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COOPERATIVE TARGETS DETECTION AND TRACKING RANGE MAXIMIZATION USING MULTIMODE LADAR/RADAR AND TRANSPONDERS

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Abstract—A LAser raDAR (LADAR) system was described in previous papers for detecting and tracking cooperative targets. The LADAR system was optimized to achieve accurate tracking with a high probability of detection and low False Alarm Rate (FAR). However, the operation range was limited to about thirty km's under clear sky conditions and less in low visibility and bad weather conditions.

To obtain operation ranges in the order of hundreds km's without affecting tracking accuracy a LADAR/RADAR dual mode system was developed. Moreover, very bulky, expensive and powerful RADAR equipments are required.

In this paper, we propose a tactical mobile tracking LADAR/RADAR systems based on a multi-mode LADAR/RADAR combination using active transponders on cooperative targets for pre-detection and tracking at higher range distances. The optimal solution described in this paper is based on a six-step multimode operation procedure, which starts from an L-band active transponder for maximal distance detection and tracking, and with decreasing distance it switches to an L-band RADAR , Ka-band RADAR with and without active transponder, LADAR with transponder and then to a LADAR without transponder for the final tracking step. Although relatively complicated (6 steps), our proposed solution requires significantly lower power levels and produces less radio interference than the former dual-mode system as shown in Table 1.

1 Introduction

2 Overview of the LADAR Sub-System Mode

3 RADAR Sub-Systems Modes

1. INTRODUCTION

In previous papers [1, 2], we have described the design of LAser raDAR (LADAR) systems used for detection and tracking of cooperative targets in the Infra Red (IR) wavelengths. In particular, we focused on design optimization for achieving maximum accuracy and long-range operation in these systems. However, extremely high propagation dispersion losses at IR wavelengths and atmospheric constraints, specially cluttering and additional absorption effects, restrict the operation range to an upper bound of few kilometers only, whereas the requested operation distance for detection and tracking of cooperative targets must reach the order of up to few thousands km's for some applications. Excessive operation distances are required in applications such as tracking of aerospace platforms, space shuttles, etc. The aim of this paper is to propose and develop a multi-mode LADAR/RADAR system for further enhancing the detection and tracking operation range of the original LADAR systems, without loosing significant tracking accuracy.

Dual and trimode LADAR/RADAR systems have been proposed [3, 4], but in order to obtain the required maximal operation ranges with moderate transmission power and weight, and without loosing tracking accuracy, a multi-mode processing system including active transponders is proposed and analyzed.

It has also been shown that using a combination of LADAR and RADAR systems, one can benefit from the relative advantages of both systems: long operation range of tracking and detection RADAR systems with yet satisfactory angular resolution, as well as Doppler frequency sensitivity of the LADAR systems [5, 6]. However, we have carried out many iterations until we arrived to the final results and conclusions presented in this paper.

2. OVERVIEW OF THE LADAR SUB-SYSTEM MODE

The LADAR system provides a high resolution and accurate detection and tracking advantages that are required during the final mode of operation. The LADAR detection and tracking systems are ideal for applications requiring high accuracy [7]. The primary drawback of LADAR systems consists of their limited operation range. The main limiting factors for the operation range are due to non favorable IR visibility conditions, atmospheric dispersion losses and attenuation as well as clutter and background effects [8].

Previous investigations [1, 2] show that the operation range of LADAR retroreflector cooperative target detection and tracking systems is restricted to less than 30 km and for the current technology only under favorable visibility conditions.

