Modular system design for a new S-band marine radar

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Modular System Design for a New S-Band Marine Radar

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Abstract—**This paper describes a new approach to marine radar design. New IMO regulations allow marine radars to be designed with solid state transmitter power amplifiers using pulse compression waveforms and coherent Doppler processing. This gives a new flexibility and better possibilities to control the transmitter spectrum. The modular system design applies to waveform generation, signal processing and RF hardware.**

Keywords-marine radar; waveform; RF amplifier; regulations

I. INTRODUCTION

Marine radars have usually been designed with magnetron transmitters, rotating waveguide array antennas, noncoherent receivers in transceiver units and separate processing and display units. In some cases the transceiver unit is separate from the antenna unit with a waveguide between them. Marine radar is heavily regulated for safety reasons and different producers have almost the same technical implementations. Many sub-systems are standard components from specialized producers. Apart from regulations, low cost and reliability are important factors for shipping customers. Present marine radars typically need to replace the magnetron transmitter every year to maintain reliability. However, new developments in solid state components and requirements from spectrum regulations have increased the need for new designs and implementations, [1], [2], [3].

Due to the new IMO (International Maritime Organization) regulations for better Safety of Life at Seas (SOLAS), a new radar standard (IEC 62388) has been adopted and implemented from 1 June 2008 with improved detection requirements for marine radar systems [4], [5]. For S-band (3.05 GHz) radar systems, the new standard allows also non-transponder based solutions, opening up for semiconductor power amplifiers to replace the magnetron transmitter. To satisfy different categories of customers a modular system design is preferable, where both semiconductor based and magnetron based RF transmitters can be accommodated.

This paper describes the cooperative development work of FOI and Consilium Navigation to design new marine radar systems that have improved performance and conform to the new regulations. This work is performed within the FOCUS Centre of Excellence to explore new possibilities in sensor technology and sensor related research at FOI.

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II. SYSTEM CONSIDERATIONS

The new marine radar design must be based on the present IMO requirements and it must have similar or improved cost effectiveness and performance as the standard marine radar products. The new design should use semiconductor based power amplifiers to allow better reliability and lower life cycle cost. The small target detection performance should be increased by coherent Doppler processing and diversity techniques. The out of band emissions from the transmitter should be decreased to conform to present and future requirements for communications and other adjacent band spectrum users. The short range coverage should be as small as possible to enhance near target ranging. The sea clutter should be suppressed by Doppler filtering. Pulse compression should be used to enhance range resolution. The present antenna system using waveguide array antennas and mechanical scanning could be kept for the time being. The processing and display units should be kept with existing tracking and operational control performance.

The system design is based on the present requirements for small target detection range performance and on keeping the long range detection performance of the existing marine radar design. The typical small target detection range requirement is 7 km for a 0.5 m^2 target radar cross section (RCS). The long range detection performance is mainly determined by the average transmitted power. For the typical magnetron transmitter the average power is about 20 W for the longest range scale and the lowest resolution. For the shortest range scale and the highest resolution the average power is about 5 W. The average power required for the small target detection range is about 2 W.

The proposed waveform design is a multiple pulse length waveform with non-linear frequency modulation (NLFM) pulse compression to get the desired range resolutions and range coverage. This waveform can be implemented with about 10% duty cycle and this translates to a required 200 W peak power transmitter. A special requirement is the minimum short range coverage of 40 m which means that the shortest pulses must be less than about 200 ns pulse length. The waveform starts with short pulses and continues with medium length pulses and finally a long pulse is transmitted in a pulse burst repetition interval. Similar pulsed waveform patterns have been proposed in marine radar applications [6], [7], [8]. Continuous waveforms were also considered but rejected for the required complex antennas and the limited dynamic range performance. Multiple pulse length waveforms with pulse compression have also been implemented earlier in other applications, such as in air traffic control radar using semiconductor based power amplifiers [9], [10].

