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CLUTTER SUPPRESSION IN X - BAND RADAR

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RESUME

La bande X est largement employée dans les radars (notamment, radar de poursuite) à cause de ses advantages typiques, en particulier pour les dimensions de l'antenne et les phenomenes de "lobing".

Cependant l'usage de la bande X implique quelque problème quand une suppression elevée du clutter (fouillis) est nécessaire.

Le problème des instabilités des oscilleurs de référence peut etre résolu par un convenable project du "genérateur des frequences".

Le problème des caractéristiques du clutter (la largueur spectrale et la fréquence döppler moyenne) n'a pas une seule, simple solution.

Le projeteur peut choisir parmi quelques solutions differentes, c'est-à-dire la suppression du clutter par un ensemble de filtres döppler (traitement FFT ou DFT) ou par des filtres de reject (MTI adaptatif) on bien par les deux.

En addition, le premier filtrage peut étre fait le long de la balayée (codage "burst") ou bien de balayée à balayée.

Ces solutions peuvent être realizées, de principe, ou avec une grande fréquence de recurrence (PRF) c'est-à-dire avec un systéme "pulse-döppler", ou avec une petite fréquence de recurrence.

Deux projets typiques de système, pour radars de poursuite, sont décris. Dans le cas examiné, la solution avec le MTI adaptatif a été preferée à l'autre, plus compliquée, qui utilize le codage "burst".

SUMMARY

The X-band is widely used in radar (specially tracking radar) because of its inherent advantages, mainly in the field of antenna dimensions and of lobing phenomena.

However, when a high clutter cancellation is required, using X-band implies some problems.

The problem of the instabilities in the reference oscillators can be solved by means of a suitable design of the "frequency generator".

The problem of the clutter characteristics (spectral width and average Doppler frequency) has neither simple nor single solution..

The system designer may choose amongst some different solutions, e.g. clutter suppression by means of a bank of doppler filters (FFT or DFT processing) or by rejection filters (Adaptive MTI) or both.

Moreover, the former filtering can be done along the sweep (burst codes) or sweep-to-sweep. These solutions can be, in principle, implemented either with an high Pulse Repetition Frequency (PRF), i.e. by a Pulse-Doppler approach, or with a low PRF, i.e. with an unambiguous measurement of the range.

Two typical system designs are described for a tracking radar application. In the examined case the solution with unambiguous range measurement and Adaptive MTI has been preferred to another more complicated solution using burst codes.

1. INTRODUCTION

1.1 PURPOSE OF THE WORK

The aim of this paper is to present a general treatment of the clutter suppression problem in X-band (or I-band, according to the most recent designation), going from 8 till 10 GHz.

The field of application is that of both search and tracking radar, in their various utilizations: ground-based or shipborne.

Each utilization can require different techniques to cope with the related problems. However some problems, common to every application, require to devise basic techniques for their omogeneous and global solution.

1.2 USE OF X-BAND IN RADAR: ADVANTAGES AND DISADVANTAGES

The use of X-band in radar arises from a trade-off between operational and technical requirements.

With the reduction of the transmitted wavelength λ it is possible to build lighter and smaller devices, with an equal accuracy of the output data (or more accurate, with equal weights and dimensions), lower dissipated power, greater propagation losses and greater difficulties in the doppler filtering of the clutter.

In the choice of radar frequencies (that span from decimetric waves to millimeter waves) there is a natural trend to put search radar in the range that encompasses X-band (wavelenghts of the order of 3 centimeters) and greater wavelenghts, and to put tracking radar in the range that encompasses X-band and smaller wavelenghts.

Exceptions to this trend are rare and due to very special applications.

Therefore, in X-band can be found many different applications and a strongly developed technology, originating a broad spectrum of devices.

Radar applications of X-band comprise, in particular:

- marine radar for navigation and collision avoidance
- low-coverage search radar
- tracking radar
- illuminator radar for semi-active guidance of missiles
- radar on missiles for active or passive guidance
- instrumental radar

Because of so many applications, a number of ECM (Electronic Counter Measures) devices, specialized for this band, has been built. Therefore, there is an increasing need for the radar designer to take into account the ECCM (Electronic Counter Counter Measures) problem, too.

This paper will only deal with the problems related to X-band search and tracking radar, both in military and civil version and both ground-based and shipborne.

A great part of these problems can be extended to other kind of radar.

