Sensor and Simulation Notes

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Antennas on Airplanes

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Abstract

There are many possible ways to mount various types of antennas on airplanes. This paper extends previous considerations to include various types of dipole arrays, including combined dipoles ($\vec{p} \times \vec{m}$ antennas), as well as various other wideband antennas suitable for pulse radiation and reception. Discussion is in terms of down looking radar, including SAR, one of various applications of interest.

1. Introduction

An earlier paper [8] has discussed the use of an airframe as an essential part of antennas operating in the HF and VHF bands. While the items added onto the airframe may be small, these are merely the feed or coupling devices to the antenna which is the large airframe itself, especially in the HF band for which the airframe is resonant (one or a few half wavelengths) for typical airplanes. As one increases the frequency so that there are more half wavelengths along the fuselage and wings one can consider the airframe as a platform for mounting an array or antenna elements which can be used to steer, say, a radar beam in transmission and/or reception.

Going yet higher in frequency the airframe significance is less dependent on its natural modes and one goes over to some high-frequency approximation such as the geometrical theory of diffraction (GTD) [20 (Section 1.4.3)]. In this case the portions of the airframe near the antenna elements are most important unless the antenna elements are in shadow regions (in reception). One also needs to be concerned with scattering from other parts of the airframe to the antenna location (e.g., wing to fuselage). This regime of frequencies (say a few 100 MHz to a few GHz) is also appropriate for broadband pulses such as may be used for synthetic-aperture radar (SAR) [26]. In this case one can use transit-time isolation (causality) to separate out this scattering (partial symmetry [24]) so that only the local portion of the airframe is important. One still needs to be concerned with waves scattered by other targets arriving in the time window of interest via such multipaths. Such clutter will need to be removed in the data processing.

For polarimetric radar measurements one needs to consider the question of polarization purity. Polarization can be an important target identifier [16, 19]. The polarization of an aircraft antenna is in general not perfectly horizontal or vertical in the usual radar *h*, *v* coordinates. It can even be frequency dependent and dependent on the direction of incidence (transmission) or equivalently of scattering (reception). To some extent this polarization variation can be removed in data processing if one has two independent polarizations that are well characterized. To the extent possible we would like frequency independent polarization over the frequency band of a pulse of interest. This can be achieved in special cases by the imposition of symmetry on the antennas and the associated platform [12].

So now let us consider various concepts for antennas and arrays of potential use for such radar applications.

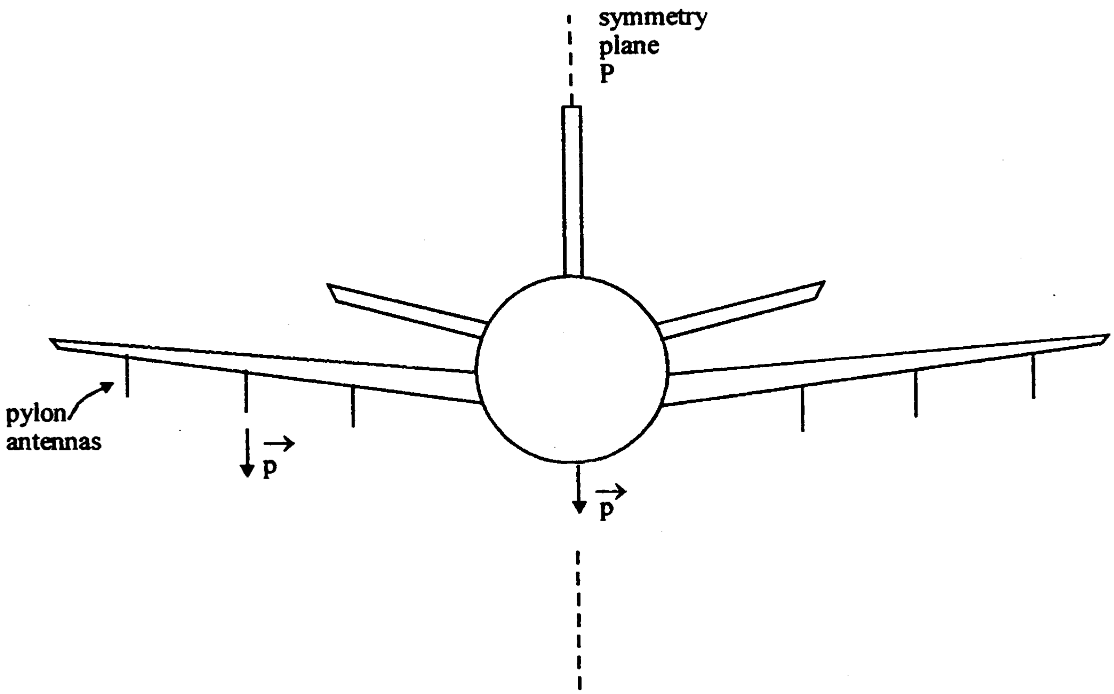
2. Arrays of Equivalent Dipoles on Airframe

