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Original Article

Multi-Function Radar for Optimization of Range Network of a Spaceport

P. Venkataramana[1], Mamatha Gannera[2]

[1]*ECE Department, JNTUA, Ananthapuramu, Andhrapradesh, India*
[2]*JNTU CEA, JNTUA, Ananthapuramu, Andhrapradesh, India*

[1]*Corresponding Author : venkatsdsc@gmail.com*

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Abstract *- Tracking Radar and weather radar are two critical systems for any spaceport or launch base for carrying out its operations. Tracking radar is employed for providing an instantaneous position of the rocket right from the lift-off for range safety. Weather radar plays an important role in planning and conducting operations safely at launch facilities. It also provides data required for launch commit criteria. If there is a radar that fulfills the functions of both radars, there will be a significant saving in the acquisition and maintenance cost of the radar systems for a launch site thereby reducing the operational cost of the launch site. This paper brings out the details of tracking and weather surveillance radars and how the idea of combining the functions of both of these radars into the Multi-Function Radar (MFR) can be utilized to optimize the requirement of multiple radars. Various methods to design such MFR using state-of-the-art technology to optimize the range network thereby reducing the operational cost of the launch base are also discussed in detail.*

Keywords **-** *Configurable, MFPCR, MPAR, Multi-function, Radar, Spaceport, SSPA, Surveillance, Weather, Tracking, TRM.*

1. Introduction

The radar system, which was originally developed to detect enemy aircraft during World War II, has shown diverse applications through the years, not just for military consumers, but also for commercial customers. Even though the military is the prime user and developer of this technology, it has been playing a critical role in a wide range of applications other than military applications, such as large-scale weather monitoring, atmospheric research, air traffic control, the precision landing of aircraft in adverse weather conditions, collision avoidance and buoy detection by ships and automobiles, mapping earth topology and environmental characteristics, etc. [1],[2]. The generic simplified block diagram is shown in the figure-1.

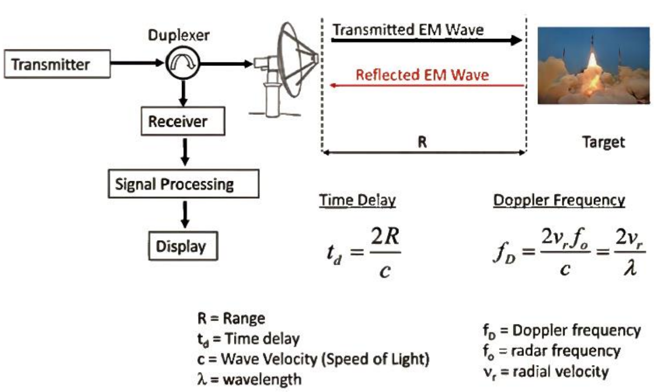

Fig. 1 General Block Diagram of a Radar and principle of operation

The details of each block can be found in [1],[3],[21]. Initially, each radar was designed to optimize the performance for a specific function like search, track, and weather monitoring [4]. So the subsystems like transmitter, receiver, signal processing and antenna were designed suitable to the requirements of one function only. Therefore, each function was fulfilled by a dedicated single-function radar. As the technology has progressed, some of these functions are integrated into a single radar by suitably designing the subsystems to cater for the needs of multiple functions. Such a radar that can perform two or more functions using suitable software and hardware either in a time-interleaved manner or simultaneously is known as Multi-Function Radar (MFR). The integrated functions are depending on the mission requirements and feasibility [5].

Moreover, designers and users of radar systems prefer a system that can be improved over its life span and that reduces the acquisition and maintenance costs. The industry is also developing technologies not only to enhance radar performance but also to integrate multiple radar and communications functions, keeping affordability as a primary requirement [6]. This has led to the development of the MFR. MFRs were initially designed to combine search and tracking functions for military applications [6]. Attempts are on to design a radar that could provide high-quality weather and primary aircraft surveillance capabilities [7], [8], [9].

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Motivated by the advancements in the technology leading to the development of MFR, a study and feasibility analysis are carried out to design an MFR to cater for the requirements of a tracking radar and a weather radar essential at a launch base so that the radar network cost is optimized which in turn helps to optimize the launch cost. This analysis is given in section 2. The cost of the MFR is estimated based on the market survey for various components and it is presented in section-2 and 3. The feasibility of MFR with the tracking and weather surveillance functions is given in section 3. Section 4 concludes the discussions.