III. MODULAR DESIGN

The modular system design approach in our development concerns both hardware and software. The RF hardware can be naturally modular by having separate components for separate RF functions. The transmitter functions as signal generation, up-conversion, power amplifiers and circulator are in a series and can be exchanged for new components. Also the receiver functions as limiter, low noise amplifier, down-conversion and signal acquisition are in a series and can be exchanged for new components. There can also be parallel RF functions such as a magnetron transmitter and a power amplifier in parallel.

The waveforms can also be modular by having time frames with different transmit pulses and receive intervals. The approach is first to design time frames with short pulses and several receive intervals for the short range coverage. The next waveform design are time frames with a medium length pulse and a receive interval for the medium range coverage. The final waveform design are time frames with either a long pulse or a receive interval.

The signal and data processing is modular by matching to the different waveform time frames. Different pulse lengths and range intervals require different receiver sensitivities to control the dynamic range. Different pulse compression waveforms require different matching filter responses.

The modular design approach allows a gradual improvement of the marine radar hardware and software. It is also easier to adapt to new requirements and to control reliability.

IV. WAVEFORM DESIGN

The waveform design is based on time frames that can contain one or several transmit pulses and one or several receive intervals. The chosen time frame is 150 µs long and several time frames with different pulses and receive intervals constitute a pulse burst interval.

The existing marine radar has three different pulse lengths 60 ns, 250 ns, 800 ns and the corresponding pulse repetition frequencies 3000 Hz, 1500 Hz, 750 Hz with the average transmit powers 6 W, 12 W, 18 W. The waveform design has equal or higher average transmit power and range resolution with a minimum range of 40 m. The waveform design has also a corresponding number of pulses and range coverage.

The proposed waveform in Fig. 1 starts with four short 0.2 µs pulses in the first time frame of 150 µs. The next two time frames contain two medium length 12 µs pulses. The next time frame contains one long 120 µs pulse and the final four time frames contain the long pulse receive interval. This gives a pulse burst repetition interval of 1200 µs.

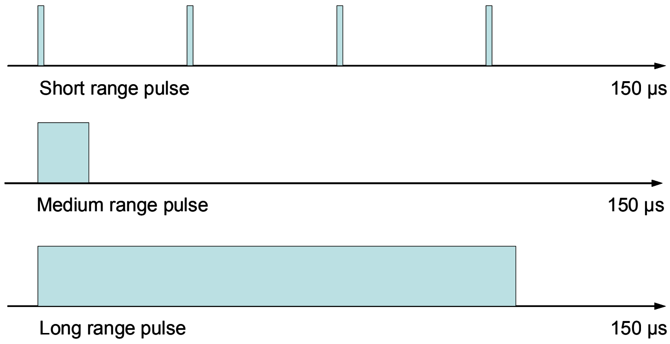

Figure 1. Multiple pulse shapes for different ranges.

The time frames and the multiple pulse shapes are shown for the first, second and fourth time frame. The short pulse coverage is 0.2 µs – 24 µs corresponding to 30 m – 3.6 km. The medium pulse coverage is 12 µs – 140 µs corresponding to 1.8 km – 21 km. The long pulse coverage is 120 µs – 630 µs corresponding to 18 km – 94.5 km. The three different range intervals should have matched performance at the range limits between the coverage intervals. The sensitivity time control can be set in three steps for the different pulse lengths and an additional variable sensitivity time control is used for the short pulse lengths. The proposed waveform is intended to cover all ranges and resolutions of the existing marine radar.

The waveform design can have different range resolutions for different pulse lengths. The centre frequencies can be different to reduce range ambiguous responses. The waveform design can be adapted to different operating conditions and range scales. For short range operation only the short and the medium pulse lengths might be necessary with high range resolution. For long range operation the medium and the long pulse lengths are sufficient with low range resolution. The pulses can be coherent from pulse to pulse to allow Doppler filtering or the pulses can have frequency agility to get diversity from pulse to pulse. Pulse staggering can be inserted by shifting the pulse start within a time frame.