The tasks of X-band search radar are the detection and location of "slow" targets, like ships and vessels (whose velocity is near to the one of the clutter) and of "moving" targets, like aircraft and missiles.

In both cases there is the problem of discriminating a target from the clutter and a target from another target, with the maximum probability of detection and of discrimination and with a given probability of false alarm [1] - [4] .

Discriminating "slow" targets from clutter require the exploiting of the different amplitude or shape of the target echo and of the clutter echo.

Discriminating moving targets from clutter require a doppler filtering of the received signals. This problem can be made more difficult by the velocity of the radar platform.

In the case of tracking radar it is necessary to distinguish between the operating modes of autonomous search (if present) and of acquisition/tracking. In the former mode, the visibility problem is quite equal to search radar, but can be more easily solved because of little angular dimensions of the antenna main beam.

In the acquisition and tracking modes the main difference (with respect to search radar) is the need to perform search only in the spatial region in which there is the target (acquisition) and to keep the lock-on even in the presence of strong clutter echoes (tracking).

2. CLUTTER SUPPRESSION PROBLEMS DUE TO THE USE OF X-BAND; POSSIBLE SOLUTIONS

The strong reflectivity of clutter at the X-band frequencies makes rather problematical the visibility of targets in a clutter environment.

With reference to the very significant case of rain, the radar cross section of an uniformely distributed rain clutter is:

$$A = \eta \frac{c\tau}{2} \theta_A \theta_E R^2$$

with

η = reflectivity ($\frac{m^2}{m^3}$)

$c\tau/2$ = pulse length (in terms of distance)

θ_A, θ_E = antenna beamwidth (in azimuth and elevation, respectively)

R = slant range

For a X-band radar with a pulse length of 0.5 μs and with $\theta_A = \theta_E$ = 2.2°, at R = 20 Km a rainfall rate of 6 mm/hr generates an echo nearly 15 dB stronger than the one of a 1 square meter target.

Obviously such a difference increases with range (more exactly, by 6 dB/octave).

To reduce A it is theoretically possible to act on θ_A, θ_E, τ .

In practical cases, θ_A and θ_E are strongly bound by other requirements (e.g. by antenna dimensions) and therefore it is only possible to act on the pulselength.

Instead of merely reducing τ , and, then, the transmitted power, it is often convenient to use the "pulse compression" technique [5] , [6] . A greater degree of sophistication is implied by this technique, that allow to obtain range resolutions and levels of distributed clutter nearly equal to the ones obtainable with a pulselength equal to τ/K , where K (usually much greater than the unity) is the "compression ratio". The related improvement, usually, is not enough, and sophisticated signal processing techniques are generally needed to bring the clutter back to harmless levels.

Such techniques are based upon the doppler filtering principle, i.e. on the very fact that clutter spectrum normally occupies a different frequency band, and anyway a much narrower one, than concerning targets (aircraft, missiles).

A doppler filter for clutter suppression is basically an high-pass filter (MTI: Moving Target Indicator) and its simplest version is the one of the "single canceller". It is based on the following algorithm:

$$y_K(n) = x_K(n) - x_K(n-1) \qquad (1)$$

where $x_K(n)$ is the MTI canceller input at the K-th range cell and at the n-th sweep, and $y_K(n)$ is the pertaining output.

A more widely used version is the "double canceller", whose algorithm is:

$$y_K(n) = x_K(n) - 2\,x_K(n-1) + x_K(n-2)$$

Both input and output are complex quantities, and therefore it is absolutely necessary, when clutter is present, that amplitude and phase of $\underline{x}$ should not be distorted.

The requirement of amplitude stability generally neither leads to special implementation problems nor has direct connections with the transmitted frequency.

On the other hand, the requirement of phase stability is a more difficult problem with increasing frequency. As a matter of fact, in the first down-conversion of the superheterodyne receiver the signal is mixed with an RF local oscillator (the RF STALO) whose frequency must be extremely stable during the whole cancellation time. In the opposite case there is, between two successive received pulses, a r.m.s. phase difference given by:

$$\sigma_\varphi = 2\pi\sigma_{fs} T$$

where T is the elapsed time between transmitted and received pulses and σ_{fs} is the r.m.s. variation of the STALO frequency during a pulse repetition period. The r.m.s. phase difference σ_φ would limit the Improvement Factor (defined as the reciprocal of the clutter attenuation between the input and the output of the MTI, when the latter has an unitary gain on white noise) to:

$$I \simeq \sigma_\varphi^{-1} \qquad (2)$$

As an example, for an X-band radar in which the Improvement Factor must not be degraded below 35 dB by the STALO instabilities, it is possible to accept (for a time period n/PRF where n is the order of the MTI canceller) an instability that, for T = 350 μs, is nearly equal to:

$$\sigma_{fs} = 8\ \text{Hz}$$

In the X-band ($\lambda \simeq 0.033$ m) the related instability is of the order of 10^{-9}, i.e. a very stringent value.

