Aeronautical Satellite Antenna Steering Using Magnetic Field Sensors

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ABSTRACT

Designers of aeronautical satellite terminals are often faced with the problem of steering a directive antenna from an airplane or helicopter. This problem is usually solved by using aircraft orientation information derived from inertial sensors on-board the aircraft in combination with satellite ephemeris information calculated from geographic coordinates. This procedure works well but relies heavily on avionics that are external to the terminal. For the majority of small aircraft and helicopters which will form the bulk of future aeronautical satcom users, such avionics either do not exist or are difficult for the satellite terminal to interface with.

At the Communications Research Centre (CRC) work has been undertaken to develop techniques that use the geomagnetic field and satellite antenna pointing vectors (both of which are stationary in a local geographical area) to track the position of a satellite relative to a moving platform such as an aircraft. The performance of this technique is examined and a mathematical steering transformation is developed within this paper. Details are given regarding the experimental program that will be undertaken to test the concepts proposed herein.

The Steering Problem

Steering an aeronautical satcom antenna using received signal strength alone is possible. However, this technique is prone to problems resulting from multipath reflections from around the aircraft, especially at the low satellite elevation angles where the wing tips, tail, and aircraft fuselage often appear within the beamwidth of the antenna.

It is believed that effective and accurate satellite antenna steering can be achieved by using the local geomagnetic field vector as a reference. By knowing the orientation of the magnetic field vector and the satellite pointing vector with respect to the aircraft's frame of reference, it is possible to maintain antenna tracking as the aircraft maneuvers.

Given that this concept works it will be possible to incorporate this electronic steering system within an aeronautical satcom terminal. This would reduce the requirement for the terminal to meet stringent avionics interface requirements and allow the use of satcom from a greater number of aircraft than currently possible. The technique has other applications, such as steering satellite antennas from ships or buoys.

The 3 Dimensional Adaptive Magnetic Sensor

Central to the magnetic field steering concept is a sensor that can resolve the instantaneous geomagnetic field in three dimensions. Such a sensor has been developed by using orthogonal adaptive magnetic field sensors.

The adaptive magnetic field sensor or compass (Ref 1) is a device which determines the angle of the magnetic field vector projected onto a

plane. This sensing plane is defined by two perpendicular magneto-resistive chip circuits. The output of these circuits is processed by a neural network which continually adapts the operation of the circuits to magnetic perturbations introduced by the aircraft. The adapted circuits give magnetic field strength readings with worst case error in the order of 2-3%. The two sensing planes are oriented orthogonally to each other to make a 3 dimensional field sensor. Currently a single board computer processes the outputs of the two sensing planes. Because of the complexity of the neural algorithms and the ancillary magneto-resistive sensor circuits, a 3 dimensional (3D) magnetic field reading is provided by the computer every 300 to 500 milliseconds. In the future the computer and supporting circuits will be integrated into several ASIC circuits which will be smaller and be capable of providing faster magnetic field readings. Currently the 3-D magnetic field sensor is housed in an aluminum box measuring 18 cm by 12 cm by 10 cm.

High Gain Antenna System

The antenna that is used in the investigation of magnetic steering (Fig.1) is an array of highly shortened helix elements (Ref. 2,3) that are wound into a conical form for better bandwidth performance. The array produces a flattened beam having gain in the order of 10-12 dBIC and a free space 3 dB beamwidth of 30 degrees azimuth by 60 degrees elevation. The antenna contains an on board diplexor/LNA and steering activation circuits and has a length of 36 inches, height of 6.5 inches and width of 13 inches.

The antenna will be used with the Ontario Air Ambulance Cessna 500 aircraft satcom terminal. The air ambulance has access to an INMARSAT channel and is used for emergency communications. Up to now the satcom terminal in the aircraft used window mounted antennas (Ref 4) which are being replaced by the new mechanically steered antenna and magnetic steering system.

Coordinate Transformations

As part of the steering algorithm it is necessary to determine a procedure for transforming changes in the pitch, roll, and heading of the aircraft to changes in the azimuth and elevation settings of the satellite antenna. Since aircraft attitude changes are sensed by the 3D sensor, the problem becomes one of accurately converting 3D sensor outputs into antenna azimuth and elevation settings (Ref 5).

