A BISTATIC PARASITICAL RADAR
(BIPAR)

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ABSTRACT

After decades of remote sensing from aircrafts and satellites with cameras and other optical sensors Earth observation by imaging radars become more and more suitable because of their night and day and all weather operations capability and their information content being complementary to those of optical sensors. The major problem with microwave sensors (radars) is that there are not many of them presently in operation and therefore not enough data available for effective radar signature research for civil applications.

This paper shows that airborne bistatic real aperture radar receivers can be operated with spaceborne transmitters of opportunity. Famous candidates for those systems are high power communications or direct TV satellites illuminating the Earth surface with a power density of more than 10^{-12} Watt per squaremeter. The high sophisticated status of signal processing technology today allows the realization of receivers correlating the received direct path signal from a communications satellite with its unavoidable reflection on the ground. Coherent integration can improve the signal to noise ratio up to values where the radiometric resolution can satisfy users needs.

The development of such "parasitical" radar receives could even provide a cost effective way to open up new frequency bands for radar signature research.

Advantages of these quiet systems for the purpose of classical radar reconaissance are evident.

1. INTRODUCTION

Bistatic radars are defined as systems in which spatial separation exists between the transmitting and the receiving radar chain. The fundamental principles of bistatic surveillance radar systems have been known from the beginning of radar history. However, interest in them declined early, doubtless driven by the desire of users, particularly military users, to have radars capable of being operated from a single site. Therefore, up to now, monostatic radars have been developed to a very sophisticated state, whereas bistatic and multistatic radar systems laid dormant for about more than two decades. However, these systems received new interest, when the development of advanced radar processing techniques allowed bistatic radars to deploy their advantages.

2. THE SYSTEM CONCEPT

A BIPAR is a bistatic radar system combining the advantages of spaceborne and airborne imaging radar systems. The transmitter is located in a geostationary orbit with a very low probability of intervention illuminating continuously the area of interest on ground. The quiet receiver is carried on an airborne platform implying a high mission flexibility, high repetition capability and less power requirements compared to a system with spaceborne receivers. It is called "parasitical" because it uses non-radar transmitters of opportunity, such as geostationary communications satellite transmitters or transmitters of direct television satellites. A typical system geometry is shown in figure 1. A geostationary communications or direct TV satellite is transmitting its RF downlink signal to Earth. Within the beam of its downlink antenna it illuminates the Earth surface and a certain portion of the RF energy is unavoidably reflected back into the air. The strength of the reflection depends on the reflection coefficient of the target areas on ground, such as the vegetation canapé, streets, houses, cars and so on.

An aircraft with a BIPAR receiver onboard, flying within the satellite downlink antenna beam picks up these reflections from the ground with a scanning pencil beam radar antenna and provides real aperture radar images of that part of the Earth surface being covered by the BIPAR scan range.