In [8] examples of loops (equivalent magnetic dipoles including images in appropriate frequency regime) were given. In that case, each magnetic moment $\vec{m}$ was oriented perpendicular to the symmetry plane P of the airplane. One could have a keel array (ventral array) running a large portion of the fuselage length, and/or a wing array utilizing pylons under the wings. In these configurations minimum disturbance is provided to the airflow. One could also place such arrays on the top of the fuselage (dorsal array) or the tops of the wings, but for a down-looking, radar such would not be appropriate, especially at the higher frequencies. For the polarization properties, scanning fore and aft gives vertical polarization on P (symmetric fields) while scanning to either side gives an approximate horizontal polarization abeam.

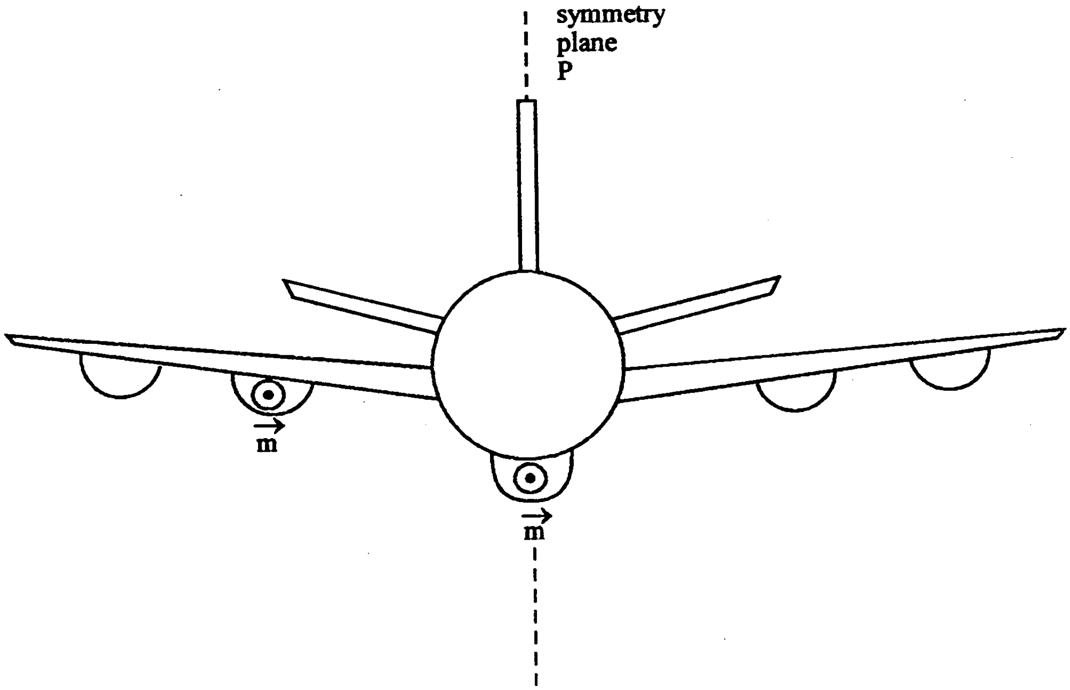
As illustrated in fig. 2.1 other kinds of dipole arrays are possible in these same locations. Figure 2.1A shows the case of electric dipoles vertically oriented. These also need not significantly interfere with the airflow. The ventral antenna array can also be enclosed in a keel-like radome if desired. These equivalent electric dipoles need not be simple whips, but can be bottom loaded by conductors running fore and aft, still retaining the streamlining inside a dielectric cover (radome). For its polarization properties, scanning fore and aft gives vertical polarization on P (symmetric fields). In this case scanning side to side also gives approximate vertical polarization abeam. The pattern, however, has a null directly underneath the airplane.

