3D location by continuous-wave radar

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> *"A failure will not appear until a*
> *unit has passed final inspection*
> *Arthur Bloch*

Most modern radar systems are based on the principle of "energy concentration in the beam" as most generally formulated by Aksel Berg. A man with a flashlight in an attempt to see and hold a night butterfly in the beam does just that. The more powerful the lamp in the flashlight and the better the reflector, the greater the range of detection, and the successful target tracking will be determined by the skill of the flashlight. But it is still dark around and you need to use other flashlights to orient yourself to the situation. There are more and more beams, and flashlights are varied, specialized, complex, expensive and require skilled operators. There is no comprehensive 3D picture of the radar coverage area, i.e. it is impossible to get an answer for any point in space at any arbitrary moment of time: the target is here or not, its speed, type, etc. And there is clearly not enough of a flashlight that evenly illuminates the area. Of course, this statement is primarily true for detecting low-visibility targets.

However, at the very dawn of radiolocation, Pavel Oshchepkov proposed the idea of developing continuous radiation systems with a promising requirement: "one measurement – one frame". At the beginning of his work (1934!) the officially confirmed detection of an all-wood plane at a range of 70 km (!) at 200 W of transmitter power was obtained. It is amazing, but already in the first device, the noise generated by the nearby powerful transmitter (signal of which was used also as a heterodyne signal) was eliminated by separating the transmitting and receiving nodes. Then, after such a success, in the best traditions of domestic absurdity, the outstanding engineer was imprisoned, and ten years were lost. He himself never returned to the radar subject and showed remarkable achievements in other fields of science.

I will allow myself to extend his author's requirement: "one measurement – one frame", taking into account the capabilities of modern computation technologies. Oshchepkov's thought can be reformulated as follows: for all (NB!) voxels of the controlled hemisphere, the radar brightness value should update with any desired frequency.

At first glance, these are prohibitive requirements, stemming from a rather crazy idea. The only justification can be the successful implementation of the project.

Fortunately, such a project exists "in metal" and has worked splendidly for decades.

Fig. 1. Illustration of global positioning systems operation (picture from radionavi.ru)

Of course, we are talking about global navigation systems, which determine the location of the receiver, and the transmitters are in known coordinates. The receiver can get its coordinates at any point of the controlled space at any time. If you "invert the system", i.e. replace transmitters with receivers and vice versa, you can continuously get the coordinates of the moving transmitter. There is very little left to do: replace the transmitter signal with the signal reflected from the target. And this is where the problems begin...

So, let there be at least one transmitter in the center of the area controlled by the system. It radiates short pulses with a repetition period of, say, 1 msec. An omnidirectional antenna with radiation "flattened" to the surface is used, its gain in this case will not be higher than 4-5 dB. Receivers (networked) receive the signal from the transmitter and the signal reflected from the target. After the amplitude detector, the digitized signal is stored in memory. The coordinates and heights of the location of the receivers and the transmitter are known with the accuracy determined by the global positioning system.