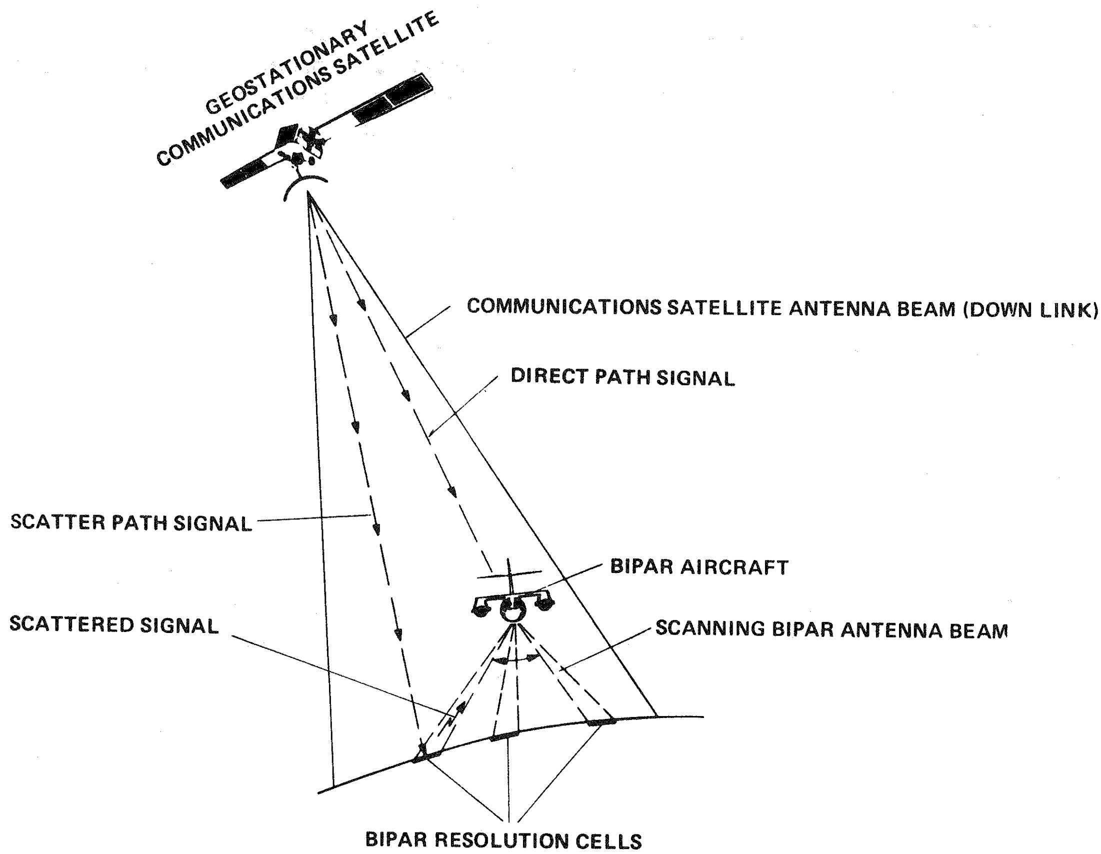

Fig. 1: Typical BIPAR System Geometry

In case of a low downlink transmit power of the satellite resulting in a low power density on ground the received signal reflections are far below the BIPAR receiver noise level. Hence correlation with a known reference and coherent integration is required. The necessary reference signal can be provided by receiving the direct path down link signal with an antenna on top of the aircraft. The differences in doppler shift and round trip delay time can easily be compensated because of its a-priory knowledge, if not-moving targets on Earth were of interest for the users.

The overall block diagram of a BIPAR receiver is shown in figure 2. The scattered signals are received via a scanning pencil beam antenna and routed through the Low Noise Amplifier and the Downconverter, which compensates the doppler shift of the scattered signals. After appropriate gain setting this noisy signal is fed to the coherent detector, where it is correlated with the respective reference signal. The reference signal, received via the telecom antenna on top of the aircraft is routed through a Low Noise Amplifier, a Downconverter compensating its doppler shift, and a variable delay line. The delay line takes care that the reference signal and the scattered signal arrive simultaneously at the detector (correlator) input. After integration, the signal is digitized and routed to the Radar Control Computer. This unit analyses the signals and derives the updates for the gain settings. In parallel, the signals are displayed in terms of a real aperture radar image and stored for further processing on ground. The doppler compensation and delay line control is driven by the Radar Control Unit based on data from the aircraft Position and Attitude Sensor, on information about the satellite position and downlink frequency, and on the actual BIPAR pencil beam orientation.

3. PERFORMANCE CONSIDERATIONS

3.1 Radar Equation

Starting from a given signal power density p on the Earth surface, the received power P_R can be estimated by

$$P_R \approx \frac{p\ G_R\ \lambda^2\ \rho_b\ G_i}{(4\pi)^2\ H^2\ L_p\ L_s} \qquad (1)$$

where G_R is the BIPAR receiver antenna gain, ρ_b is the bistatic radar cross section, G_i is the signal integration gain, λ the wavelength, H the flight altitude, and L_p and L_s are the propagation loss and other system losses.

The antenna gain G_R is a function of the antenna effective area A_R and the radar wavelength.