2. Requirement of Radars at Launch Base

2.1. Tracking Radar

Protection of assets and people in the range of a spaceport and downrange, the horizontal distance from the launch site, is the paramount task of a launch base system [10]. when the launch vehicle deviates from the predefined safe launch corridor, it has to be terminated with no loss to the people and property. This calls for an accurate instantaneous position of the rocket from its liftoff to the range at which the rocket attains orbital velocity [11]. Tracking radars are used to provide this accurate trajectory of the launch vehicle. As this information is very critical and it is essential in real-time, no failures in the tracking radars are acceptable.

There is a requirement of at least three tracking radars in real-time as the trajectory of any two radars has to match to confirm the trajectory of the launch vehicle even in case of any tracking break or deviation due to some tracking issues in one radar [12]. Since radar consists of many subsystems, providing redundancy for all the subsystems is very complex and expensive. So, at least one more radar is essential for redundancy. Therefore, there is a requirement for at least four radars. Typical tracking radar requirements are given in Table 1.

Table 1. Performance Requirements of tracking radar

Parameter	Value
Operating Frequency	2.7-2.9 GHz
Angular Resolution	1degree
Polarization	Vertical
Radial range resolution	40m
Radar cross-section	$1m^2$ - $400\ m^2$
Sensitivity	$1m^2$ @ 300 km

2.2. Weather Radar

The weather has many impacts on the operations of ground facilities at a launch base and also on the space lift of the launch vehicle [13]. Lightening, both triggered by a rocket as well as the natural phenomenon, boundary layer winds, upper-level winds, precipitation cloud ceilings, temperature and severe weather are some of the impacts on the launch base [14]. A significant number of launches were postponed because of adverse weather conditions. During the preparations of launch vehicles and spacecraft, many activities involving propellants and sensitive electronic systems are at risk from severe weather, lightning and rain [14].

Radar can be used to monitor the weather and provide high-precision forecasts for lightning, convective wind, cyclones etc. Weather radar can be used effectively to save significant costs on launch operations through timely forecasts of adverse weather. This also enhances personal and launch safety [14]. The weather radar basically measures the reflectivity from the cloud and various reflectivity levels contributing to various phenomena. One weather surveillance radar is essential to forecast adverse weather and plan activities accordingly. Since any failure in the radar affects the weather forecasting for critical operations, one more radar shall be available as a redundancy. Therefore, a total of two weather surveillance radars are essential. Typical weather radar requirements are given in Table 2.

Table 2. Performance Requirements of weather radar

Parameter	Value
Operating Frequency	2.7-2.9 GHz
Angular Resolution	1degree
Polarization	Vertical & Horizontal
Radial range resolution	75m
Sensitivity	23dBZ @ 300 km

2.3. Optimization of the Radar Network

As explained in the previous subsections, a network of radars consisting minimum of four Tracking radars and two Weather surveillance radars is essential for launch base operations. The acquisition and maintenance cost of these radars is very high as they are complex consisting of many subsystems and require a lot of inventory.

As these two types of radars viz. tracking and weather surveillance radars, are realized using different hardware and software components, two different types of components have to be procured and maintained for replacement during any failures. The cost of these components is very high leading to higher inventory costs leading to high maintenance costs. The acquisition cost and maintenance cost of the existing tracking and weather radars are given in Tables 3 and 4 respectively based on the market survey.

Table 3. Acquisition and maintenance cost estimation details of a tracking radar

Subsystem	Acquisition Cost(₹Lakh)	Maintenance Cost(₹Lakh)
Magnetron-based Transmitter (1MW)	350	150
Antenna Reflector & Waveguide assembly	150	10
Monopulse Feed assembly	150	0
Az & El mount , Slipring	150	0
Servo Motors & Power Amplifiers	50	10
LO Source and RF Front End	100	20
Signal & Data Processing software	130	30
Console & Displays	20	2
Civil & Auxilary Systems	150	3
Integration, Testing& Commissioning	100	0
TOTAL	**1350**	**225**