A further, not smaller problem is due to the mean doppler frequency of the clutter spectrum and to the spectral width at high transmitted frequencies.

Such a width is usually given in terms of the standard deviation σ_c of the spectrum.

With a steady antenna, σ_c is given by:

$$\sigma_c = \frac{2\sigma_v}{\lambda} \qquad (3)$$

where σ_v is the standard deviation of the velocity spectrum.

The Improvement Factor, apart from the dependance on the kind of canceller, increases with the ratio between the pulse repetition frequency and σ_c and therefore increases with λ.

The average doppler frequency, i.e. the centroid of the clutter spectrum, is:

$$f_c = \frac{2V_R}{\lambda} \qquad (4)$$

where V_R is the radial component of the relative velocity between clutter and radar.

In the case of X-band ($\lambda \simeq 0.033$ m) typical values are [3] :

σ_v = 2.5 m/s (rain clutter)

V_R = 0 ÷ 25 m/s (shipborne radar with a platform speed up to 50 knots)

By introducing them in relationships (3) and (4) we have:

σ_c = 150 Hz

f_c = 0 ÷ 1500 Hz

Even in the more favourable case of a fixed radar platform it is easy to have, because of the wind, rain clutters with a central frequency up to 300 Hz (in X-band).

From relationship (2) and from previous considerations it results that high Improvement Factors can only be achieved by:

a) the use of ultra-stable STALO's ;

b) the use of high pulse repetition frequencies in order to cope with the broad spectrum of the clutter and, whenever possible, to the (different from zero) average doppler (or "carrier");

c) suitably filtering the clutter with carrier.

The latter method can be implemented by various techniques. In this paper will be mentioned the techniques of non-coherent adaptive MTI and of coherent adaptive MTI or special coherent filtering.

A "non-coherent MTI" receiver has a simple envelope detector before the canceller.

The cancellation algorithm is always represented by (1) (with obvious extension to multiple cancellers) except that the involved quantities are real.

A single isolated echo has constant amplitude and is cancelled (apart from its possible amplitude fluctuations) whereas superimposion of two echoes with different doppler frequencies (typically: a steady clutter and a moving target) implies an amplitude modulation that may pass through the canceller (unless the relative phase has unfavourable values, or "blind phases").

There have been studies to overcome the missed capability of detecting targets "in the clear" i.e. without clutter, by the injection, in non-coherent MTI receivers, of a synthetized steady clutter ("pseudo-non-coherent MTI").

A coherent MTI receiver makes use of the phase information by means of suitable reference oscillators. The phase-detected signals are sent to the canceller, that, as previously mentioned, can be of the adaptive kind [7] , [8] , [9] . When the coherent MTI is adaptive the center of the canceller stop-band is automatically locked to the average doppler. The required stop-band for an adaptive canceller only depends on σ_c and is, then, much narrower than in a high pulse-repetition-frequency system (pulse-doppler radar) with fixed (non-adaptive) MTI.

An open-loop adaptive MTI can be implemented by putting a "rephaser", i.e. a digital mixer, before a conventional canceller. The digital mixer eliminates the effect of average doppler by multiplicating the complex clutter sample by a suitable phasor.

Average doppler is obtained by a proper estimator (see figure 1).

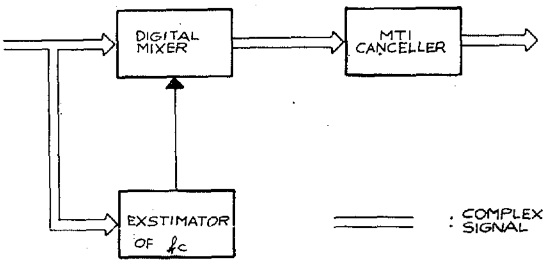


FIG. 1 - Open-loop adaptive MTI

Finally, it is worthwhile to remark that even more advanced processings (than MTI canceller) are being introduced today for the coherent doppler filtering. They are based on Fourier transform (DFT and FFT) with which the optimum filter for the detection of targets in clutter can be more closely approximated [10] .