$$G_R \approx \frac{4\pi\ A_R}{\lambda^2} \qquad (2)$$

The bistatic radar cross section ρ_b can be expressed by

$$\rho_b = \delta_A\ \delta_E\ \sigma_{ob} \qquad (3)$$

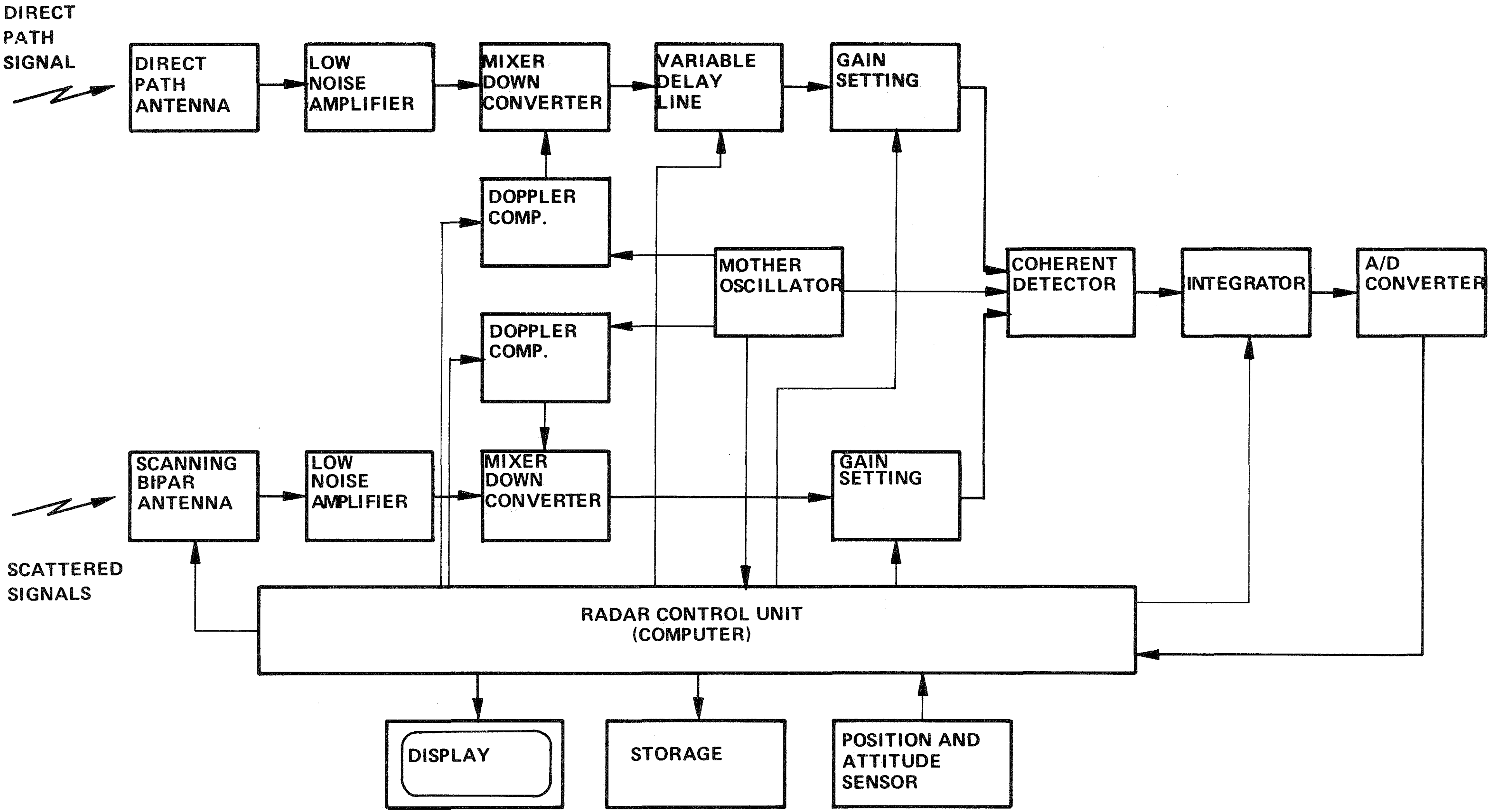

Fig. 2: Block diagram of a BIPAR receiver

and

$$\delta_A \, \delta_E \approx \frac{H^2 \, \lambda^2}{A_R} \tag{4}$$

where δ_A and δ_E are the spatial resolution in azimuth and elevation and σ_{ob} is the normalized bistatic scatter coefficient.

The resulting equation for the received power of a BIPAR system indicates, that this power is moreless independent from the BIPAR pencil beam antenna dimensions and the aircraft flight altitude.

$$P_R \approx \frac{1}{4\pi} \, p \, \lambda^2 \, G_i \, \sigma_{ob} \, \left(\frac{1}{L_p \, L_s}\right) \tag{5}$$

This is due to the fact that changes in flight altitude and in antenna beamwidth implying loss and gain variations are compensated by resolution cell variations being consequently a result of the above changes.