Table 4. Acquisition and maintenance cost estimation details of a weather radar

Subsystem	Acquisition Cost(₹Lakh)	Maintenance Cost(₹Lakh)
Klystron-based Transmitter (1MW)	400	150
Antenna Reflector & Waveguide assembly	100	10
OMT Feed assembly	100	0
Az & El mount , Slipring	150	0
Servo Motors & Power Amplifiers	25	10
LO Source and RF Front End	100	20
Signal & Data Processing software	130	30
Console & Displays	20	2
Civil & Auxilary Systems	150	3
Radome	100	10
Integration, Testing& Commissioning	150	0
TOTAL	**1425**	**235**

It can be found from Tables 3 & 4 that the Cost of the four tracking radars is ₹6300Lakh ((1350 + 225) × 4) and the cost of two weather surveillance radars is ₹3320Lakh ((1350 + 225) × 2). So the cost of the range network is ₹9620Lakh (3320 + 6300).

In addition, the operational cost of each of the radars is also high as it requires more human resources for operation and maintenance. Moreover, the tracking radar has a limited period of operation as the tracking duration is small and used only during the launch phase. So it is idle most of the time. This can be avoided by incorporating a weather surveillance function in this radar. The number of radars required will reduce from four tracking radars and two weather surveillance radars to four MFRs. The total cost of the radars including the acquisition, maintenance and operational costs directly affects the launch cost.

So it is very much useful to optimize the cost of the radar network.

Table 5. Specifications of Tracking, Weather surveillance and Multi-Function Radars

Parameter	Tracking Radar	weather surveillance Radar	MFR
Frequency (GHz)	2.7-2.9	2.7-2.9	2.7-2.9
Transmitter Peak Power (kW)	1000	1000	1000
Pulse width (μsec)	0.25	0.5	0.25, 0.5
Type of Transmitter	Magnetron	Klystron	Klystron or Solid state
Polarization	V	V & H	V & H
Antenna Gain (dBi)	44	44	44
Antenna Diameter (m)	6.6	8.4	8.4
Sidelobe level (dB)	-17	-26	-26
Receiver Bandwidth (MHz)	4	2	2, 4
Number of RF Channels	3	2	3
Number of Digital IF Channels	6	4	6
Antenna Acceleration (Deg/sec^2)	20	10	20
Antenna Speed (Deg/sec)	20	30	30
Monopulse Feed	Essential	Not Essential	Essential
Doppler Processing	Optional	Compulsory	Compulsory

3. Feasibility of Multi-Function Radar for Tracking and Weather Surveillance

The feasibility of developing a radar by combining tracking and weather surveillance functions of a launch base into a single radar is discussed in this section. Consider the requirements of tracking radar and weather radars as given in Tables 1 and 2. Various parameter values of different subsystems of the radar are derived using the radar range equation for tracking provided in [15] and for weather surveillance provided in [16] and other well-known information from the standard references like [2] and [3]. These parameters are given in Table 5. If a radar has to be designed for both functions, it should have the parameter values better of the two. They are also shown in the last column of the same Table 5.

It can be observed from the table that there are a few differences in the values of some of the parameters like antenna side lobe level, type of transmitter etc. If an MFR has to be designed to meet the functional requirements of both radars, it should have the value of a parameter that is better than the two values of the individual radar parameters. Accordingly, the values of the parameters are chosen and given in the last column of table 5. Until recent years, individual radars were designed using conventional technology and are being operational for the last few decades. So there was no scope for integrating the two functions.

But, recent developments in signal processing technology with high-speed computers coupled with real-time capabilities of operating systems [17] and Field Programmable Gate Arrays (FPGA) based hardware has given the motivation to study the feasibility of integration of the functions using these advanced technologies. Another motivation is the availability of cost-effective TR modules along with phased array technology for antenna development. The following subsection explains how each parameter value can be best achieved using advanced technology.

3.1. Antenna

Tracking radars are generally designed using a parabolic dish antenna and monopulse comparator for better tracking accuracy. A single-polarization feed is sufficient for tracking applications.