It has been previously shown [2] that in the case of retro-reflective targets, backscattering signals can be neglected for relatively large distances ($R > 1\,\text{km}$), and the dominant noise is due to clutter effects. As pointed out in the introduction, by using an active repeater on the target, one can introduce a sufficiently long delay between the reception and retransmission of the laser signals and thus significantly reduce the clutter signals. In order to allow for a comparison between the proposed system and the conventional retroreflection system [2], the following equations assume that the clutter effects dominate over all other noise and interference sources [1]. In case of a conventional passive retro-reflecting target the desired received radiant power of the reflected signal can be expressed as [8]:

$$P_{ret} = \frac{4 \cdot P_t}{\pi \cdot \theta_{BW}^2} \cdot \tau_t \cdot \tau_1 \cdot \frac{A_{TAR}}{R^2} \cdot \tau_2 \cdot \tau_r \cdot K_{1.0} \cdot \rho_{tar} \cdot \frac{A_{det}}{\Omega_{ret} \cdot R^2} \tag{1}$$

where the solid angle of the retroreflector, Ω_{ret}, is given by:

$$\Omega_{ret} = \frac{4 \cdot K_{ret} \cdot \lambda^2}{\pi \cdot D_R^2} \tag{2}$$

In the above equations P_t is the transmitter (Tx) power $[W]$, θ_{BW} is the transmitter beam-width [rad], $A_{TAR} = \pi D_R^2/4$ is the target effective area [m^2], where D_R denotes the equivalent target aperture diameter [m], R is the one-way distance between the base transmitter and the target [m], A_{det} is the receiver detector antenna area [m^2], ρ_{tar} is the target reflectivity, τ_t and τ_R are, respectively, the transmitter and receiver optical transmission ratios, τ_1 and τ_2 are, respectively the optical transmission ratio of the forward and return one way propagation path, $K_{1.0}$ is the target factor due to atmospheric turbulence, K_{ret} is the retro factor of the retroreflector (for circular cross-section $K_{ret} = 3.7$) [8], and λ is the radiation wavelength [m].

The received interference noise power $P_{c\ell}$ due to clutter effects can be expressed by:

$$P_{c\ell} = \frac{P_t}{\pi \cdot R^2} \cdot \tau_t \cdot \tau_1 \cdot \tau_2 \cdot \tau_r \cdot \rho_{dif} \cdot A_{det} \tag{3}$$

where ρ_{dif} is the equivalent reflection factor due to clutter effects [2, 9].

The signal to noise ratio for the case of passive cooperative retro-reflective targets is obtained by dividing Eq. (1) by Eq. (3):

$$SNR\Big|_{\text{passive}} \equiv \frac{P_{ret}}{P_{c\ell}} = \frac{\pi^2 \cdot A_{TAR} \cdot D_R^4 \cdot \rho_{ret}}{4 \cdot \lambda^2 \cdot K_{ret} \cdot \rho_{dif} \cdot \theta_{BW}^2 \cdot R^2} \tag{4}$$

which shows that in case of passive targets the SNR decreases according to $\frac{1}{R^2}$ due to cluttering interference. It has been shown that for detection probability and low False Alarm Rate (FAR) the operation range will not exceed 25 km in normal propagation conditions [1, 10].

We will now consider the case of a cooperative target carrying an active transponder (signal repeater). The received power P_{rec} due to the retransmitted signal can be written as:

$$P_{rec} = \frac{4 \cdot P_{rep}}{\pi \cdot \theta_{BW}^2} \cdot \tau_t \cdot \frac{A_{det}}{R^2} \cdot \tau_2 \cdot \tau_r \tag{5}$$

where P_{rep} is the repeater Tx power, θ_{BW} represents the angular (full) beam-width of the cooperative target Tx and τ_t is the optical transmission of the target Tx. The clutter noise power is actually the same as shown by Eq. (3).

We shall introduce the following ratios:

$$r_p = \frac{P_{rep}}{P_t} \tag{6}$$

$$r_\tau = \frac{\tau_t'}{\tau_t} \tag{7}$$

Using these normalized expressions, the signal to noise ratio for the case of a cooperative target with an active repeater is given by:

$$SNR\Big|_{\text{repeater}} \equiv \frac{S_{rep}}{S_{c\ell}} = \frac{4K_{1.0} \cdot r_p \cdot r_\tau}{\pi \cdot \theta_{BW}^2 \cdot \tau_1 \cdot \rho_{dif}} \tag{8}$$

According to Eq. (8), when the cooperative target is equipped with a repeater the SNR is practically unaffected by the detection range. In this case, the maximum LADAR operation range is determined by the minimum detectable signal ($S_{\min}$) of the tracking station Rx [11, 12]:

$$R_{\max} = \sqrt{\frac{4 \cdot P_{rep}}{\pi \cdot \theta_{BW}^2} \cdot \tau_t \cdot \frac{A_{det}}{S_{\min}} \cdot \tau_2 \cdot \tau_r} \tag{9}$$

where $S_{\min}$ denotes the minimum detectable signal.