3.2 Spatial Performance

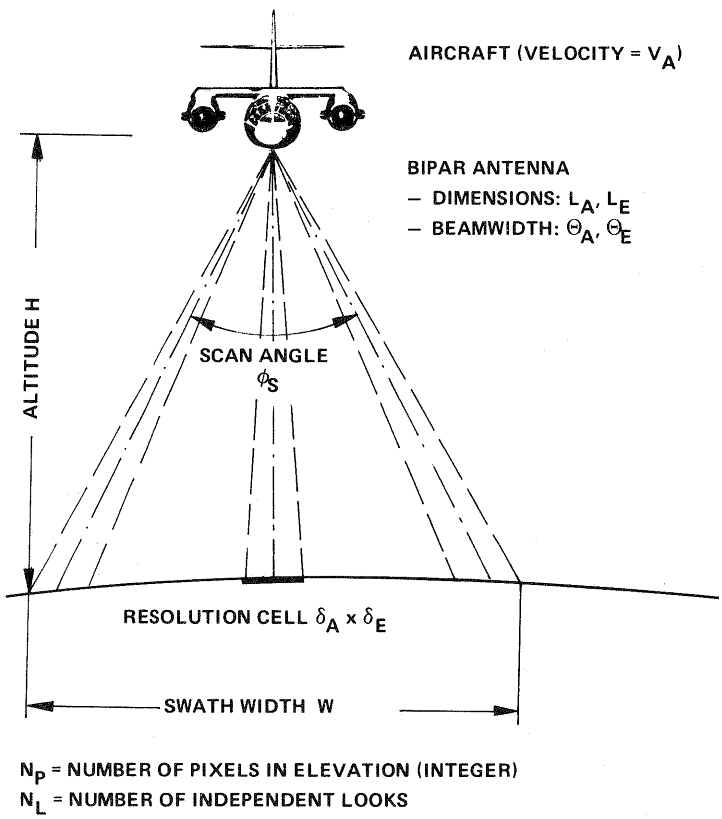

Fig. 3: BIPAR Scan Geometry

The spatial resolution of a real aperture BIPAR system is defined by the beamwidth of the scanning pencil beam antenna (see fig. 3). The nominal value of the spatial resolution in azimuth δ_A (flight direction) and elevation δ_E (perpendicular to flight direction) is defined at a scan angle of 0 degrees.

$$\delta_{A/E} \approx \frac{H \cdot \lambda}{L_{A/E}} \quad \text{(for Nadir)} \tag{6}$$

When the pencil beam is pointed to a outermost edge of the swath the spatial resolution is degraded to

$$\delta_{A_{max}} \approx \frac{H \cdot \lambda}{L_A \cos(\varphi_s/2)} \tag{7}$$

$$\delta_{E_{max}} \approx \frac{H \cdot \lambda}{L_E \cos^n(\varphi_s/2)} \tag{8}$$

where L_A and L_E are the effective antenna dimensions in azimuth and elevation, φ_s is the maximum scan angle between left and right edge of the swath and n is an integer value being n=2 for mechanical and n=3 for electronical scanning of the pencil beam. This difference considers a broadening of the antenna elevation beam toward the swath edges in case of electronical scanning.

The width of the BIPAR swath W is given by

$$W \approx H \left[2 \tan(\varphi_s/2) + \frac{\lambda}{L_E \cos^n(\varphi_s/2)}\right] \tag{9}$$

and the available pixel integration time T_i is defined by

$$T_i \approx \frac{\delta_A}{v_A N_p N_L} \tag{10}$$

with $N_p \approx \left(\frac{\varphi_s + \Theta_E}{\Theta_E}\right)$ and $\Theta_E \approx \frac{\lambda}{L_E}$

where v_A is the aircraft velocity, N_L is the number of independent looks required for improvement of the radiometric resolution, and Θ_E is the antenna elevation beamwidth. The theoretical integration gain is defined by the time-bandwidth product $T_i \cdot B_s$.

3.3 Radiometric System Performance

Applying the time-bandwidth product and the integration efficiency η_i equation 6 can be written as follows:

$$S = P_R \approx \frac{1}{4\pi} \, p \, \lambda^2 \, \sigma_{ob} \, T_i \, B_s \left(\frac{\eta_i}{L_p \, L_s}\right) \tag{11}$$

where S is the received signal power and B_s is the system bandwidth assuming a matched receiver chain.

The system noise power N is defined by

$$N = kT_o\ F_R\ B_s \tag{12}$$

where k is the Bolzmann's constant, T_o is the system temperature and F_R the receiver noise figure.