V. PERFORMANCE ESTIMATION

The performance estimation is based on the regulated small target detection range requirement [5]. The medium pulse length is used to get the required detection range of 7 km for a 0.5 m^2 target RCS. This corresponds to a required average power of 2 W which is obtained by a single 200 W peak power medium pulse length of 12 µs in the pulse burst repetition interval of 1200 µs. The two transmitted medium pulses can be used for ambiguity reduction, diversity or coherent integration to increase the performance margin.

The short pulse range interval must be matched to the medium pulse range interval to get continuous coverage of the small target detection. Using a single 200 W peak power short pulse length of 0.2 µs, the average power is 33 mW which gives a detection range of about 2.5 km. This range is well above the medium pulse minimum range of 1.8 km. When all the four short pulses are used with coherent integration, the detection range is increased to about 3.5 km. Depending on the medium pulse receive switch transients, the range interval limit can thus be set to about 2.5 km.

In the same way the medium pulse range interval must be matched to the long pulse range interval to get continuous coverage of the larger target detection. The medium pulse average power of 2 W is sufficient for detection of a 40 m^2 target RCS for the medium pulse maximum range of 21 km. The long pulse minimum range is 18 km and depending on the long pulse receive switch transients, the range interval limit can thus be set to about 20 km. The long pulse average power of 20 W is sufficient for detection of a 40 m^2 target RCS at 37 km. The long range detection range performance for ships or shorelines above 1000 m^2 target RCS is more than 80 km.

The range coverage will have gaps depending on the target RCS. Targets with RCS below 0.5 m^2 will have coverage gaps for ranges shorter than 7 km. Targets with RCS between 0.5 m^2 and 4 m^2 will have continuous coverage for ranges from 7 km to 12 km. Targets with RCS between 4 m^2 and 40 m^2 will have gaps for ranges from 12 km to 37 km. Targets with RCS above 40 m^2 will have continuous coverage for ranges longer than 37 km. The continuous coverage is important for the tracking performance requirements for ship targets.

VI. RF Power Amplifier Design

For the design of a semiconductor based RF power amplifier, several types of materials and components are available: Silicon-Carbide, Gallium-Nitride, but also pure Silicon based bipolar and MOS technologies. The first two materials are still more expensive and less well-known compared to Silicon. At slightly different center frequencies for broadcasting and cellular-phone applications, there are a number of commercial Silicon based power amplifier solutions available. After an analysis of price and performance of all available power amplifier solutions, our choice is a Silicon based bipolar solution with four amplifier stages. The experimental breadboard power amplifier is shown in Fig. 2 and the performance in Fig. 3.

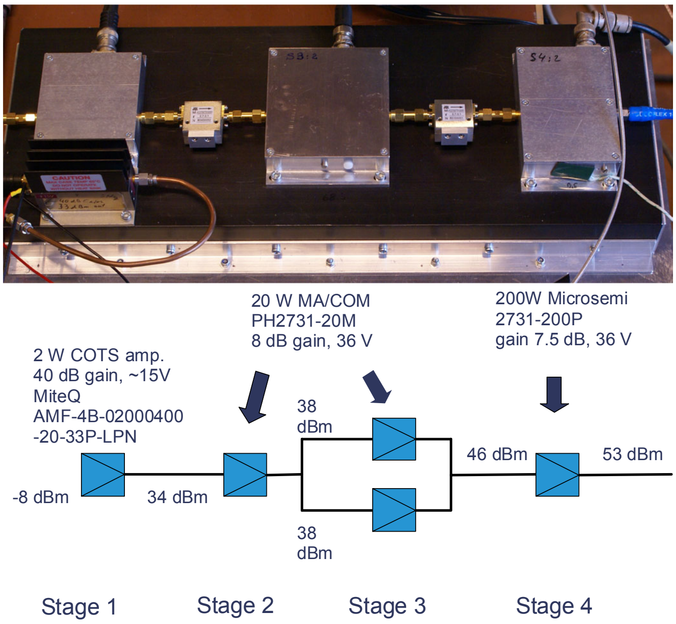

Figure 2. Four stage 200 W pulsed S-band experimental power amplifier. Stage 1 class A GaAs, stages 2-4 class C Si bipolar.