Thus, using a moderate power level it is possible to achieve a significantly higher operation range, which can reach 50 km even under adverse propagation conditions.

3. RADAR SUB-SYSTEMS MODES

In order to obtain extended detection and tracking operation ranges, RADAR systems modes are mandatory. The operation range of ground-to-air RADAR systems is limited by the Line-Of-Sight (LOS) distance d_{LOS}. It has been shown [13] that under normal atmospheric conditions, d_{LOS} can be estimated by the empiric formula:

$$d_{LOS} = \sqrt{17}\left(\sqrt{h_1} + \sqrt{h_2}\right) \quad [\text{km}] \tag{10}$$

where h_1 and h_2 are, respectively, the heights of the target and the ground located RADAR systems, expressed in units of meter. For the common case of high altitude targets $h_1 \gg h_2$, and Equation (1) can be approximated as

$$d_{LOS} \approx 130\sqrt{h_1} \tag{11}$$

Here, d_{LOS} and h_1 are both in units of km.

For distances $d < d_{LOS}$, the statistics of signal detection and interference are all governed by the Gaussian or Rician distribution functions [14]. For distances exceeding d_{LOS}, the Rayleigh and Log Normal distribution functions must be used, resulting in a much reduced detection probability and an increased False Alarm Rate (FAR) [7]. Therefore, practical operation ranges of very high frequency RADAR systems are limited to d_{LOS}, especially due to the reduction caused by the diffraction effect.

The medium operation range, d_m, for a cooperative target tracking RADAR is computed using the following equation [15]:

$$d_m = \sqrt[4]{\frac{P_P \cdot \tau_d \cdot g_T \cdot A_R \cdot \eta_a \cdot \sigma \cdot n \cdot E_i(n)}{(4\pi)^2 \cdot K_B T_0 \cdot F_{OA} B \cdot \tau \cdot f_P \cdot (S/N)_i \cdot L_S}} \tag{12}$$

where P_P is the Tx peak power (W), τ_d is the duty cycle, g_T is the Tx antenna gain, A_R and η_a are, respectively, the effective area (m^2) and efficiency of the Rx antenna, σ is the retroreflector cross section area (m^2), n is the number of integrating pulses [2], $E_i(n)$ is the incoherent integration efficiency, k_B is the Boltzmann constant ($J/^oK$), T_0 is the ambient temperature (^oK), F_{OA} and B are, respectively, the overall noise figure and the bandwidth of the Rx (Hz), τ is the pulse duration (sec), f_P is the Pulse Repetition Frequency (PRF) (Hz), $(S/N)_i$ is the signal to noise (including distortions) ratio at the input of the tracking RADAR Rx, and L_S represents the system's marginal losses.

As Eq. (12) shows the intensity of the returned signal and hence $(S/N)_i$ at the RADAR Rx decrease as d^{-4}.

Table 1. RADAR parameters and operation ranges as a function of frequency band.

Frequency band f_0 /characteristic	Ka band 35 GHz		L band 1.33 GHz	
	A	B	A	B
Tracking Tx average power, P_{av}(kW)	5	1	40	0.17
Tracking Tx peak power (kW)	100	20	400	1.7
Tracking Tx Duty Cycle, DC (%)	5	5	10	10
Tracking Dish Antenna Diameter, D (m)	0.5	0.6	2.0	0.6
Tracking Tx Antenna Gain, G_T (dBi)	43	44.5	27.7	17
Tracking Tx Antenna Efficiency, η	0.6	0.55	0.75	0.7
Rx Antenna Cross Section (m^2) or Gain (dB)	0.2	10dB	3.2	10dB
Number of Integrating Signal Pulses, n	16	16	16	1
Rx Equivalent Noise Figure, Feq (dB)	6	6	3	4
Rx IF Bandwidth, B (kHz)	500	500	333	333
Severe Rainfall Attenuation (at 16 mm/h), a_r (dB/km)	4	4	0.01	0.01
Medium Operation Range, d (km)	165	350	450	1200
Operation Range under 16 mm/h Rainfall, d_T (km)	25	60	445	1170