The radiometric resolution ρ_R of an imaging radar is estimated by

$$\rho_R \approx 1 + \left(\frac{(\frac{S}{N}) + 1}{\sqrt{N_L}\ (\frac{S}{N})}\right) \tag{13}$$

as a function of the number of independent looks N_L and the signal to noise ratio being derived from equation 11 and 12.

4. SYSTEM EXAMPLE

The following example of a feasible system shall indicate the general capabilities of BIPARs.

The transmitter of opportunity could be an ECS-type communications satellite illuminating the Earth surface with a power density of -120 dBW per squaremeter or a direct TV satellite with about 10 times more output power. The transmit frequency is assumed to be about 11 GHz with a bandwidth of 27 MHz.

The BIPAR uses an electronically scanning antenna of 1 m x 1 m effective area with a scanning angle of ± 30 degrees. It flies on an aircraft at 1000 m flight altitude with a velocity of 100 km/h. The scan repetition rate is 1 Hz. It is a step scan with 40 positions within ± 30 degrees. At each beam position 3 independent looks are assumed resulting in an integration time per look of about 8.3 milliseconds. This leads to a coherent integration gain of 52 dB considering an integration efficiency of 70 % due to the noisy scattered signal, its doppler spread of about 30 Hz, and misalignments within the time and doppler compensations.

Typical values for the scatter coefficients might be between -10 dB and +6 dB (one sigma) assuming that there is not much difference between 9.6 GHz and 11 GHz and between bistatic and monostatic systems. Under the umbrella of the German/Italian X-SAR project σ_o values have been researched intensively and these results could be used as a guideline for a preliminary BIPAR performance assessment.

Assuming furthermore a clear air propagation loss of 0.5 dB, a receiver noise figure of 6 dB, and a kTo of -204 dB/Ws, table 1 shows that a signal to noise ratio between 0 dB and 19 dB could be reached. An overall margin of 3 dB for other systems losses is included in this calculation.

Power density (ECS)	-120 dBW/m²
(1/4π)	-11 dB
λ^2	-31.5 dBm²
σ_{ob}	-10 dB thru +6 dB
Integration gain	52 dB
Propagation loss	-0.5 dB
(1/kTo)	204. dBWs
(-) Receiver noise figure	-6 dB
(-) System bandwidth	-74 dB/Hz
System loss margin	-3 dB
Signal to noise ratio	0 dB thru 19 dB

Table 1: Link Calculation

If a direct TV satellite is available as transmitter of opportunity the link budget will typically be improved by about 10 dB.

The performance of this BIPAR system based on ECS is summarized in table 2.

• Spatial resolution	
Nominal:	27 m x 27 m
Worst case at swath edges:	31 m x 41 m
• Swath width	1.2 km
• Signal to noise ratio per look (for a σ_{ob} of -10 dB thru + 6 dB)	0 dB - 19 dB
• Radiometric resolution for 3 looks	2 dB - 3 dB
• Scan repetition rate	1 Hz
• Integration time per look	8 ms
• Number of pixels in elevation	40

Table 2: System Performance

5. CONCLUSION

The objectives of this short paper have been to show that a relatively simple version of a bistatic radar system comprising an airborne real aperture radar receiver operating with the unavoidable ground reflections of geostationary communications satellite downlinks is capable to achieve a satisfactory system performance.

There are several system options under discussion comprising for example a mechanically steered or even fixed pointed antenna. The latter results in a simple 1 pixel system, where the swathwidth is provided by several parallel flights and the signal to noise ratio is improved by 16 dB due to a longer integration time per look.

Another system option is the leasing of one of the satellite transponders during BIPAR operations and the transmission of a cooperatively modulated communications signal. This could reject the need for the reference signal chain within the BIPAR receiver because the structure of the received signal is well known.

Last but not least, arrival time separation (range gating) and synthetic aperture principles (doppler gating) could be applied in order to improve the system performance once again.

All these options are up to further investigations and their viabilities are primarily driven by user requirements and available financial budgets.

Compared to classical monostatic and bistatic radars, it can be concluded that BIPAR systems have the following advantages:

- Low power consumption
- High operational flexibility
- Quiet and secret systems
- Low cost.

BIPAR systems are typically not optimized with respect to radar applications, but they could provide a good compromise between user requirements, their need for a high amount of data, and funds available. BIPARs cannot replace large operational airborne and spaceborne radar systems, but in many cases they can support the scientific research, if no operational system was available.