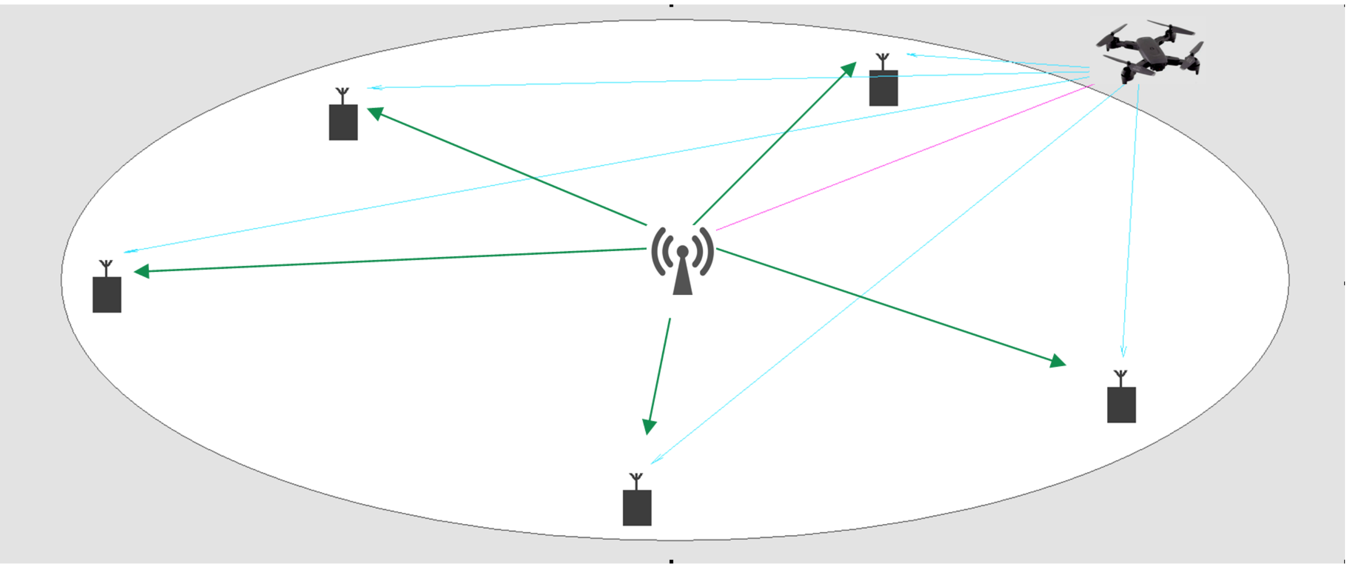

Fig. 2. Location of receivers and transmitter in the monitored area. The target is at the top right. For each receiver there is a triangle (red, green, blue) of RF signal propagation paths, i.e. both the direct signal from the transmitter (green) and the signal reflected from the target (red – blue) are received.

Note: the signal pulse from the target in this scheme cannot be received before the transmitter pulse. Thus, the moment of reception of the transmitter signal becomes a marker from which we can count time and, accordingly, find the distance along the "red-blue" path (the "green" path is known by definition).

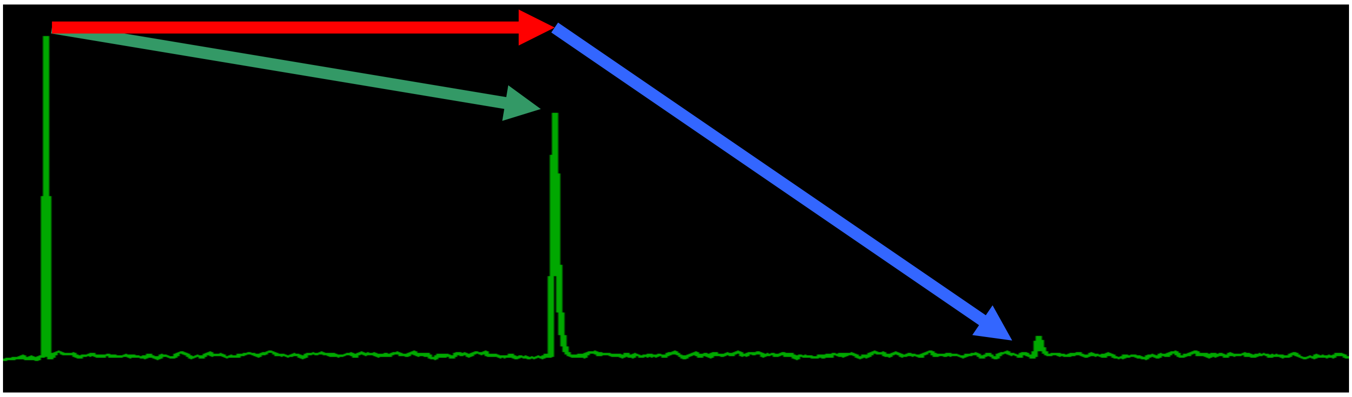

Fig. 3. Expected oscillogram of the location process (model): the moment of radiation – on the left, in the center the moment of receiving the transmitter signal, on the right – reflection from the target. The colors of the arrows correspond to Fig. 2.