A- Classical RADAR

B- RADAR using a cooperative active transponder

Table 1 provides the main RADAR parameters required for computing d_{LOS} at the RADAR frequency ranges used in this research, namely 35 GHz (Ka band) and 1.33 GHz (L band) [3]. The performance of RADAR systems is affected by the operating frequency in different ways as follows. For a fixed value of antenna gain, the detection and tracking resolution increases as frequency increases whereas the antennas dimensions and weight decrease at higher frequencies. Lower frequencies, on the other hand, allow higher Tx power output and efficiency. Furthermore, atmospheric losses and scattering effects are reduced as the frequency decreases but accuracy decreases significantly. As it is shown in Table 1 the operating range increases significantly at lower frequencies. Therefore, the maximum operation range is obtained for L-band frequencies. A brief comparison of tracking and detection characteristics of the proposed system is given in Table 2.

Table 2. Comparison of tracking and detection performance of the proposed multiple-mode system.

	Average power required	Maximum range (km)	Rain attenuation	Accuracy	Base RADAR/LADAR size
L-Band+transponder	low	1200	negligible	very poor	medium
L-band RADAR	high	450	negligible	poor	large
Ka-band+transponder	Low- medium	350	medium	medium	medium
Ka-band RADAR	medium	165	medium	medium	medium
LADAR+transponder	low	70	high	high	small
LADAR	medium	20	high	high	small

4. ACTIVE TRANSPONDER OPERATION RANGE

Previous investigations have shown that using transponders it is possible to develop an efficient solution allowing very long operation ranges with yet reduced RADAR Tx power and antenna dimensions [4]. In order to achieve the best performances, the active transponders should be based on a superheterodyne Rx that is tuned to the RADAR frequency f_0, and excites a coded signal at certain non-harmonic frequency f_T, which is amplified and radiated back to the RADAR Rx, as shown in Fig. 1. The transponder is operated only when the input signal exceeds a certain preset threshold value. This results in a significant reduction of the FAR probability and prolongs the lifetime of the battery in the cooperative target. For the case of active transponders, the well-known radio communication Friiss equation (instead of the RADAR equation) can be used to find the operation range. In this case the received (returned) signal decreases as d^{-2} instead of d^{-4}, resulting in significantly higher signal to noise ratio or operation ranges as compared to the RADAR systems. But for transponders we have to provide separate computations for the up-

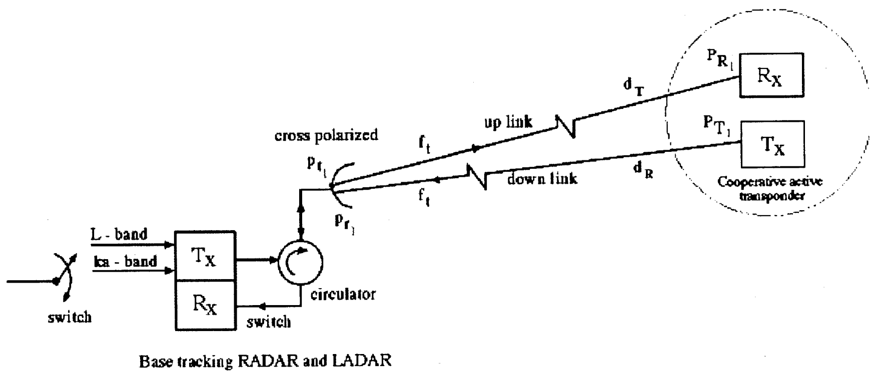

Figure 1. Radar active transponder for multimode operation.