For radar that are not ambiguous in range, a very promising processor is the MTD [11] , based on a bank of doppler filters and a staggered pulse-repetition-frequency.

The case of "pulse-doppler" radar, however, is the one where FFT results most advantageous, due to the large number of samples (pulses in the beamwidth); with a suitably weighted FFT and the suppression of some filters of the bank it is possible to obtain a quite good Improvement Factor [12] .

FFT or DFT - based filtering require the coherence of the signal (and, then, the constance of the frequency) during the whole time of the transform or, in other words, for a number of pulses equal to the DFT size.

In military applications, this requirement is against the need for changing the transmitted frequency as often as possible for ECCM reasons.

On the other hand, in civil radar nothing, apart from a greater complexity of implementation, is against the use of those techniques, that showed significant advantages even in the practical and experimental field.

3. COHERENT CANCELLATION OF CLUTTER: APPROACH TO THE PROBLEM

3.1 GENERAL

The requirement of having very stable oscillators, of ensuring the cancellation of clutter beyond the radar unambiguous range, of fast changing with no limit the transmission frequency and of using high repetition frequencies can only be met with coherent transmission systems.

These systems employ an assembly with a set of crystal oscillators. The oscillators work at rather low frequency, are very stable and can be selected with switching times of the order of microseconds.

The output from the oscillators assembly is a continuous wave signal provided by the selected crystal: this signal is frequency-multiplied, modulated according to the transmitted waveform shaping and coherently power-amplified.

The coherent amplification preserves the input signal frequency and retains a fixed phase relation between the output and the input signals.

Usually the final power amplifier is a TWT (Travelling - Wave - Tube) that is well suitable for these applications, accounting of its wide instantaneous bandwidth, its good stability and its high gain.

The transmission signal is obtained by the local oscillator (STALO) RF signal by mixing the latter with a reference oscillator (COHO).

The COHO is also used for the phase detection of received signals.

Such coherent chain is outlined in figure 2.

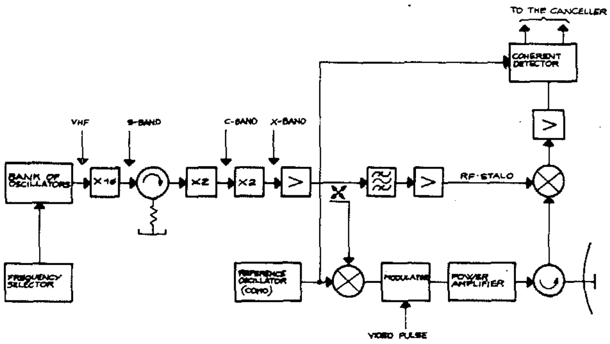


FIG. 2 - Coherent chain

Many kinds of cancellation techniques can be implemented with this schematic.

The most significative techniques are herein described; they are:

a) "pulse doppler" technique;
b) "hybrid coding of transmitted pulses" technique;
c) "adaptive MTI" technique.

3.2 "PULSE DOPPLER" TECHNIQUE

This technique implies the transmission of low repetition period pulses.

With reference to previous paragraph 2, such technique allows to have a very high Improvement Factor, to reach a very wide MTI cancellation notch (while remaining narrow if referred to the pass band) and to obtain good oscillator stabilities also after many transmitted pulses.

The high Improvement Factor makes attractive this technique wherever detection of small targets is required in intensive clutter environment.

The wide MTI cancellation notch also allows the suppression of moving clutter (that is clutter with a speed much smaller than targets speed, as rain, clouds or chaff supported by wind) or of clutter, as seen by a moving platform, or of clutter having a wide spectrum, due to internal turbolence.

As a special matter, there is the opportunity to have a drastic cancellation of clutter as received by a moving radar through its antenna side lobes or through the unwanted reflections of surrounding structures.

In such cases the clutter has different carrier frequencies according to the angle between the echo direction and the radar movement direction.

When clutter is received by many lobes or reflected by many structures, the radar receives many echoes having different doppler frequencies.

The possibility of maintaining the required oscillators stability during many transmitted pulses allows the realization of multiple MTI cancellers.