To construct the surface of a solid of revolution (SOR) containing all possible "red-blue" trajectories, it is sufficient to apply a simple formula for calculating the cross section radius of such a solid (in contrast to global positioning systems, which operate with the surfaces of spheres). Let us denote the maximal radius of the cross section as H (the target altitude), the distance between the receiver and the transmitter as a, and the ranges to the target as b and c. Then:

$$H=\frac{2\sqrt{P(P-a)(P-b)(P-c)}}{a}, \text{ where } P=\frac{a+b+c}{2}.$$

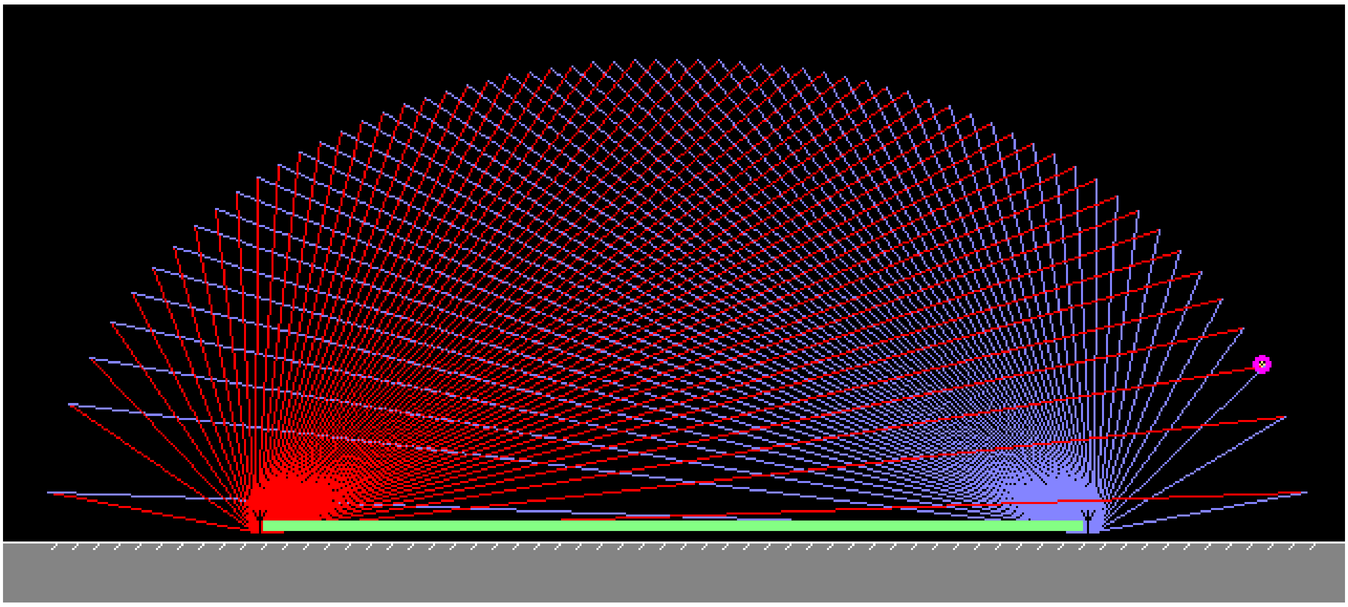

Fig.4. Longitudinal slices of solids of revolution (for equidistant paths). The transmitter on the left, the receiver on the right, the target in the middle on the right, with the green line showing the direct connection between the receiving and transmitting nodes.

Obviously, the target is always on the surface of "its" solid of revolution. All receivers have different such solids. And a single point of intersection of all surfaces will give the exact coordinates of the target (of course, here is full compliance with the GPS algorithms).

Naturally, each target position in latitude-longitude-altitude coordinates (or azimuth, range, elevation angle) corresponds to a time delay (different for each receiver), which can be represented as a recalculation table, i.e. calculated only once at system startup. Therefore, the analysis of the monitored space becomes a low-cost operation in terms of computation, which can easily be performed in real time.