link distance from the main tracking Tx to the transponder Rx of the cooperative target and the down link from the transponder Tx to the main tracking Rx. For the uplink direct channel, the Friiss equation can be written as:

$$P_{r2} = P_{t1} g_{t1} \left(\frac{\lambda_t}{4\pi d_t} \right)^2 \frac{g_{r2}}{L_{S1}} \tag{13}$$

where P_{r2} and P_{t1} represent, respectively, the signal powers at the input of the transponder Rx and at the output of the tracking station $Tx\,(W)$, λ_t is the RADAR Tx wavelength (m), d is the distance from the RADAR to the transponder Rx (m), g_{t1} and g_{r2} are the gains of the RADAR Tx and transponder Rx antennas, respectively, and L_S is the system marginal losses at frequency $f_t = c/\lambda_t$. Eq. (13) can be rewritten as:

$$d_t = \frac{3 \cdot 10^{-3}}{40\pi f_t} \sqrt{\frac{P_{t_1}}{P_{r_2}} \cdot \frac{g_{t1} g_{r2}}{L_{S1}}} \tag{14}$$

Here, d_t is the uplink path tracking distance from the tracking station Tx antenna to the cooperative target transponder Rx (km).

The threshold power sensitivity of the transponder can be computed using the following equations

$$P_{th2} = F_{r2} k_B T_{02} B \tag{15}$$

and

$$P_{r2} = P_{th2} \cdot K_{th2} \tag{16}$$

where F_{r2} is the total noise figure of the transponder Rx, T_{02} is the ambient temperature at the transponder input (^oK), B is the

Intermediate Frequency (IF) bandwidth of the transponder Rx (Hz), K_{th2} is the threshold relative factor of the transponder and P_{th2} is the power threshold sensitivity level of the transponder Rx (W).

The downlink distance d_r, from the transponder Tx to the tracking station Rx, can be computed in a similar fashion. Using the radio-link reciprocity principle, the following equation can be developed

$$d_r = \frac{3 \cdot 10^{-3}}{40\pi f_{rt}} \sqrt{\frac{P_{t2}}{P_{r1}} \cdot \frac{g_{t2} g_{r1}}{L_{S2}}} \tag{17}$$

and for our RADAR link using an active transponder the following equations can be used:

$$P_{th1} = F_{r1} k_B T_{01} B \tag{18}$$

$$P_{r1} = P_{th1} \cdot K_{th1} \tag{19}$$

where P_{t2} represents the signal power at the output of the transponder Tx, g_{t2} and g_{r1} are the gains of the transponder Tx and tracking station RADAR Rx antennas, respectively, and L_{S2} is the RADAR Rx input losses P_{th1} and K_{th1} represent the threshold sensitivity power and the threshold relative factor for the tracking station Rx.

It must be clear that for our radio-link the condition $d_t = d_r$ must be fulfilled.

5. DETECTION AND TRACKING PROCEDURE

The proposed method for enhancing the operation range of the multimode LADAR/RADAR system using active transponders consists of the following 6 steps (see Table 2):

(i) **<u>L-band Active Transponder</u>**

In the first detection step, an active transponder operating at L band is activated on the cooperative target. As shown in Table 1 -Columns B, using a transponder with an average power of about 170 W the detection range in this stage can exceed 1200 km under good visibility conditions. Note that at L band, worst weather related events (most severe rainfall conditions) produce negligible losses and attenuation leading only to a minor reduction of the operation range, as shown in Table 1.

Following detection of the right target, the tracking station process is initiated. In this first step, the angular accuracy is limited due to relatively low gain of the tracking Tx RADAR antenna.

(ii) **L-band RADAR**

As the cooperative target gets closer to the tracking station, e.g., below 450 km, the signal received at the tracking station Rx is enhanced. Upon detection of a signal exceeding a certain threshold power level at this operation range, the tracking station will send a control signal to the cooperative target, which switches off the active transponder. An L-band RADAR mode link is then operated. In this second step, the tracking accuracy increases as the time delay associated with the transponder is significantly reduced. This RADAR system can cover tracking ranges down to about 250 km with a better accuracy. The angular accuracy in tracking the position of the cooperative target is also increased due to the increase in the gain of the Tx RADAR antenna.