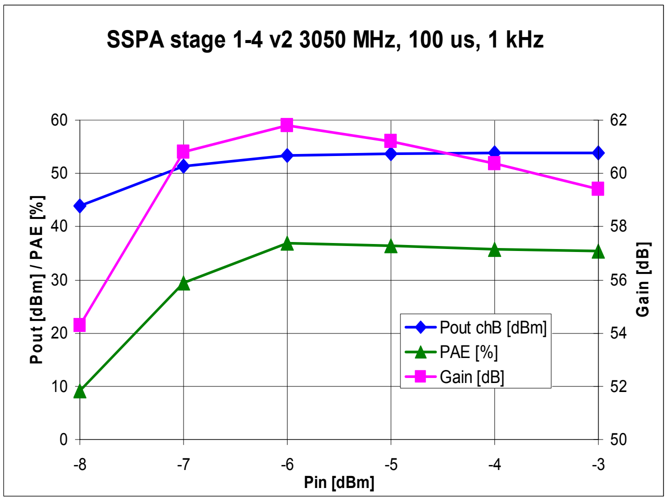

Figure 3. Pulsed power output, gain and efficiency as a function of input power for the experimental four stage power amplifier.

The four stage RF power amplifier in Fig. 2 is built form commercial transistor modules with additional matching networks. The class C operation means that the output power is very sensitive to the input power level and the leakage signal from the up-conversion between pulses is quite small.

The complete power amplifier has a power consumption of 85 W and an average output power of 24 W at 12% duty cycle, leaving about 60 W to be dissipated as heat. The peak output power is 200 W. Stages 1-4 were mounted on a fan-cooled heat sink. The case temperature of the last stage stabilizes to 31°C after about 30 minutes of operation with 22°C ambient temperature. The combined current for stages 2-4 was 2 A at 12% duty cycle. The longest pulse in the proposed waveform (120 µs) is longer than what is recommended by the supplier for stages 2 and 3 (100 µs).

Power measurements were carried out with a single frequency input signal at 3050 MHz, 100 µs pulse length and 10% duty cycle. Fig. 3 shows the output power, gain and power added efficiency (PAE) as a function of input power. Due to the use of class C amplifiers the output power decreases nonlinearly when the input power is reduced. Moderate overdrive is acceptable but higher input power than indicated in Fig. 3 or an input signal with duty cycle larger than 12% (10% recommended) should be avoided.

The pulse rise-time seems to be influenced by two different processes. First there is a relatively rapid rise to 70% of the maximum output power in less than 100 ns Stage 4 seems to be responsible for the largest increase in this initial rise-time. After stage 2 and 3 the rise-time is about 15 ns. After the initial increase, the output power continues to increase so that the 10-90% rise-time becomes 2.5 µs, and this is most likely a thermal process. The fall-time is about 5 ns and it is more critical for transmit-receive switching.

The rise-time and the fall-time affects the transmit signal spectrum as well as other transient effects and spurious signals between pulses. However, the spectrum requirements need further reduction of the spurious levels and a pulse switch is used to reduce the up-conversion leakage signals.

VII. EXPERIMENTAL SYSTEM

The experimental marine radar system is built from an existing experimental radar at UHF band with digital control of waveforms, digital receivers and recording equipment for field trials. The experimental UHF radar LORA feeds on transmit the up-conversion to S-band, the solid state power amplifier and the existing marine radar antenna. On receive, the limiter and the low noise amplifier feed the down-conversion to UHF signals and the UHF radar receiver and recording equipment. The experimental marine radar system is shown in Fig. 4.

The LORA radar has a flexible digital waveform generation operating at 204.8 MHz sampling frequency and up to eight digital receiver channels operating at 25.6 MHz sampling frequency. Each receiver channel has 10 MHz bandwidth and they can be coherently combined to cover 80 MHz bandwidth. All frequencies are coherently generated from a stable 10 MHz GPS controlled oscillator. The IF frequency is about 640 MHz to reduce filtering requirements for the S-band conversion. The RF section is built with standard components.