The sidelobe level of around *-17dB* is sufficient for a single object tracking radar with an acquisition aid. But for weather surveillance, sidelobe levels better than *-26dB* is preferred to obtain accurate weather products. An antenna with dual linear polarization using OMT feed and a parabolic dish is generally employed for weather radars. Multi-Function radar should have both polarizations with a monopulse comparator. It can be designed as given in the figure-2. Alternatively, if an array antenna is selected using patch antenna elements dual linear polarization can be achieved using two feed lines and the design methodology and tools as described in [19],[22]. The array antenna option with electronic beam steering is very complex and costly as there is a requirement to provide a phase shifter to each element and a control circuit to operate it.

Moreover, electronic beam steering is limited to +/-60° in azimuth and elevation which calls for at least three arrays to cover 360°of azimuth which is very much essential for weather surveillance applications. Electronic beam steering also has a limitation on the polarization as the beam is steered away from the bore sight due to depolarization of the beam. Hence mechanical steering with an array antenna has more advantages. It can be used to synthesize the beam with various beam widths and various sidelobe levels by exciting the limited number of antenna elements.

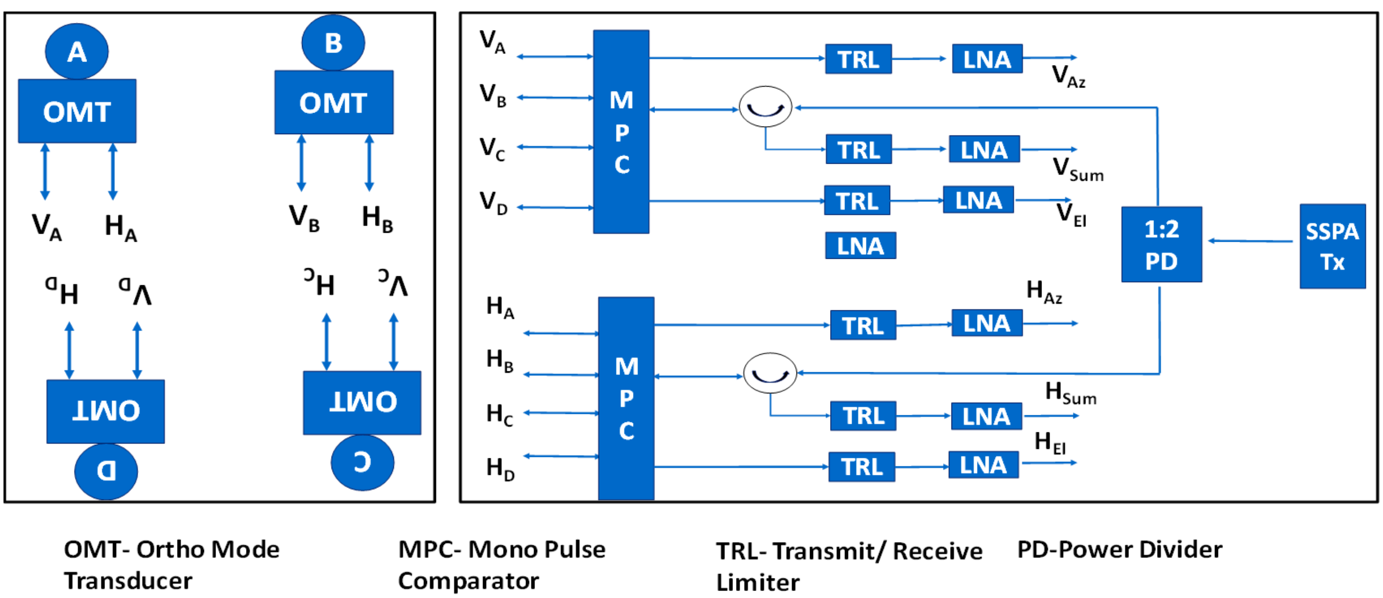

Fig. 2 Configuration of Antenna with dual polarization and Monopulse Comparator

Antenna size has to be increased when better sidelobe levels are desired. Moreover servo drive capacity needs to be increased to meet the huge acceleration and velocity requirements of the tracking application. As per the requirement given in Table 5, a suitable antenna control system shall be designed to have the required acceleration for meeting tracking application requirements even though it is not essential for weather surveillance applications. This can be achieved with a minor increase in the cost of the drive and associated servo motors.

These critical requirements might have been the limitations to developing MFR for these applications. Nowadays, the usage of an array antenna, as explained earlier and making use of solid-state technology for the transmitter which is discussed in the next subsection are aiding to overcome these limitations.