Figure 2.1B shows the case of magnetic dipoles, now oriented with $\vec{m}$ parallel to P and basically pointing horizontal fore/aft. For the polarization properties scanning fore and aft gives horizontal polarization on P (antisymmetric fields). Scanning side to side give approximate horizontal polarization abeam. The ventral antennas now have greater thickness abeam, but these can be enclosed in a streamlined radome to allow greater loop area, especially for transmission. Under the wings appropriate pylons can also be used. An alternate approach would have the airflow pass through the loops. This has been done successfully previously in the case of an MGL-2 B-dot sensor on the nose pitot boom of a NASA F-106 [3, 17, 18].

So as we can see, there are three possible sets of equivalent dipoles (electric and magnetic) that can be mounted underneath an airplane for radar applications. For signal-to-noise purpose these dipoles may be desired to be large in transmission. In reception smaller may be acceptable. We need not confine ourselves to one of these three types of array elements, but may use combinations. The different types of elements may be located in different places, or may be combined in elements operated to give the various moments separately via separate antenna ports (such as the O3L B-dot sensor [21]), or may give combined dipole moments (such as in a $\vec{p} \times \vec{m}$ antenna [1]).



A. Electric Dipoles



B. Magnetic Dipoles

Fig. 2.1. Arrays of Equivalent Dipoles Under Fuselage and Wing: Front

3. Fore or Aft Magnetic Dipole

An interesting part of locations for antenna placement lie on the symmetry plane fore and aft of the airplane [3, 17, 18, 23]. Originally considered as the locations and orientations for a receiving magnetic-dipole antenna, which is minimally affected by scattering from the airframe, by reciprocity, they apply equally well in transmission.

The basic theory considers dividing the fields into symmetric and antisymmetric parts vis-à-vis the airplane symmetry plane P. The antenna is oriented with $\vec{m}$ parallel to P on P, thereby interacting only with antisymmetric fields and eliminating symmetric scattering such as the fuselage resonances. With remaining degrees of freedom of rotation of $\vec{m}$ parallel to P and movement on P one finds locations P_1 and P_2 in Fig. 3.1 on a path passing through the wing and horizontal-stabilizer projections on P with orientations parallel to this path so as to minimize coupling to antisymmetric scattering from the wings and horizontal stabilizer. Placing the antennas an appropriate distance from the airframe also reduces antisymmetric scattering from the fuselage. If one uses electrical cables to connect the antenna to positions inside the airplane, then a conducting boom is appropriate for mounting the antenna. The end of the boom (at the antenna) is in reception a current minimum, but a charge maximum, thereby being more suitable for a magnetic-dipole antenna than for an electric one (conveniently).

This particular type of antenna is then well suited for an approximately vertically polarized radiator and/or receiver for use with a side-looking radar. The polarization is quite frequency independent. Perhaps by selection of a particular airplane the polarization can be made accurately horizontal, such as in the example in [3, 17, 18].

Note that the derivation leading to these locations and orientations for such an antenna minimized unwanted scattering by the airplane over all frequencies. As such the antenna can be designed to operate over frequency bands extending from wavelengths large compared to the airplane dimensions to wavelengths small compared to such dimensions. It can then also operate in a wideband pulse mode, suitable for ultra-wideband SAR.