Indeed, for each voxel with x, y, z coordinates, one need only refer to the $M(x,y,z)$ memory location of receiver 1, receiver 2, etc. Then the weighted sum of the signal levels is converted into a radar brightness value. After processing all the voxels will be ready three-dimensional image, updated no more often than the period of pulse repetition of the transmitter.

However, despite the fundamental similarity to the ideology of GPS, such a system is a real lemon and can not work well for two reasons. First: extremely low antenna gain and, as a consequence, the need for a very high transmitter pulse power. Second and main: the underlying surface will give absorptions/reflections much more powerful than the signal from the target. In addition, the multiple re-reflections and multipath propagation of the signal will provide a constant background of a variety of false signals. A target having a small RCS will simply not be visible against their background. In addition: "if signals exist simultaneously and their spectra overlap, then complete separation of signals is impossible" – this basic provision of the theory of information can not be canceled in any way.

It is necessary to find some solution allowing to minimize the contribution of various undesirable effects, i.e. it is necessary to distinguish a useful signal on the background of overreflections, without resorting to coherent accumulation. Otherwise the quote in the epigraph will manifest itself.

Obviously, in our case for the separation of the signal mixture it is necessary that the emitted signal has some time-varying parameters (pilot signal). There must be additional information in the transmitter signal itself about how long ago this signal fragment was emitted. This information must be in the frequency (NB!) domain. The simultaneously arrived signals at the receiver input must have non-overlapping spectra. Such a solution will provide their necessary separation in the time domain. But the pulse mode of the locator is not suitable for solving the problem; it will be necessary to fill all the time of the transmitter with a signal. Anticipating the widespread and categorical objection about the impossibility of long-range location by continuous radiation, we give a simple comparison.

Let there be an overview radar with a power of 1 MW in a pulse with a duration of 1 μsec, a pulse frequency of 1 kHz and a directional antenna, providing a circular view in 1 sec, i.e. 1000 pulses for one revolution of the antenna. Then the energy received by the target in one second will be equal to the energy received from a 1 kW constant-power radar with a circular antenna. The gain of the pulse radar would come exclusively from the gain of the antenna working for reception (since the reflecting surface of the target works as a omnidirectional antenna). But let's not forget about necessary bandwidth of receiver: in first case it is 1 MHz, in second case – 1 Hz. So, in this case (up to an antenna gain value of 60 dB) continuous-wave radars have the formal advantage (due to better signal/noise ratio on receiver output). Significant loss can be only due to noises by a powerful transmitter pumping heterodyne mixer and reflections from the ground, which happens in reality (if there is no distance between the receiving and transmitting nodes).

Let us propose a palliative (at first sight) solution: let the transmitter emit a sequence of orthogonal frequencies in each cycle of operation. Then the radiation mode becomes continuous, and let the sequence of frequency packets repeats with a constant period. Accordingly the issue with the pulse power is solved, because the range of target detection always depends on the average power of the transmitter.