The magnetic field vector β is resolved in 3D space using the two planar orthogonal magnetic field detectors (Fig. 2). One detector is set to sense the magnetic field in the heading (or azimuth) (XY) plane of the aircraft at an angle ϕ_m. The second detector is set to sense the angle of the field in the Z plane (either the pitch (XZ) plane or the roll plane (YZ)). Pitch plane readings are defined as Ω_m; roll plane readings as Ψ_m. By manipulating the projections of β into each of the three planes; it can be shown that:

$$\tan\Omega_m = \frac{\sin\theta_m \cos\phi_m}{\cos\theta_m} = \tan\theta_m \cos\phi_m \qquad (1)$$

$$\tan\Psi_m = \frac{\sin\theta_m \sin\phi_m}{\cos\theta_m} = \tan\theta_m \sin\phi_m \qquad (2)$$

where θ_m is the angle between β and the Z axis. Alternately;

$$\Omega_m = \tan^{-1}(\tan\theta_m \cos\phi_m) \qquad (3)$$

$$\Psi_m = \tan^{-1}(\tan\theta_m \sin\phi_m) \qquad (4)$$

and

$$\tan\Omega_m = \frac{\tan\Psi_m}{\tan\phi_m} \qquad (5)$$

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Aircraft attitude changes can be resolved as changes in heading (θ_A); pitch (θ_T) and roll (θ_B) of the aircraft (Figure 3). Now; whereas heading changes of the aircraft will result in only purely azimuthal changes in the magnetic sensor (i.e. $\Delta\theta_A = \Delta\phi_m$), pitch and/or roll changes of the aircraft will result in simultaneous changes to both ϕ_m and θ_m.

$$\Delta\theta_P = \Delta\Omega_m = F_1(\Delta\phi_m, \Delta\theta_m) \qquad (6)$$

$$\Delta\theta_R = \Delta\Psi_m = F_2(\Delta\phi_m, \Delta\theta_m) \qquad (7)$$

Equations 6 and 7 can be expressed in a differential form:

$$
\begin{bmatrix} \Delta\theta_P \\ \Delta\theta_R \end{bmatrix} = \begin{bmatrix} \Delta\Omega_m \\ \Delta\Psi_m \end{bmatrix} = \begin{bmatrix} \dfrac{\partial\Omega}{\partial\theta_m} & \dfrac{\partial\Omega}{\partial\phi_m} \\ \dfrac{\partial\Psi}{\partial\theta_m} & \dfrac{\partial\Psi}{\partial\phi_m} \end{bmatrix} \begin{bmatrix} \Delta\theta_m \\ \Delta\phi_m \end{bmatrix} \qquad (8)
$$

After calculation of the partial derivatives of the matrix coefficients, equation (8) become:

$$
\begin{bmatrix} \Delta\theta_P \\ \Delta\theta_R \end{bmatrix} = \begin{bmatrix} A_m\cos\phi_m & -B_m\sin\phi_m \\ C_m\sin\phi_m & D_m\cos\phi_m \end{bmatrix} \begin{bmatrix} \Delta\theta_m \\ \Delta\phi_m \end{bmatrix} \qquad (9)
$$

with the coefficients A_m, B_m, C_m and D_m defined as:

$$A_m = \frac{1}{(\cos^2\theta_m + \cos^2\phi_m\sin^2\theta_m)} \qquad (10)$$

$$B_m = \frac{\sin\theta_m\cos\theta_m}{(\cos^2\theta_m + \cos^2\phi_m\sin^2\theta_m)} \qquad (11)$$

$$C_m = \frac{1}{(\cos^2\theta_m + \sin^2\phi_m\sin^2\theta_m)} \qquad (12)$$

$$D_m = \frac{\sin\theta_m\cos\theta_m}{(\cos^2\theta_m + \sin^2\phi_m\sin^2\theta_m)} \qquad (13)$$

The equation (9) can be re-written using matrix syntax as:

$$\Delta\Theta_P = M_m \Delta\Phi_m \qquad (14)$$

where the indices p and m relate respectively to the platform (aircraft) and the magnetic sensor readings.