An electric-dipole antenna at P_1 or P_2 parallel to P and perpendicular to the boom may still have some interest. However, there is still the symmetric scattering (fuselage, vertical stabilizer) with which to deal. This gives a common mode signal which may be reduced by various techniques such as by not positioning the antenna near the boom tip (charge maximum), use of a transformer or bifilar choke, and use of a choke on the boom itself.

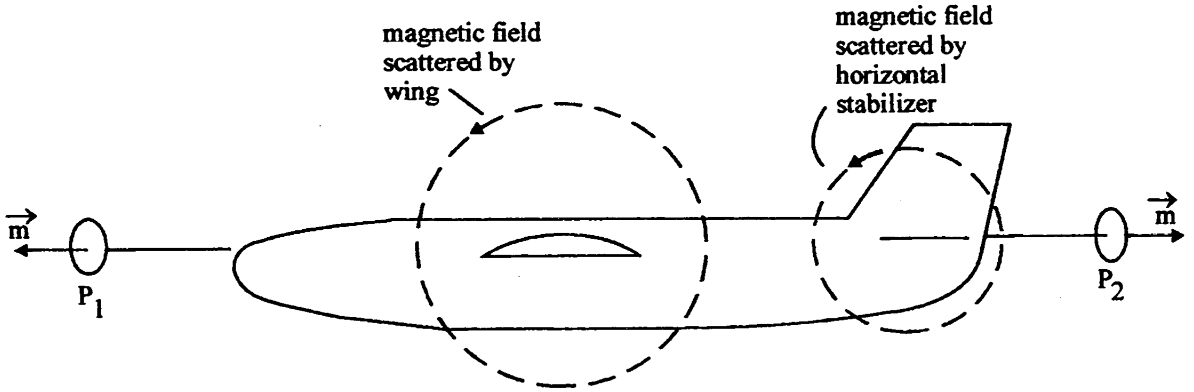


Fig. 3.1. Magnetic-Dipole Antenna Locations and Orientations which Minimize Coupling from Fuselage (Symmetric Scattering) and Wing and Horizontal Stabilitzer (Antisymmetric Scattering).

4. Ventral Combined-Dipole Elements on Symmetry Plane P

An interesting kind of antenna for use with SAR is a kind of combined electric- and magnetic-dipole antenna, also known as a $\vec{p} \times \vec{m}$ antenna [1, 2, 4, 5, 10, 11]. In this case we have electric- and magnetic- dipole moments related by

$$\begin{aligned}
\tilde{\vec{p}}(s) &= \tilde{p}(s)\,\vec{1}_p \quad , \quad \tilde{\vec{m}}(s) = \tilde{m}(s)\,\vec{1}_m \\
\vec{1}_c &= \vec{1}_p \times \vec{1}_m \quad , \quad \vec{1}_p \cdot \vec{1}_m = 0 \\
\tilde{p}(s) &= \frac{\tilde{m}(s)}{c} \\
c &= \left[\mu_0 \varepsilon_0\right]^{-\frac{1}{2}} \equiv \text{speed of light} \\
s &= \Omega + j\omega \equiv \text{two-sided Laplace-transform variable or complex frequency}
\end{aligned} \tag{4.1}$$

An important property of such an antenna is that it has a cardiod pattern ($[1 + \cos(\theta)]^2$ in power sense with θ measured from the $+\vec{1}_c$ direction) with maximum in the $+\vec{1}_c$ direction and a null in the $-\vec{1}_c$ direction [5]. This has interesting properties as a SAR antenna in that it has a broad pattern while being able to distinguish signals arriving from one side of an aircraft from those arriving from the other side (in reception). In transmission such an antenna can transmit to one side without transmitting to the other.

As illustrated in Fig. 4.1 an interesting place to locate such an antenna is as a ventral antenna on P. In the illustration radiation is to starboard ($+\vec{1}_c$) with reception of signals propagating in the $-\vec{1}_c$ direction. Note, however, that $\vec{p}$ is symmetric and $\vec{m}$ antisymmetric with respect to P [14, 23]. So in general they interact differently with the airframe on which they are mounted. Ideally one can think of these dipoles and their moments as including simple images (factors of two) in the fuselage approximated as locally flat. Over some band of frequencies (in general sufficiently high) and for related pulses and perhaps restricted down-looking angles from the airplane such an image approximation may be valid.