With such cancellers the suppression notch may be so shaped to enhance the output "signal to clutter residues" ratio.

If the radar radiates with an high repetition frequency, a rather high number of pulses are received during the time on target.

This characteristics reduces the unavoidable correlation of clutter residues and noise, that is typical of multiple MTI cancellers, and allows the transmission frequency to change during the time on target.

This last feature protects the radar against random or wanted interferences and enhances the clutter decorrelation so providing a better visibility of targets in clutter environment.

Practically an high clutter cancellation and a partial frequency agility can be simultaneously obtained.

Pulse doppler technique has its drawback in the short unambiguous range due to the small repetition period of transmitted pulses.

As a result this technique is well suited to short range radar.

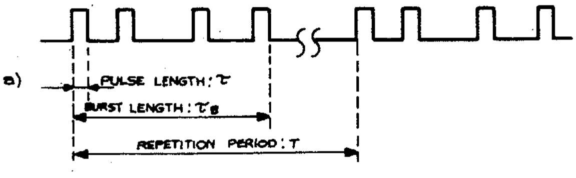
However the range ambiguities can be removed with a programmed change of the repetition frequency.

Although theoretically valid, this possibility has some limitations because more targets in the same direction could not be rightly allocated in range and the radar can have "missed visibility rings" that arise when far and weak targets are overimposed to close-in strong clutter.

3.3 THE "HYBRID CODE" TECHNIQUE

With this technique the transmitted waveform is a burst of close-in, not contiguous pulses.

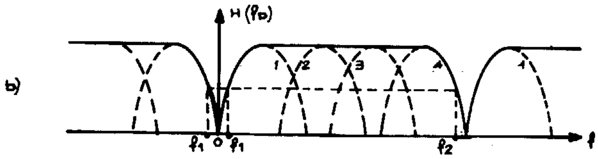
This waveform is radiated with a relatively high repetition period (see fig. 3a).



a) EXAMPLE OF TIMING OF THE TRANSMITTED SEQUENCE

FIG. 3 - The burst code

On reception a coherent cancellation is made among the the pulses of the same burst (see fig. 3b) in a compression filter matched to the burst.



b) EXAMPLE OF DOPPLER RESPONSE (f_1 > MAXIMUM DOPPLER OF CLUTTER; f_2 > MAXIMUM DOPPLER OF TARGETS)

FIG. 3 - The burst code

Then, no coherence is required among the pulses of different bursts: as a result the transmission frequency can be changed on a burst-to-burst basis with no limitation.

In such manner a true "sweep-to-sweep" frequency agility is obtained and this is a very effective ECCM feature.

At the same time there is no range ambiguity (maximum unambiguous range is related to the spacing between two bursts) and a good clutter cancellation is achieved.

The obtainable cancellation is related to the selected kind of burst and grows up with the number of pulses inside the burst.

However "priviledged" sequence can be found so that the detection probability of range side lobes from clutter or targets is negligible and at the same time a good doppler filtering is obtainable.

As a matter of fact, sequences of this kind allow to have a strong cancellation of any clutter (whichever is its frequency doppler) and a quite flat frequency response on useful targets.

But a satisfactory response requires a limitation to the number of pulses inside each burst.

As a result it is difficult to reach Improvement Factor better than 15 or 20 dB. However a very low false alarm probability on clutter residues can be ensured with an hard limiting of the received signal before their decoding.

The subclutter visibility can be enhanced by a frequency or phase pulse compression in each pulse of the burst.

This technique has the singular advantage to provide a good anticlutter device having at the same time a very sophisticated antijamming (ECCM) capability.

3.4 "ADAPTIVE MTI" TECHNIQUE

This technique is, theoretically, simpler of all other techniques.

The radar pulses, coherently radiated at low repetition frequency, are sent in a single or multiple MTI canceller.

The carrier doppler frequency of the clutter is evaluated by multiplying and averaging the clutter complex signal in each range bin with the same signal at the next sweep.

The frequency shift of the clutter spectrum is carried out in a "digital mixer" (see fig. 1) based on a complex multiplier.

The radar can operate at its own repetition frequency, in order to achieve the required unambiguous range, and radiates single pulses.

The MTI Improvement Factor is related to the clutter spectrum width and to the radar repetition frequency.

The "adaptive MTI" technique is mainly effective when the clutter spectrum has only one carrier.