In equation 14 we see the relationship between a moving frame of reference (the aircraft) with respect to a fixed magnetic field. The pointing vector to the satellite (defined by the antenna azimuth and elevation angle θ_a, ϕ_a), is also with respect to this aircraft. Consequently equation (14) can be re-written to apply to antenna coordinates.

$$\Delta\Theta_P = M_a \Delta\Phi_a \qquad (15)$$

where the indice a refers to the antenna. Combining (14) and (15) we have:

$$\Delta\Phi_a = M_a^{-1} M_m \Delta\Phi_m \qquad (16)$$

which relates any change in the magnetic sensor readings to an equivalent change in the antenna position.

It can be useful to calculate the exact relation given by the equation (16). Using an equivalent equation (9) but for the antenna frame of reference, the inverse matrix M_A^{-1} can be expressed as:

$$
M_A^{-1} = \begin{bmatrix} \dfrac{\cos\phi_a}{A_a} & \dfrac{\sin\phi_a}{C_a} \\ -\dfrac{\sin\phi_a}{B_a} & \dfrac{\cos\phi_a}{D_a} \end{bmatrix} \qquad (17)
$$

It follows that:

$$
\begin{bmatrix} \Delta\theta_a \\ \Delta\phi_a \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} \\ Q_{21} & Q_{22} \end{bmatrix} \begin{bmatrix} \Delta\theta_m \\ \Delta\phi_m \end{bmatrix}
$$

where

$$Q_{11} = \frac{A_m}{A_a}\cos\phi_a\cos\phi_m + \frac{C_m}{C_a}\sin\phi_a\sin\phi_m$$

$$Q_{12} = \frac{D_m}{C_a}\sin\phi_a\cos\phi_m - \frac{B_m}{A_a}\cos\phi_a\sin\phi_m$$

$$Q_{21} = \frac{D_m}{D_a}\cos\phi_a\cos\phi_m + \frac{B_m}{B_a}\sin\phi_a\sin\phi_m$$

$$Q_{22} = \frac{A_m}{A_a}\cos\phi_a\cos\phi_m + \frac{C_m}{C_a}\sin\phi_a\sin\phi_m$$

$$(18)$$

This relation transforms any variation in the readings of the magnetic sensor due to a pitch or roll of the aircraft, to an equivalent variation in the antenna satellite pointing angles. It is interesting to note that for the case where an axis of the aircraft's antenna frame of reference aligns with the magnetic field or satellite pointing vector, the above relationship reduces to a unit matrix. The pitch and roll variations measured by the compass will directly translate to equivalent changes for the antenna. Similarly, if the antenna is pointing opposite to magnetic north (i.e. satellite pointing vector is 180° away from magnetic north), the relation (18) transforms to a negative unit matrix resulting in steering variations being opposite to aircraft variations. Overall if the satellite pointing vector and magnetic field vector are within 30° of each other then the variation in readings of pitch or roll will closely approximate equivalent antenna variations.

Steering Ambiguity

The 3D sensor in conjunction with the aircraft possesses a number of ambiguities which can affect the accuracy of antenna steering. During instances where the magnetic field vector is parallel to any of the three coordinate axis of the magnetic sensor, it will be impossible to detect rotation of the coordinate axis about the magnetic vector. As a consequence, steering the antenna becomes ambiguous and the problem is accentuated as the antenna pointing vector becomes perpendicular to the magnetic field vector.

The ambiguity can be resolved by the steering algorithms which can detect the unique situations described above. Antenna steering under these circumstances becomes more reliant on signal strength tracking than on magnetic field tracking.

Signal Strength Sensor System

Antenna beam steering cannot be controlled solely by responses to magnetic sensor outputs. Magnetic sensor readings are produced no more than two or three times a second. Given that aircraft such as helicopters can make orientational changes of up to 45 degrees per second, an antenna steered by magnetic steering alone could be over 20 degrees off angle from the satellite before any correction attempt was made by the steering system.