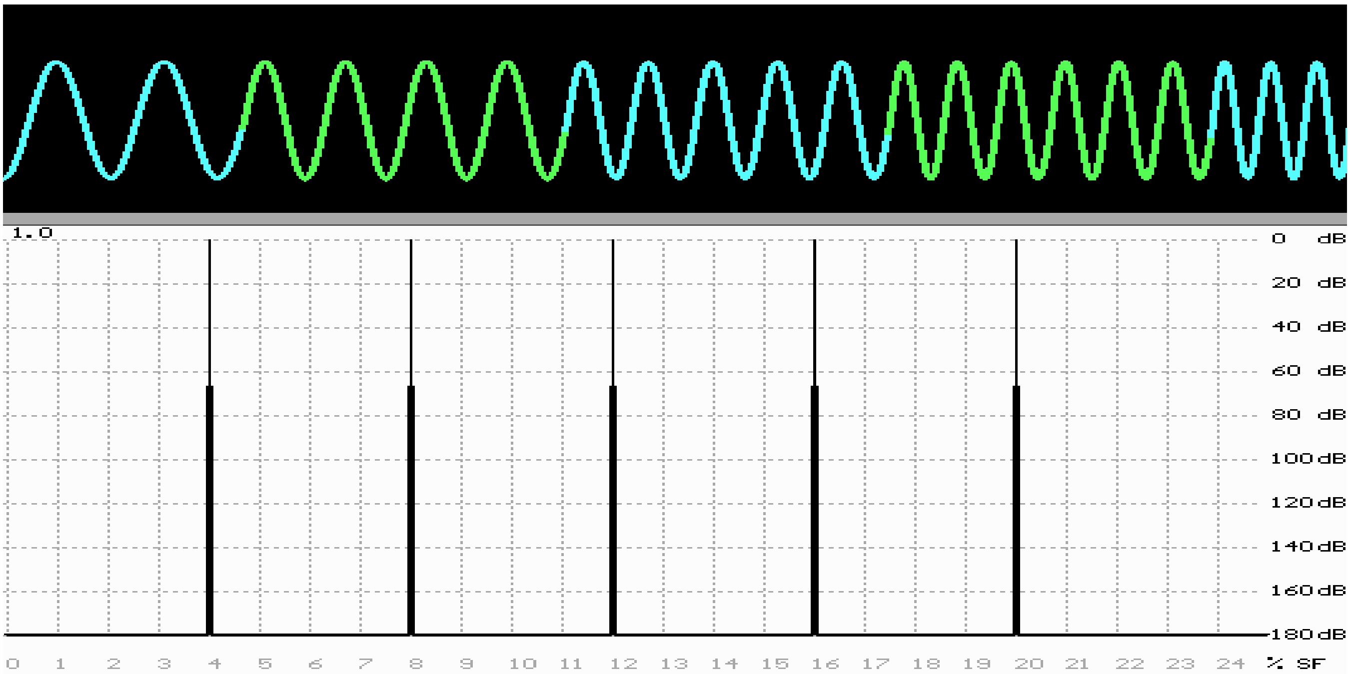

Fig. 5. The sequence of orthogonal frequency packets and its spectrum at full synchronization of data windows in the time domain.

Let us assume that for this signal, under the conditions of separation of its fragments in time, the overlap of spectra is excluded. The main problem remains the same: for any voxel with x, y, z coordinates one must constantly know the radar brightness, which will now be determined by the energy of the main spectral lobe. The time delay for this voxel is known initially. Consequently, we always know what is the frequency of the signal reflected from the target, which is probably at a given location, at a given moment in time.

So, the energy corresponding to the brightness of the voxel arrives at the input of the receiver all the time. The receiver receives a useful signal, and this signal has a delay t_1, which coincides with the one known geometrically. I.e. in a given time interval we receive a signal at frequency f_1 (it corresponds to the current delay), then at frequencies f_2, f_3 ... f_n, and the cycle repeats. Of course, the signal is received continuously at all frequencies, but the choice of frequency for the voxel to be analyzed is determined by the calculated delay. Naturally, the data array for the voxels becomes two-dimensional: the first parameter is the delay value, and the second is the frequency at which this signal is received.

During operation at the input of the receiver there are constantly a lot of reflected and scattered signals with delays that differ from the delay of the useful signal. However, due to the peculiarities of modulation, the frequencies of these signals are always orthogonal to the frequency of the useful signal.

Let’s make sure that the algorithm is correct, and once again check the intersecting hemispheres. There is a hemisphere filled with transmitter radiation. The signal having discretely changing frequency propagates inside it from the center to the surface. There is also a virtual receiver hemisphere, where radial ranges are uniquely related to delays, and each delay corresponds to the frequency at which the signal is received.

The basic geometric theorem states that “the line of intersection of the surfaces of two spheres is a circle”. For hemispheres, only an arc remains of the circle. Note that for all voxels within this arc, the signal will be identical, and the resolution within the arc will only appear when compared to data from other receivers: note here the full consistency with the GPS algorithm.

