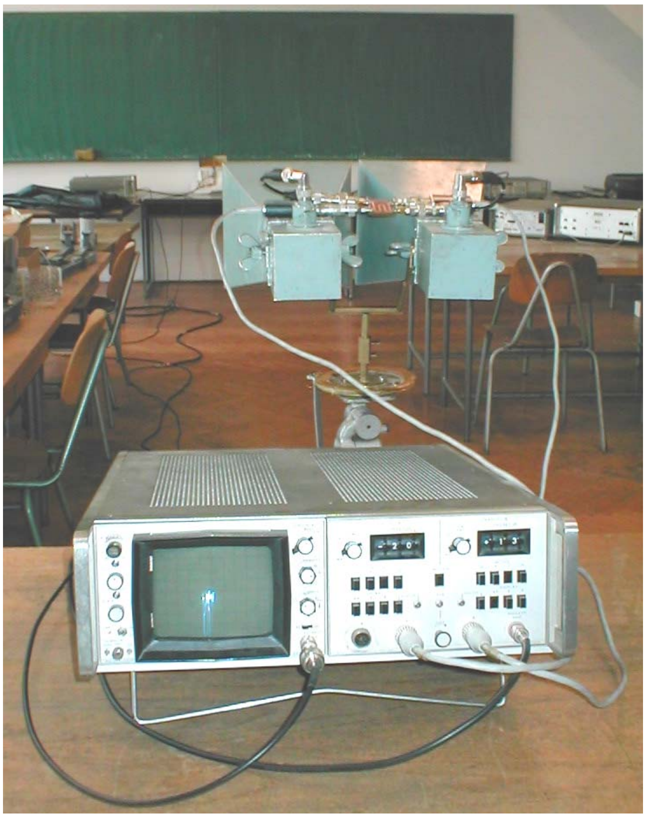

Fig. 10. Laboratory demonstration system using a scalar network analyzer as indicator.

Fig. 10 shows the student laboratory setup with the scalar vector analyzer and the antenna system. The antenna system is placed on a turntable with angular scale in degrees. The "target echo" - the transmitting antenna (quarter-wavelength monopole with corner reflector) - is located on the table bellow the blackboard on the left of the receiving antenna system (Fig. 10). Further to the left of the transmitting antenna is the signal generator. The transmitting antenna, which simulates the target echo, should also be directive to avoid reflections from the room walls. These reflected signals, combined with the direct signal can produce undesired error in angle measurement.

3.4 Student Measurements

With the described radar system model the students can measure the angular position of the "target" in two ways.

For the first measurement the principle of the angle measurement used by tracking systems with sequential lobing can be used. The target angular position is determined by two measurements, measuring the angles where e.g. the 3 dB change in signal strength occurs. In the described system, by using the sum pattern alone the –3 dB points are spaced at ±9° with respect to the antenna system axis. By using only the difference pattern the +3 dB points are spaced at ±6° with respect to the antenna system axis. For these measurements the levels of the A and R channels on the network analyzer are used. The values are measured relatively to the maximum (measurement with sum pattern) and minimum (measurement with difference pattern).

The second measurement should show the improvement in angular measurement by simultaneously using the Σ-Δ pattern. By switching the scalar network analyzer to A/R measurement, the instrument is measuring the ratio Σ/Δ. In this case the 3 dB change in signal strength occurs at ±4° with respect to the antenna system axis. Although the improvement is not so striking, the measured results clearly show to the students the advantage of simultaneously using the sum and difference patterns (and their ratio) for angle measurement.

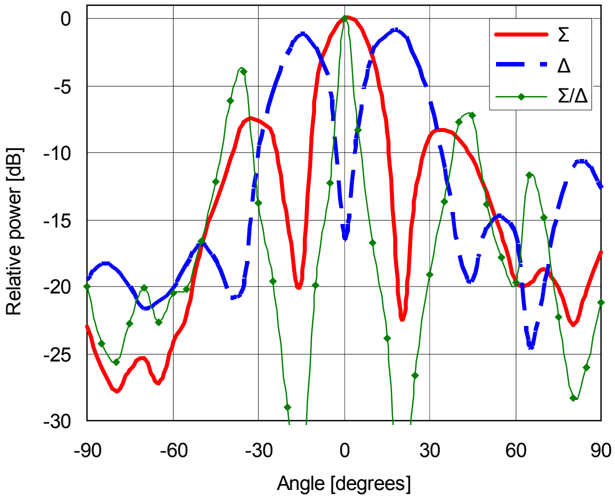

Fig. 11. Measured sum (Σ) and difference (Δ) patterns obtained by the antenna system in Fig. 9 and calculated Σ/Δ pattern.

The students can also measure the simultaneous sum and difference radiation patterns and the Σ/Δ pattern (Fig. 11). The latter can be measured directly by the network analyzer or calculated by the students from the measured values of the sum and difference patterns. The Σ/Δ pattern has a narrower beam, which also evidently explains why the measurement accuracy of the angular coordinate is improved by using a monopulse system. The sum and difference patterns in Fig. 11 are normalized to the sum pattern maximum (value at 0°). The Σ/Δ pattern is normalized to its maximum value at 0°.

3.5 Discussion and Model Improvements

Instead of the scalar network analyzer, the described system can be realized with one or two instruments which can be used to measure received RF power or field strength like power meter, spectrum analyzer, diode detector with an appropriate voltmeter, etc. If two instruments are available, the received power level in the sum and difference channels can be measured simultaneously. If only one instrument is available, it has to be switched between the sum and difference output ports. The disadvantage of the power level indication with one or two power-measuring instruments is that the indication is not as obvious as in the case with network analyzer and needs some additional calculation (calculating the Σ/Δ ratio) performed by students. This approach also does not give any information about the phase of the signals in sum and difference channels.

The application of a vector network analyzer with the possibility of R, A and B signal measurement would allow also phase measurements to be performed and with it to determine if the "target" is on the left side or on the right side of the antenna system axis.

4. Conclusion

A model of a monopulse radar system, used for demonstration in the student laboratory, was described. The antenna system was realized of two identical horn antennas. A π-hybrid was used to obtain the sum and difference patters, while a scalar network analyzer was used as indication instrument. Alternative parts and instruments which can be used to assemble the described model are discussed in order to allow the realization of the model with an existing laboratory equipment and minimum cost. This simple model can be operated by students allowing them to experience how the application of simultaneous sum and difference patterns improves angle measurement accuracy.

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Julijana JANČULA was born in 1978, in Banja Luka, Bosnia and Herzegovina. She has graduated from the University of Zagreb, Faculty of Electrical Engineering and Computing in 2005 majoring in Wireless Communications. Currently she is employed as Junior Planning Specialist at FM & TV Department of the Croatian Telecommunications Agency. Her research interests include monopulse radar systems and FM and AM signal propagation.

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September 2007, Volume 16, Number 3

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