The different waveform patterns are programmed using the 150 µs time frames as building blocks for the waveform. Eight time frames were used in the experiments to get a pulse burst repetition interval of 1200 µs. Several waveforms have been programmed as described in section IV. Short pulses with 25 µs or 50 µs pulse repetition interval were programmed to check range ambiguities and detection performance at short range. Medium pulses with 150 µs or 300 µs pulse repetition interval were programmed to check range ambiguities and detection performance at medium range. Long pulses with 1200 µs pulse repetition interval were programmed to check detection performance at long range. Combined multiple pulses were programmed to check the proposed waveforms.

All pulses have 20 MHz bandwidth pulse compression waveforms using linear or non-linear frequency modulation. The received signals are recorded with two receiver channels covering the 20 MHz bandwidth. The received digital data can be coherently combined to a single 20 MHz signal. An example of the measured transmit signal spectrum using the combined multiple pulse waveform is shown in Fig. 5.

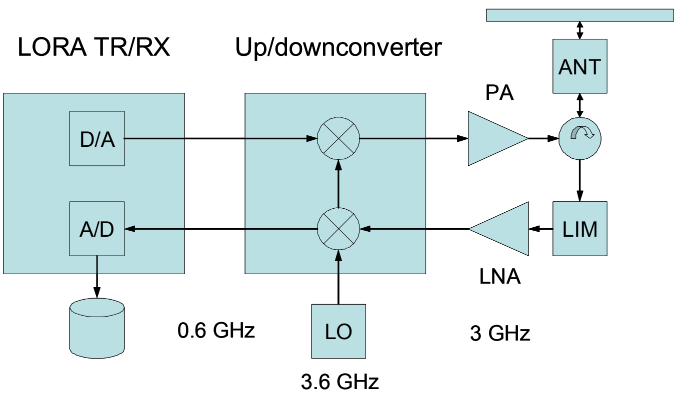

Figure 4. Experimental radar system based on the LORA UHF radar, up and down-conversion to the S-band, the 200 W power amplifier, circulator, limiter and low noise amplifier and the existing rotating waveguide array antenna.

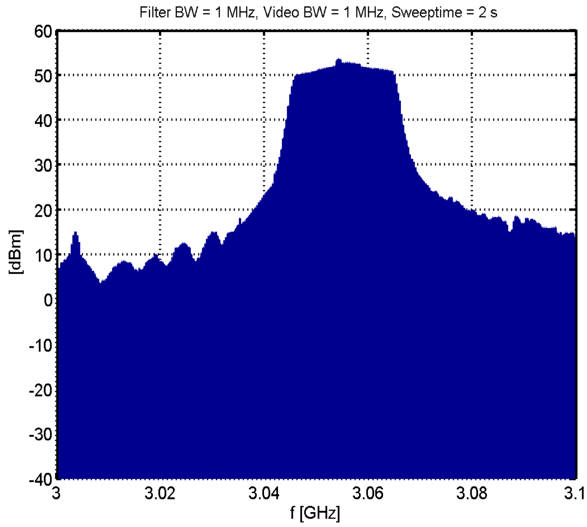

Figure 5. Measured frequency spectrum of the output power for the four stage amplifier. Linear FM modulation with 20 MHz bandwidth.

The following experiments have been carried out on the four-stage amplifier chain in the experimental radar system. Measurements have been performed of signal levels and gain after each of the stages using the pulse compression RF signal with the proposed pulse burst as input. Frequency spectrum measurements and comparisons have been carried out with the IEC 62388 maximum frequency spectrum mask at each stage level. The spectrum falls well inside the required frequency spectrum mask of the IEC 62388 regulation.

VIII. FIELD TRIALS

The experimental radar has been tested in field trials from roof-top locations and ships using the existing radar antenna installation. The purpose is to check the radar performance using the new waveforms and the new power amplifier chain and comparing the results with the magnetron based solution. Fig. 6 shows the near range clutter environment from a ship. Fig. 7 shows the PPI image of the experimental radar system and Fig. 8 shows the PPI image of the existing radar system.

Figure 6. View of the wind turbines outside Landskrona harbour, Sweden.