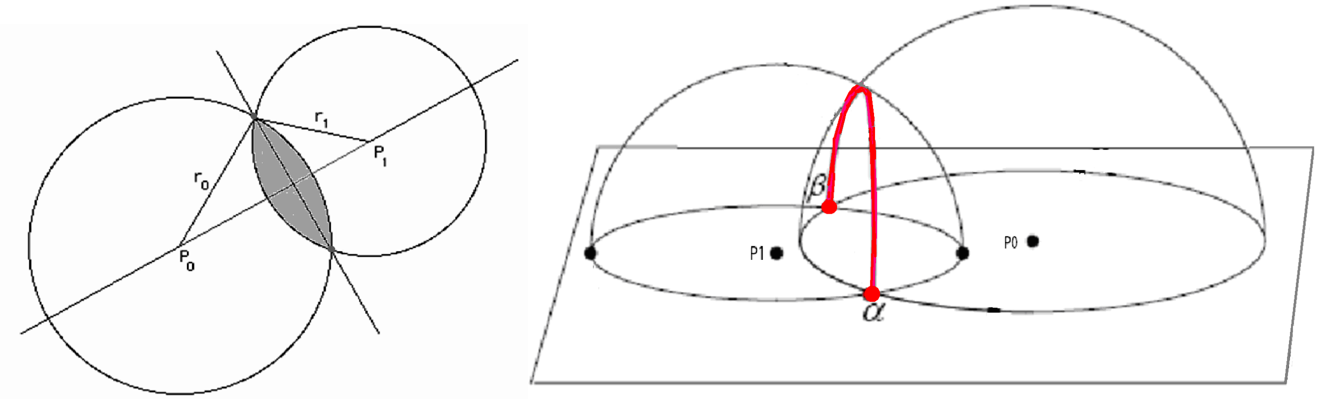

Fig. 5. The radius coincidence conditions are satisfied only for the arc marked in red.

Obviously, reflections from other targets and from the underlying surface, except for the part of the arc of “its” ellipse, where it touches the ground (points “α” and “β” in the figure), must be suppressed by the resolution value of the frequency analyzer. Let us check this statement experimentally: let the interference exceeds the useful signal by 150 dB.

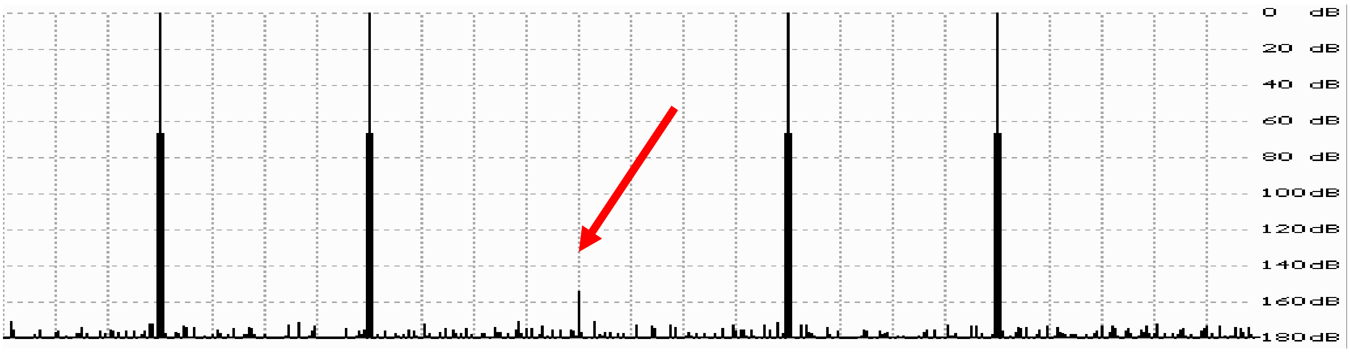

Fig.6. Signal (model) at the output of the spectrum analyzer with 0 dB interference at all orthogonal frequencies, the useful signal -150 dB at frequency F3 (shown by arrow) and ABGS -170 dB. The analyzer's own data window.

The output signal for all receivers, the weighted total voxel brightness is formed in the same way as described above, i.e. the weighting function can be the most varied for the current task – from median filtering to any probabilistic criteria.