(iii) **Ka-band Active Transponder**

Once the distance from the target becomes less than 350 km under good weather conditions or 60 km under high rainfall rates, the L-band RADAR system is disconnected. This is done once the Rx input signal exceeds a preset power threshold level. A more accurate Ka-band RADAR system with an active transponder is then operated. Operating at frequencies in the Ka-band offers several advantages such as high accuracy, smaller transmitters, receivers and antennas. In addition, the higher operation frequency allows for smaller duty cycles, so that lower average power levels are required. Along with these benefits, however, there are also some disadvantages such as high attenuation levels due to atmospheric conditions (rain and clouds). However since this RADAR system operates in an atmospheric window frequency range [4, 13] the worst rainfall attenuation is limited to a value of 50 dB. The active transponder for the Ka-band is also more costly and less sensitive than for L-band.

(iv) **Ka-band RADAR**

The final RADAR step consists of disconnecting the Ka-band RADAR system and operating the LADAR system when the RADAR received signal exceeds a new high power threshold. The switching system for the LADAR mode operates automatically taking into consideration climatic changes as well as other losses such as dispersion.

(v) **LADAR with and Active Transponder**

The switching from Ka-band RADAR to a LADAR sub-system is aimed at improving the accuracy of the final step of target tracking.

As the distance between the cooperative target and the tracking base station is reduced to 70 km in clear visibility conditions, the RADAR tracking system is turned off and replaced by the LADAR systems, starting with an active transponder operating in the IR portion of the spectrum. The step is initiated upon receipt of RADAR signal above a certain threshold level indicating that the target is sufficiently close. At this step, IR signals from both the target and the tracking system are exchanged, yielding an effective tracking down to a distance of about 10 km.

(vi) **LADAR**

The final step of the detection and tracking procedure consists of using a (passive) LADAR system (with the transponder disconnected) characterized by the best accuracy. This step is most suited to the last 10 km as the trade-off between resolution and required transmitting power is optimal, as shown in previous papers [1, 2].

6. DISCUSSION

The improvement of the operating range in the proposed method is achieved at the price of electronic circuitry complexity, cost and accuracy. However, our solution enables the use of a relatively light mobile tracking system. Otherwise, excessive power, very costly and bulky RADAR equipments would have been required to achieve the significant operation range of up to 1200 km. In addition excessive LADAR system complexity would have been required to achieve a high tracking accuracy for long distance operation.

A multi-mode RADAR/LADAR cooperative tracking system operating at two different microwave frequency bands and an IR wavelength, in addition to active microwaves and optical transponders provide the optimal operation range and accuracy under line-of-sight and even under the most adverse weather conditions [3, 6]. The main parameters of our proposed system are shown in Table 1.

7. CONCLUSIONS

We have presented a method for enhancing the operation range of cooperative detection and tracking RADAR systems. The proposed system is particularly dedicated for analyzing and improving operation ranges and accuracy, signal to noise ratio and false alarm rate which are significantly improved.

Multimode LADAR/RADAR cooperative tracking systems described in this paper are required for achieving maximum operation range and sufficient angular and distance resolution and accuracy.

It is shown, by simulations and practice that a maximum operation range exceeding 1000 km can be reached only by using the multimode combination of an L-band RADAR system operating at the RADAR band of 1.33 or 1.35 GHz and using an active transponder for extended operation ranges. Only for smaller operation ranges, less than 350 km in favorable propagation conditions one may use a more accurate and compact Ka band RADAR system operating at the atmospheric window around 35 GHz, which at first is operated with an active transponder in order to spare tracking Tx power level and for lower distances the transponder is disconnected.

For the final tracking steps the high accuracy of the LADAR mode is used. First, with an IR transponder which is switched out for the last docking steps of the cooperative target.

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