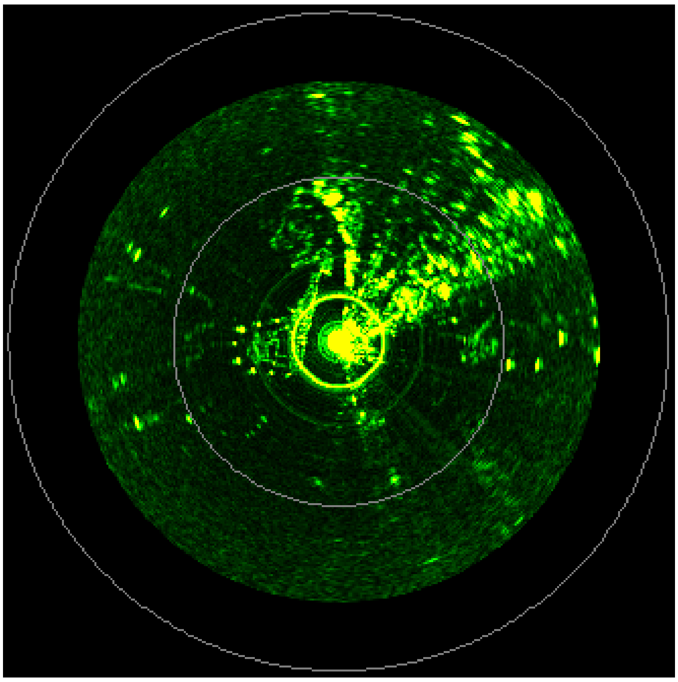

Figure 7. PPI image from the experimental radar system using the short range pulses. The radar was placed on a ship in a harbour and using the existing S-band antenna. The grey circles show the 1 NM range rings.

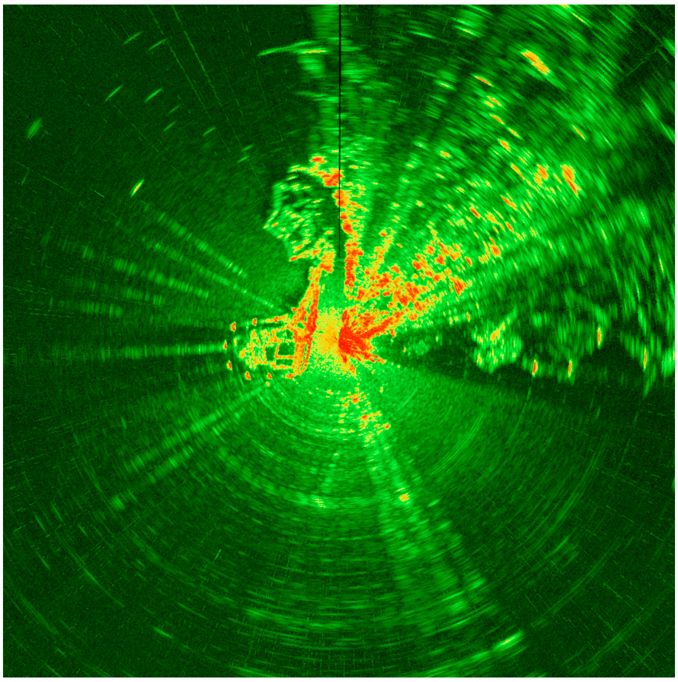

Figure 8. PPI image from the existing magnetron radar using short pulses and a color coded display. The conspicuous spoke like scattering to the left is from the wind turbine towers bistatic scattering of the surrounding clutter.

The field trials show that the experimental radar system works as planned. Future work includes combining the received data from different pulse lengths to the full range coverage and integrating the design into a prototype system.

IX. Conclusions

A modular system design approach for S-band marine radar has been proposed. The design approach concerns both hardware and software. RF components and sub-systems can be put in series or parallel to achieve the desired performance. Waveforms can be constructed using a time frame approach to get both short range and long range performance and also to adapt the marine radar to different operating conditions. An experimental marine radar system has been designed for radar trials on ships and roof-top locations.

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