Of course, the brightness signal is obtained quantized in time with a frequency determined by the period of change of operating frequencies, i.e. high enough for subsequent recognition of the target by amplitude modulation signal (a turboprop – by beats, a helicopter – directly). If it is possible to install two antennas with orthogonal polarization on the receivers, for each voxel we can get the total and difference amplitude signal (not in the sense of full-scale Jones vector, but as an additional parameter). Then target maneuvers with changes in roll and pitch could be tracked continuously. Target recognition would also improve.

It should be noted that designing such a system will not be easy. For example, Doppler shifts of targets with non-zero radial velocity will have to be compensated for by expanding the main lobe of the spectroanalyzer with an appropriate window (probably Gaussian or Nuttall windows). Also, the chosen voxel size (i.e. the required azimuth, range and elevation resolution) will determine the transmitter signal format, both in terms of duration and the number of orthogonal frequencies used. Moreover, we will probably have to solve the difficult mathematical problem of choosing a frequency set code and cipher to minimize multipath penetration from the underlying surface and intentional interference. However, the successes in the development of OFDM for communication systems in the last decade allow us to express cautious optimism.

Despite the obvious labor intensity of development, such a system will have a definite advantage over the existing three-axis radars.

1. Due to the multistatic layout, the true RCS value of the target will always be determined correctly. Thus, all methods of disinformation about the RCS value are meaningless: neither stealth technology, nor Luneburg lenses, nor even active SAS systems in MALD-type decoys can distort the true value of the target scattering surface (since it is impossible to "serve" receivers located in an unknown place with interference).
2. Given the absence of the need to form a sharp beam, the operating frequency range can be any. Basically, the choice will be determined by the minimum over-reflection from the underlying surface.
3. Selection of moving targets can become two-level: filtering of voxel brightness curve by IIR low-pass filters while matching the cut-off frequency with the spectrum of AM interference from wind effects of vegetation on the ground (this is the first and main stage) will have undoubted advantages over the existing methods. For example, ultra-wideband unmodulated in amplitude noise interference can be compensated in a few seconds.
4. Due to the compactness and low power consumption of the receiver units, they can be placed on the UAV, which will dramatically improve both the range characteristics and the detection of low-flying targets with ultra-low RCS. In this case, there is a good prospect for future fights between UAVs. In addition, the entire system, including the transmitter, will be able to move during operation (of course, only if the geographic coordinates of each element are constantly updated).
5. If one of the receiving units is placed on the interceptor itself, its "silent" approach to the target can be ensured up to the radius of operation of the ARH, and until that point the target's RWR can in no way detect the tracking.
6. Active jamming by the enemy would be difficult, because it would have to be done off-target; in turn, the use of a FHSS in the transmitter signal would further complicate the active jammer operation. Self-covering targets will be complicated by the need to break the code and cipher, otherwise unrealistic jamming power will be required.
7. The use of anti-radar missiles by the enemy can disable the transmitter (which is much cheaper than the missile) only for a short time, during which time the reserve module will turn on and the equipment will restore its functionality. In this case, the absence of a complicated and expensive transmitter sharp-directional antenna increases the survivability of the system.
8. Detecting receivers will be a non-trivial task, and even destroying some of them will only lead to a small drop in resolution, but the system will remain operational. Note that the low cost of the receivers will allow them to be used in large numbers (increasing the sensitivity and resolution of the system).

9. For civilian applications, we can assume that airport controllers are unlikely to refuse a three-dimensional picture, which by the primary (!) location method will allow to see all aircraft in real time. In turn, the receiver of such a system on a civil airliner will make course-glide systems and driving beacons superfluous.

10. The proposed locating algorithm is also suitable for sonar and ultrasonic intrasonic systems, it will undoubtedly work, but here the competence of the author rushes to zero.

Disadvantages: High labor intensity of development and the need for a significant amount of experimental work. Besides the resolution of system has inherent dependence from accuracy of positioning of receiving and transmitting antennas, i.e. at inclusion in work the data of differential GPS will be necessary.