At low frequencies such as the HF band where the fuselage and wings are resonant one may wish to minimize this coupling to these ventral antennas. One can operate these antennas at frequencies higher than these resonances as an isolation technique. One can also try to place the antennas at positions where these modes have surface-charge-density nulls (for $\vec{p}$), and surface current-density nulls (for $\vec{m}$) noting that there are two components in the latter case [15, 20 (Section 2.1.2.1.4)]. One might separate the $\vec{p}$ and $\vec{m}$ as separate antennas each with its own optimal locations, and combine the signals (in reception) with appropriate delays in a computer.

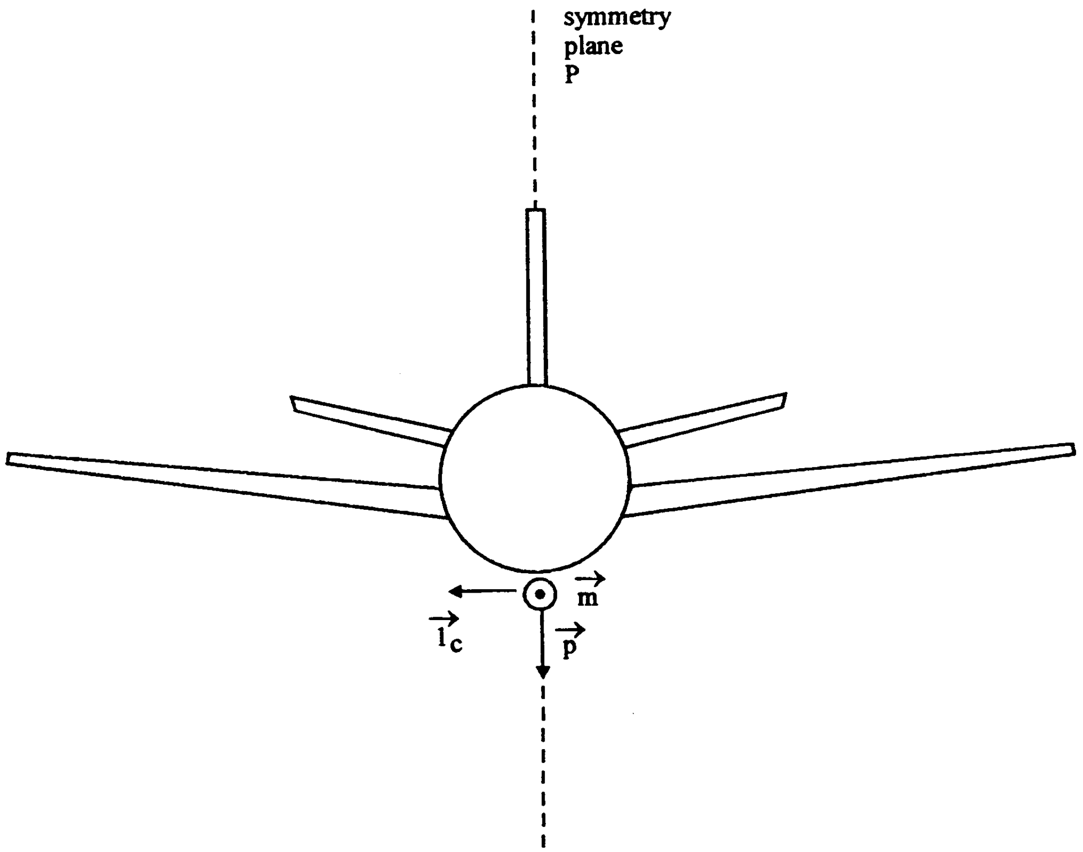


Fig. 4.1. Side-Looking Ventral Combined Dipoles: Vertical Polarization

Of course, one can transmit and/or receive the electric- and magnetic-dipole parts separately and relate them through the measured or calculated fuselage interaction to achieve the desired back null (port side in Fig. 4.1). In reception this could be accomplished by combination in a computer. Various designs of such combined dipoles involve a resistive load to achieve the balance in a single element. This may not be advantageous in transmission due to the power loss. However, in reception, with signals transmitted to a recorder via a terminated transmission line there is a comparable resistive load here anyway. The transmitter might use a larger antenna elsewhere (as in Sections 2 and 3) for greater radiated fields, even though it might radiate to both sides of the aircraft. The single-side-looking character of the combined dipoles can discriminate between the two sides to avoid clutter from the unwanted side mixing in with the radar data (e.g., SAR data).