If the clutter spectrum has many carriers, the MTI performance is reduced:to avoid this drawback a device allowing a multiple adaptivity must be envisaged.

Such a device is thinkable but it is very sophisticated.

4. SYSTEM SOLUTIONS FOR X - BAND TRACKING RADAR

In the following two implementations for X-band tracking radar are envisaged (radar A and B).

Both of them provide strong clutter cancellation, high Improvement Factor, good interference resistance and extended unambiguous range.

4.1 RADAR A

The radar is splitted in two receiving channels: a "slow" channel and a "fast" channel.

Each channel operates in different half band of the X-band (see figure 4).

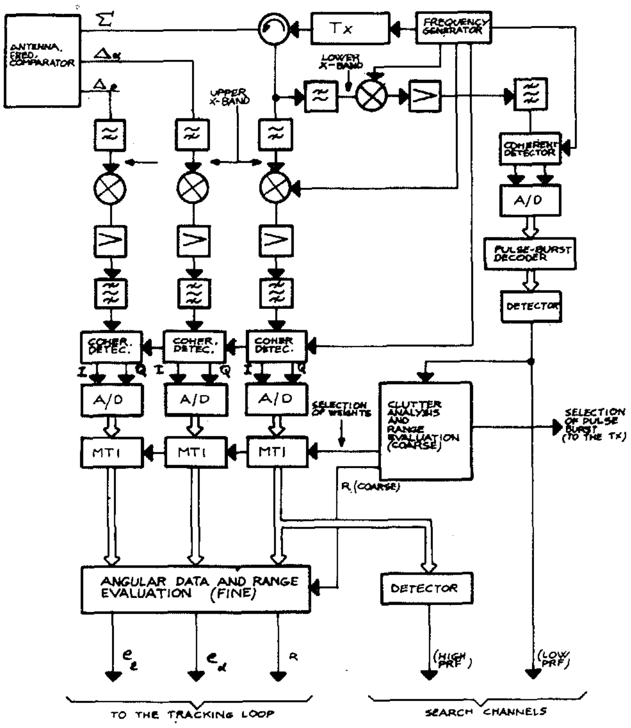


FIG. 4 - Block diagram of radar "A" (double conversion, AGC and range loops not shown)

Only a single transmitter and a single antenna are provided. Both of them have a wide instantaneous bandwith and can simultaneously operate at two different frequencies, each concerning one receiving channel.

The radiated waveform, as associated to the "slow" channel, is based on the "hybrid code" technique; the waveform associated to the "fast" channel is based on the "pulse doppler" technique.

When the radar operates in the search or acquisition phases both "slow" and "fast" channels are employed.

The "slow" channel, that is characterized by an higher average power, has the searching task on long distances where the clutter is lower; the "fast" channel has the searching task on nearby targets overimposed to the surrounding clutter.

During the tracking phase on a well defined target the angular coordinates are extracted by the "fast" channel: the range ambiguities, if any, are solved by the "slow" channel.

Then the two channels are strictly correlated and their operation is controlled by a suitable processor.

In addition the "slow" channel analyzes the clutter distribution along the target direction and evaluates the target radial speed.

These data are used by the radar processor to select the pulse repetition frequency of the "fast" channel.

With this approach the "missed visibility rings" are avoided and the canceller speed response is well matched to the target speed, so allowing also a speed preselection on all possible echoes.

4.2 RADAR B

The radar (see figure 5) is characterized by a "long range" mode, with an adaptive MTI and no range ambiguity, and by a "short range" mode, with high repetition frequency and pulse doppler MTI. These modes are alternative each other.

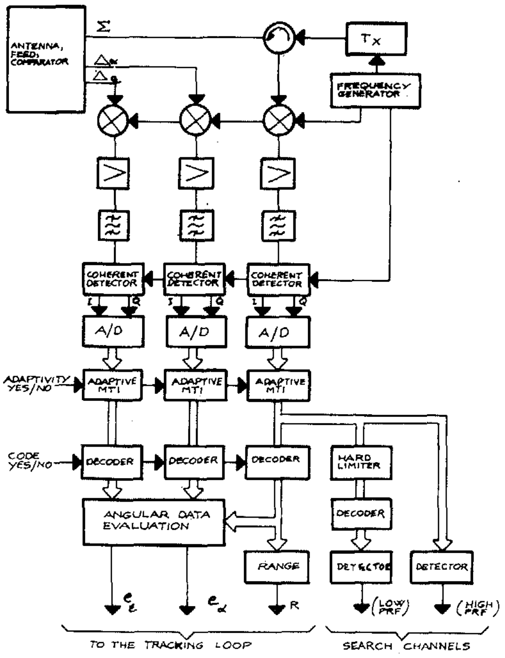


FIG. 5 - Block diagram of radar "B" (double conversion AGC and range loops not shown)

The radiated waveform in the "long range" mode employs the pulse compression (in phase or frequency) in order to reduce the clutter cell and to make use of a TWT Transmitter with little peak power. In the "short range" mode the radiated waveform is based on single pulses.