3.2. Transmitter

Most of the conventional tracking radars use Magnetron-based transmitters because of their cost advantage and weather surveillance radars use klystron amplifier-based transmitters because of the requirements of better phase noise and coherency for Doppler frequency. Even though Doppler frequency can be estimated using a Magnetron transmitter using a coherent on-receive technique, it is limited by its complete and inferior performance compared to using a klystron-based transmitter. Hence MFR shall be realized using a klystron-based costlier transmitter.

Solid-state technology provides an alternative cost-effective solution without compromising on performance. There are two options available again. First, developing a central Solid State Power Amplifier (SSPA) based transmitter and distributing the power to the parabolic dish antenna through a waveguide as in the case of the tube-based transmitter. The peak power of this transmitter is less but the average power or the energy of the pulse is equal to that of conventional transmitters.

An SSPA-based transmitter with 100µsec pulse width and *10 kW* peak power generates a pulsed sinusoidal signal of energy equal to that pulse which is generated by a transmitter with *1MW* peak power and *1µsec* pulsed sinusoidal signal. But the range resolution shall be degraded proportional to pulse width and blind range shall increase. Range resolution shall be retained as that of a narrow pulse by modulating the transmit waveform and compressing it to a short pulse in the receiver after the reception. Linear Frequency Modulation (LFM) and phase coding are some of such modulation schemes[20].

The advancements in the computational power of processors and FPGAs are making it possible to compress large pulse-width signals into smaller pulse-width signals. If the pulse width is increased beyond *100µsec*, the peak power shall be reduced proportionally or the requirement on the gain of the antenna shall be reduced so that size of the antenna shall be reduced. This further reduces the requirements of the antenna control system leading to a lower cost for the radar.

The cost of the SSPA-based transmitter is around 50 % lower than tube-based transmitters even when the average power is doubled. Solid-state transmitters also provide graceful degradation leading to the high availability of the transmitter.

3.3. Receiver and Signal Processing

Most of the modern tracking radars are designed using three RF channels and six IF channels to process sum, azimuth error and elevation error signals for better accuracy and high receiver dynamic range of the order of 90dB. Two-channel monopulse is also possible with some limitations like reduced data rate and Signal Noise Ratio (SNR) and the possibility of cross-coupling between azimuth and elevation errors [15].

Weather surveillance application requires only two RF and four IF channels as there is no requirement of processing azimuth and elevation error signals but are required to process echoes due to horizontal and vertical polarization transmit signals simultaneously.

Optimization of the IF receives channels can be possible by adopting multiplexing of the RF and IF channels. Here, there is a provision to utilize the best polarization for tracking. In this method, only four IF channels are sufficient for tracking as the signals from the RF channel can be controlled in real-time using a digital attenuator based on the input signal level.

3.4. Cost Estimation of MFR

As described in the previous subsections, most of the additional requirements of MFR compared to individual radars are possible to realize with a minor increase in the cost of the subsystems. The cost of some of the subsystems like the antenna and transmitter shall be reduced with the proposed concept as most of the high-power RF components can be avoided by using array antenna and TR Modules which require only low-power and low-cost components.

Moreover, the size of the antenna can be reduced to half by increasing the pulse width of the transmit waveform up to 400µsec and compressing it to 1µsec without affecting the range resolution of the individual radars. The number of IF channels also can be reduced to four from six by following the concept explained in the previous section.

Considering all these novel ideas, the acquisition and maintenance costs are estimated and given in Table 5. It can be observed that the total cost of the MFR is ₹1650 Lakh (1455+195) which is approximately equal to the cost of one conventional radar. The cost of four MFRs which can replace conventional radars is ₹6600 Lakh (1650 × 4). This clearly shows that it is possible to reduce the cost of the range network by 31%, thereby saving launch operations costs.

4. Conclusion

The importance of tracking and weather surveillance radars for a spaceport and the optimization of these radars for reducing the launch cost is discussed in detail. The proposed Multi-Function Radar as a solution to minimize the cost of these radars and its feasibility using various modern technologies is discussed in detail.

It is shown that MFR can be realized without compromising the performance of any radar application with the cost of conventional single-function radar. The requirement of four tracking radars and two weather surveillance radars can be reduced to four MFRs. The total cost of the range network can be reduced by 31%.

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