As shown in Fig. 4.2, it is quite possible that to construct such combined dipoles with two antenna ports so as to transmit to and/or receive from both sides in a separated way. For transmission to the left consider the cable impedance Z_c of the right cable as the load on the loop, and conversely for transmission to the right. This allows a SAR to operate simultaneously to both sides of the airplane if desired with port data in one channel and starboard data in another channel, both utilizing the same transmitting antenna radiating to both sides of the aircraft.

There are various ways to construct properly matched dipoles. One of the earlier ways was to use a TEM transmission line as a wire or plate over a ground plane, or two wires or plates in a differential configuration [2, 4]. As a receiver this has been called the BTW (balanced transmission-line wave) sensor. While this works, one might improve on this by a circular-loop design as in Fig. 4.2 and as discussed in [1, 9, 11]. Noting that the transmission-line type only operates as a $\vec{p} \times \vec{m}$ device for wavelengths long compared to the length (i.e., as an electrically small antenna) [2], one can increase the loop area (and hence $\vec{m}$ and $\vec{p}$) for a given length by making it taller in the middle, at the expense of more complexity in the analysis [11]. However, this analysis having been performed [11], one can relate the wire radius and loop radius to the required load impedance to obtain the balanced dipole effect. Noting the cable feeds as in Fig. 4.2 one can match to these or introduce matching networks at the antenna ports. There is also a version in which the loop is continuously resistively loaded [11], but this is more suitable for single-port operation (and hence to one side of the airplane).

Another way that the bidirectional combined dipoles in Fig. 4.2 can be used is, in reception, to take the sum of the two signals to obtain the symmetric part $(\vec{p})$ and the difference to obtain the antisymmetric $(\vec{m})$ part. One can process these separately to reduce the airframe scattering effects, and then take sum and difference to obtain corrected port and starboard signals.