The transmitter is quite similar to the one of radar A, while the receiver is simpler and consists of three conventional monopulse channels, used both in "long range" and in "short range" modes.

The monopulse channels are identical with the only exception of a duplexer on the "sum" channel.

The radar video processor treats:

a) the sum channel signal, in all the radar range, during the search and acquisition phases;

b) the three monopulse channels signals, in a range gate allocated around the target range, during the tracking phase.

In each phase an MTI processing is provided to allow the detection of targets flying at low altitude in clutter environment.

When the "long range" mode is used the speed response of the MTI canceller is shown in fig. 6 (remind that, due to the adaptivity, the Improvement Factor is always related to a clutter spectrum allocated around the zero speed, whichever is the relative clutter-radar speed).

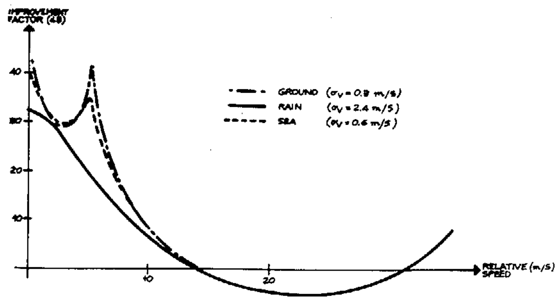


FIG. 6 - Improvement factor vs velocity (adaptive MTI)

As shown in figure 6, this MTI (not recursive- four pulses type) allows to have Improvement Factors greater than 35 dB for the sea and than 40 dB for the land, if the adaptivity is included.

On the contrary, without the adaptivity, just a 10 m/sec relative speed should almost nullify the MTI cancellation.

The adaptivity is specially effective because of the low probability of having clutter with different carriers in the same elementary cell, due to the small size of this cell.

The "short range" mode can be also used in all the radar operating phases. It is characterized by:

a) high pulse repetition frequency (about ten KHz);
b) small unambiguous range;
c) short transmitted pulses.

The "short range" mode is selected for close-in targets when higher cancellation and enhanced range resolution are required.

As far as the clutter cancellation is concerned, the high pulse repetition frequency allows to employ the "pulse doppler" technique with a fixed (not adaptive) MTI.

In fact the MTI canceller notch is wide enough to include the ship motion effect, the ring-around effect (due to clutter echoes received through the antenna side lobes) and the clutter spectrum spreading due to the wind.

The MTI Improvement Factor in the "short range" mode, as referred to the relative speed, is shown in fig. 7.

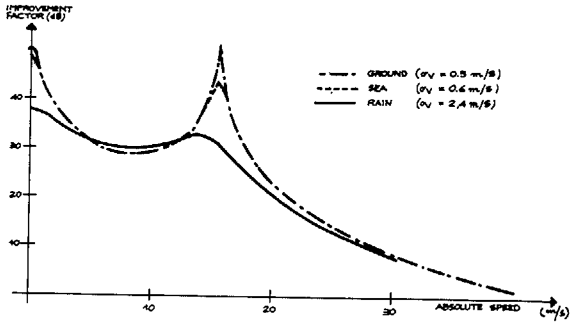


FIG. 7 - Improvement factor vs velocity (fixed MTI, high PRF)

The tracking of targets can be carried out either with the "long range" or the "short range" mode, according to the target distance.

In such a way the operation is optimized with no need of any trade-off.

5. CONCLUSIONS

An effective clutter suppression in the X-band radar requires special, advanced solutions.

Many techniques can be envisaged : all of them impose the employment of high stability devices.

The choice of the most suitable technique depends on the required application.

After an examination of the most advanced MTI techniques, a solution (B) for a shipborne tracking radar has been suggested.

This solution ensures high performances in every operational condition, with no need for bulky or complicated circuitries.

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