physics@mit

MEMORANDUM

To: Doug Eardly, Graham Candler

From: Peter Fisher

Subject: An X and K-band radar for ranging during a terminal engagement

Date: July 16, 2018

In any interception, knowing the time to intercept, t_{go}, is essential and requires two measurements: separation distance and closing velocity. This note describes the use of an X or K-band radar that measures range and range-rate during a final head-on terminal engagement. The first section describes the problem, deriving requirements for the radar. The next section shows constructing a radar that meets these requirements may be possible.

1 Range and range-rate during a head-on terminal engagement

A target and interceptor approach each other at a relative speed V =10 km/s. An imaging system on the interceptor will detect evasive maneuvers by the target, best carried out at the last possible instant. The interceptor's response requires knowing t_{go} and its uncertainty to plan responses. In addition, a precise enough measurement of the range-rate may cue an evasive maneuver before the imaging system detects a change in angle.

An X-band radar provides a good starting point. The system needs to operate at 100 km with SNR=10 or better. An target with a 100 g transverse maneuvering capability can move 1 m the the side in 50 ms and during this time, the vehicles close by 0.5 km. The round trip pulse time is 3 μs and this sets a good minimum distance for the radar to operate, so the pulse length is $\tau = 1\mu$ s and the minimum bandwidth is $B = 1$ MHz.

The interceptor will use the radar information for maneuvering, so these measurements must update in a time short compared to the maneuvering time of the interceptor, about 100 ms. If 1μs pulses are sent at $\nu_{sample} = 50$ kHz, then $N_{sample} = 500$ measurements will take place during each 10 ms update. Averaging these samples will reduce the variance by a factor of $\sqrt{500}$.

From [1], the range uncertainty is then,

$$\sigma_R = \frac{c}{4B\sqrt{N_{sample}}\sqrt{SNR}}$$

and the velocity uncertainty is,

$$\sigma_V = \frac{\lambda}{4\tau\sqrt{N_{sample}}\sqrt{SNR}}.$$

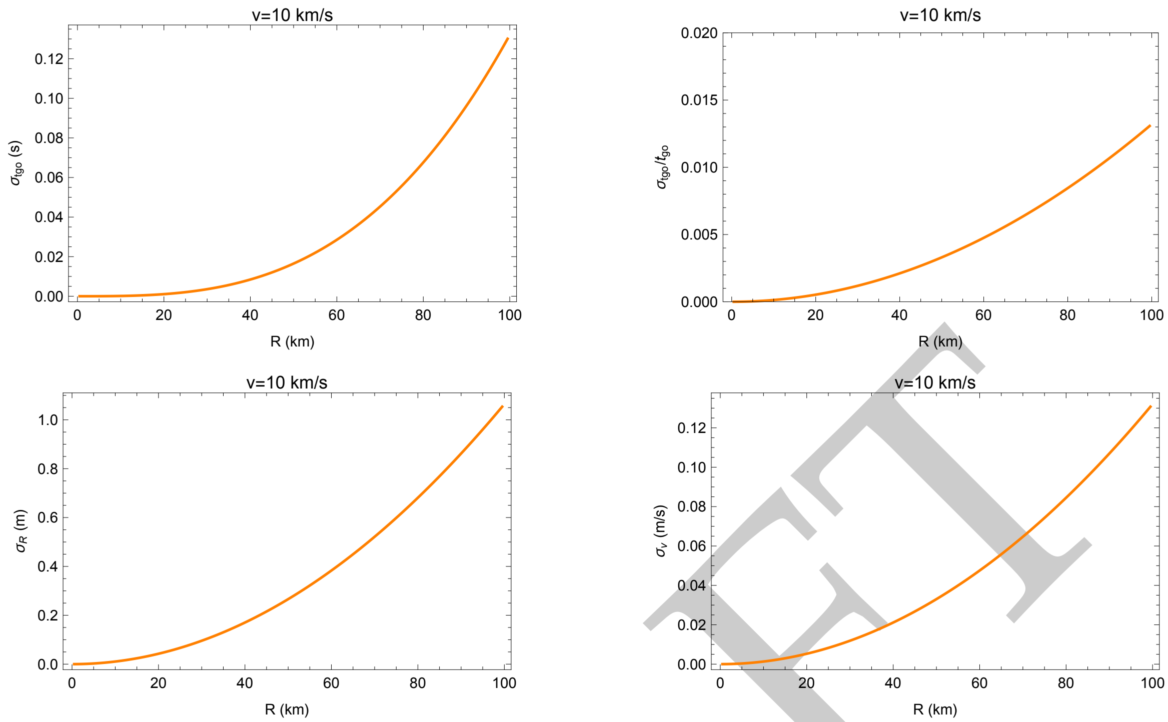

Figure 1: Resolution of t_{go}, fractional resolution for t_{go} and uncertainties in range and range-rate, all as a function of distance.

$t_{go} = R/V$ and with an uncertainty of

$$\sigma_{t_{go}} = t_{go}\sqrt{\left(\frac{\sigma_R}{R}\right)^2 + \left(\frac{\sigma_V}{V}\right)^2}.$$

The returned power varies as R^{-4} and the noise power is fixed, so $SNR\left(R\right) = 10\text{dB}\left(100\text{km}/R\right)^{-4}$.

At 100 km, $\sigma_R = 1$ m, $\sigma_V = 0.13$ km/s, giving $sigma_{t_{go}} = 0.13$ s. Fig. 1 shows the results as a function of time as the vehicles approach. In addition, the velocity uncertainty is always quite small and this could be useful. In the target maneuvers 100 ms out with a 100 g transverse thrust, after 50 ms, the target will have moved 1 m and picked up 50 m/s in transverse velocity and will not longer be traveling directly at the interceptor but at an angle of about $\epsilon = 0.005$ rad. The usual Doppler acquires an additional shift of $-\nu\beta\epsilon^2/2 \sim 100$kHz. This corresponds to a velocity of 0.25 m/s, which is discernible in the ideal case at 100 km.

2 X or K band Radar Requirements

K band radar operating at 27 GHz, $\lambda = 1.1$cm, has the advantage of a narrower beam pattern, but the disadvantage of high absorption in the atmosphere.

The X-band radar needs a transmit power of 100 kW. The radar only needs to operate for 10 s with a 5% duty factor, during which time it will consume 50 kJ. Current SAFT UHP[2] batteries can provide 10 kW/kg, continuous, operating at 60 C. This battery can be used to charge capacitors to be drawn on during the 5% duty factor pulse transmission, so the need batteries will weight less than 1 kg. The dish has a 30 cm radius and an efficiency of $\eta = 50\%$. At 70 km, the radar will illuminate the target with 6.4×10^{-8} W/cm^2. If the target has an RCS of 1 m^2, the return power is 2.9×10^{-15} W, against a thermal noise of 2.7×10^{-16} W if the dish and receiver are cooled to 20 K. This gives SNR=10.

The dish size and need for cooling challenge the size and weight of the interceptor and it would perhaps be good to use a shorter wavelength to decrease the beam spread or allow for small radiating elements.

A K-band radar could achieve the same performance with 40 kW and 20 cm radius dishes.

Kalman filter can also improve performance and will be discussed in a subsequent note.

References

[1] Zmuidzinas, J.,“Radar Sensitivity”, July 20, 2017.

[2] Lewis, N, and J. Vesecky, “Primer on Li-ion batteries”, July 2018.