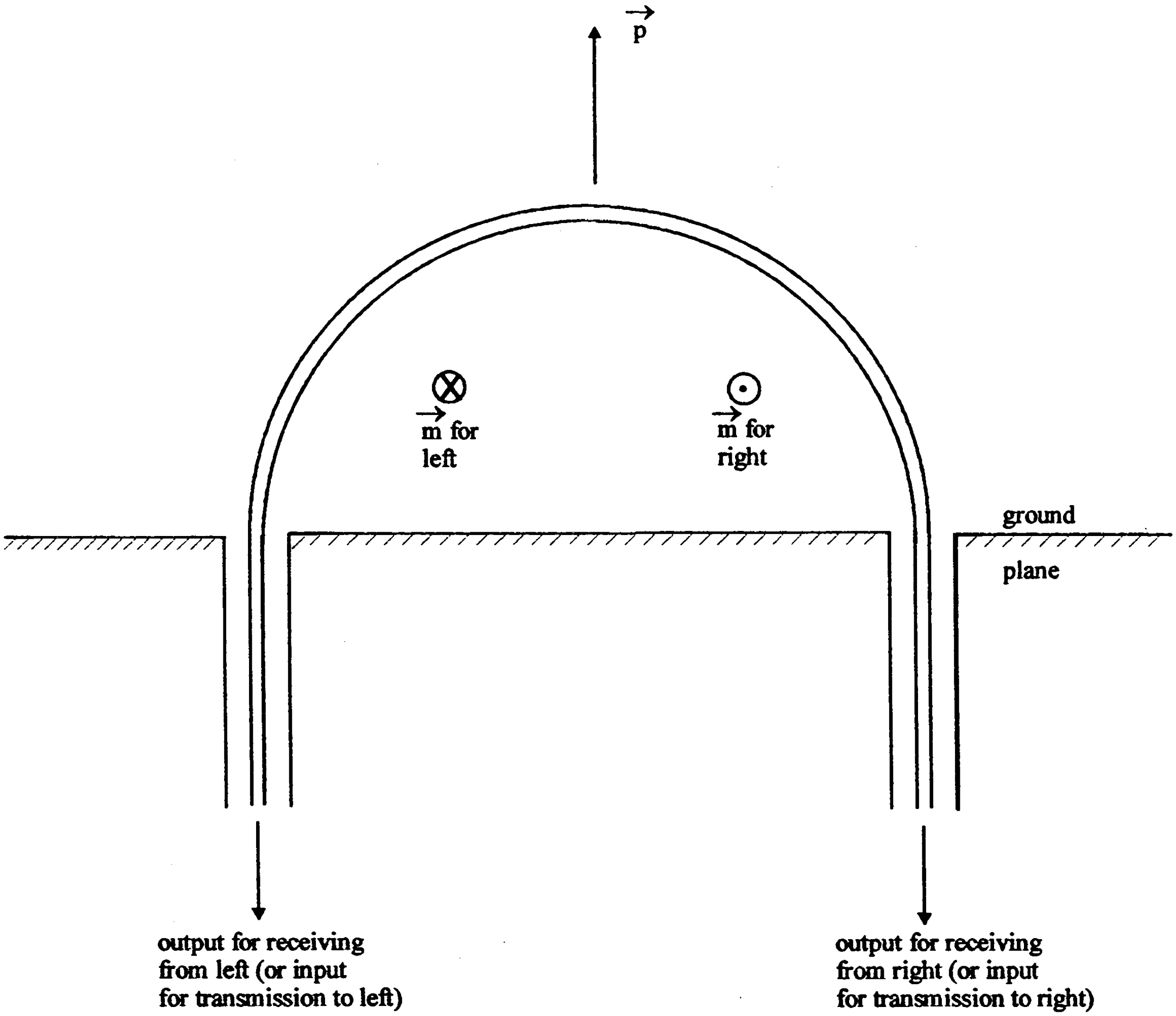


Fig. 4.2. Bidirectional Combined Dipoles

5. Ventral Array of Combined Dipoles

Consider now an array of combined dipoles such as discussed in Section 4. Each element can be considered separately noting its broad pattern and back null, suitable for SAR application. For a side-looking SAR this is called the *strip-map* mode.

There is another type of SAR referenced as spotlight mode [22]. In this case the antenna is continuously pointed (rotated) toward the target as the aircraft moves along its flight path. This allows the use of higher gain (narrow beam) antennas while still retaining the large synthetic aperture for high resolution. Higher gain of course means more signal and less clutter (from outside the antenna beam).

Another way to achieve high gain is by an array of antennas. In this case let the elements be the combined dipoles previously discussed. By combining the signals (in reception) with appropriate time delays one can obtain a narrow-beam antenna pattern that one can steer as desired. There is still the option of whether to combine the signals with mathematical delays in a computer, or to combine real signals via variable physical delay lines. This involves signal-to-noise and signal-to-clutter issues.

This type of SAR might be described as array spotlight SAR, or just array SAR for short.

6. Pulse-Reflecting Antenna Elements on Airplane Side

Another place to consider for antennas for a side-looking radar is the side of the fuselage. Such lateral antennas (or arrays) have the advantage that for sufficiently high frequencies the fuselage shadows signals to or from the opposite side of the airplane. However, not being on the symmetry plane P complicates the analysis of the scattering by parts of the airplane away from these antennas. For sufficiently high frequencies (and related pulses) and restricted directions (angles) of transmission and reception one can significantly reduce this scattering problem.

The use of laterally posed reflector impulse-radiating antennas (IRAs) is considered in [7]. In this case the reflector is made integral with the aircraft metal skin and the feed arms are outside the fuselage, perhaps with the slipstream passing between the feed arms, or perhaps with the feed arms enclosed in a dielectric blister. Various ways of moving the feed arms to orient the beam focal direction are also presented there. Such antennas also have potential SAR utility, especially for pulses with frequencies in the range of a few 100 MHz to several GHz.

Alternately one might defocus the antennas to obtain a broader beam as often used in SAR. This might be as simple as a flat-plate reflector fed by the usual TEM feed arms with resistive terminations at the reflector/fuselage. This might have the usual four-arm configuration as shown in Fig. 6.1. This gives options for both horizontal and vertical polarization as do the configurations in [7]. The two polarizations can be handled by separate antennas or can be combined in the same antennas. Also as indicated in Fig. 6.1, one can have an array of such antennas (or two arrays using both sides of the fuselage). The beams from each element will need to take account of large scatterers such as the wing, thereby limiting the scan angles in varying degrees for the various array elements.

Such defocused antennas have their own problems as discussed in [13]. Various shapes of reflectors are possible including hyperboloids [6] with useful pulse-reflection properties. Future research may find yet additional useful shapes.

This type of pulse-radiating antenna is not an IRA since it is not focused at infinity. Perhaps this type of antenna can be referenced by PRAE (pulse-reflecting antenna element) which is a Latin word meaning: in front, ahead, before. (The ae dipthong can be pronounced as y in "pry" in classical Latin, or ay in "pray" in ecclesiastical Latin.)

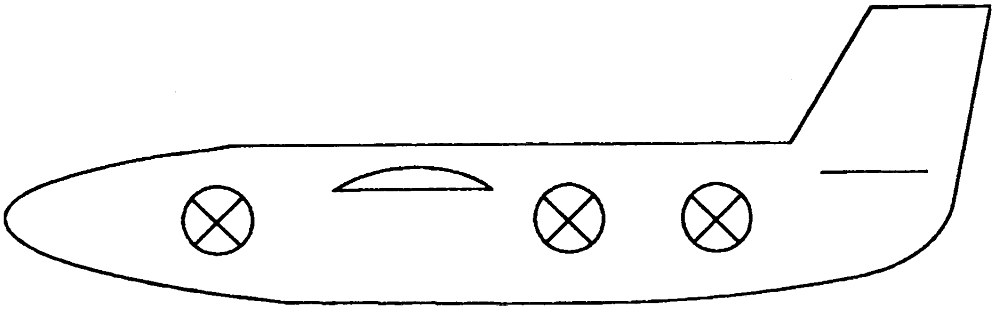


Fig. 6.1. Pulse-Reflecting Antenna Elements on Fuselage: Port Side

7. Concluding Remarks

In this paper we have filled in some of the additional possible antenna types and locations on an airplane for use with radar, including SAR and wideband pulses. Various frequency bands are possible from wavelengths long compared to airframe dimensions to wavelengths short compared to such dimensions. Appropriate locations for such antennas on an airplane depend on antenna type and frequency bands and use in transmission and/or reception.

There are advantages and disadvantages associated with the various types of antennas. One type might be used for transmission of a particular polarization, while another type might be used for reception of a particular polarization. The directional (pattern) properties are also important, and antennas can be combined into arrays for electronic beam steering. Of particular interest are the combined dipole $(\vec{p} \times \vec{m})$ antennas because of their back null, which can be used to separate signals to and/or from port and starboard sides of an aircraft. Here we have considered their possible use as ventral antennas on the symmetry plane. However, other locations, such as under the wings are also possible.

While our discussion has been in terms of radar use, including SAR, such antennas can have various other electromagnetic uses as well. Particularly for the wideband antennas (band ratios of two decades having been achieved [25]) one can envision multiple signals, including both narrowband and pulsed, operating through such antennas. This paper has filled in some of the possibilities, but there are still many details to be addressed.

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