Since received signal strength information can be obtained from a terminal tracking a satellite, it is advantageous to use such information to enhance and supplement the magnetic tracking. Signal strength information comes at a much faster rate than magnetic sensor information at one reading every 50 milliseconds. At high C/No (45 dBHz) the signal sensor can have a resolution of 0.35 dB. For the Ontario Air Ambulance experiments we have a choice of satellite pilot signals that can be monitored to provide signal references. In an operational system such as the Inmarsat Aeronautical system, one could monitor the P-channel signal. Figure 4 shows the magnetic and field sensor configuration for steering the antenna.

Satellite Acquisition and Beam Steering Considerations

There are a number of factors which have to be considered in the development of a suitable satellite tracking algorithm. Antenna motor response speed and beam deformation which results in variations of axial ratio, discrimination, and gain as a function of antenna to ground plane (fuselage) interaction, are factors which affect the performance of the

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steering algorithm. To some degree, the fact that the antenna beam is quite broad, having less than 0.5 dB of gain variation over a 7 by 15 degree area relaxes some of the steering requirements in that changes in orientation may be detected before noticeable changes in signal strength arise.

Probably the most important event in the activation of magnetically steered antenna is satellite acquisition. This procedure will rely heavily on the detection of a pilot signal from the satellite. The antenna, under control of the steering processor, must search the sky for the host satellite. This means searching for a signalling channel at a particular frequency. Since frequency stability of the terminal may not be within some prescribed operational bounds at power up, we are faced with a three dimensional search in frequency, antenna azimuth, and antenna elevation. Such a search will be further complicated by multipath, which will be present when the aircraft is close to hangars and other metallic structures while it is on the ground.

Beam Steering Algorithms

Steering algorithms will need to monitor a number of thresholds in a tracking sequence and will need to have a variety of responses to the detected orientation changes. Very quick changes will be detected as a drop in the signal strength. The first magnetic sensor reading after a signal drop will provide important information regarding the direction of the orientation change. It will also be possible in this first instant to calculate an angular acceleration for the change and choose a response by setting antenna motor speeds. Slow changes will be handled primarily by the magnetic field steering because such changes will not result in rapid signal strength variation and will be harder to detect by signal strength sensing. Nevertheless, once a tracking search is initiated by the magnetic sensor system there will probably be a

requirement to dither the antenna to maximize the signal strength

In view of the above considerations, the steering algorithm will take on a complex form. It will have to move from the acquisition mode to the tracking mode; it will have to differentiate between slow and fast orientational changes; it will have to predict angular rates of change and directions and then actuate motors to respond to such changes. The algorithm will strive to maintain the received C/N_0 at a maximum and in essence, this will be the final objective of any algorithm.

Conclusion

With the Ontario Ambulance several types of algorithms will be tested. The experimental system is being designed in such a manner that real time performance of an algorithm can be monitored and stored for analysis. This information will be useful in determining optimal tracking strategies.

References

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4 Recent Technical Advances in General Purpose Mobile Satcom Aviation Terminals, J. Sydor, IMSC Conference '90 Proceedings., JPL Pulication 90-7, pages 579 - 586.

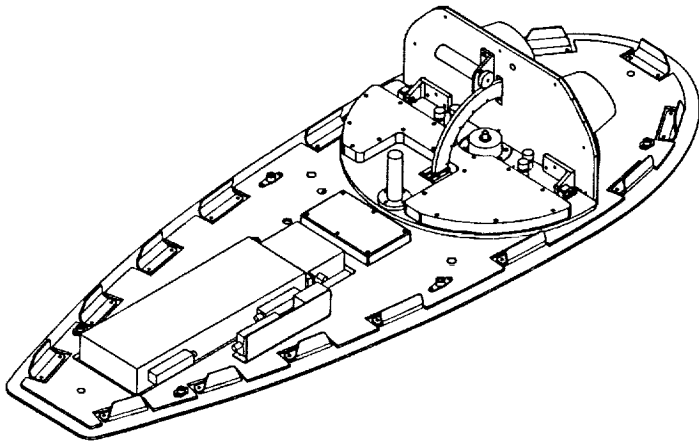5 Solid Analytic Geometry, Adrian Albert, McGraw-Hill 1949, Ch. 8, Section 4.

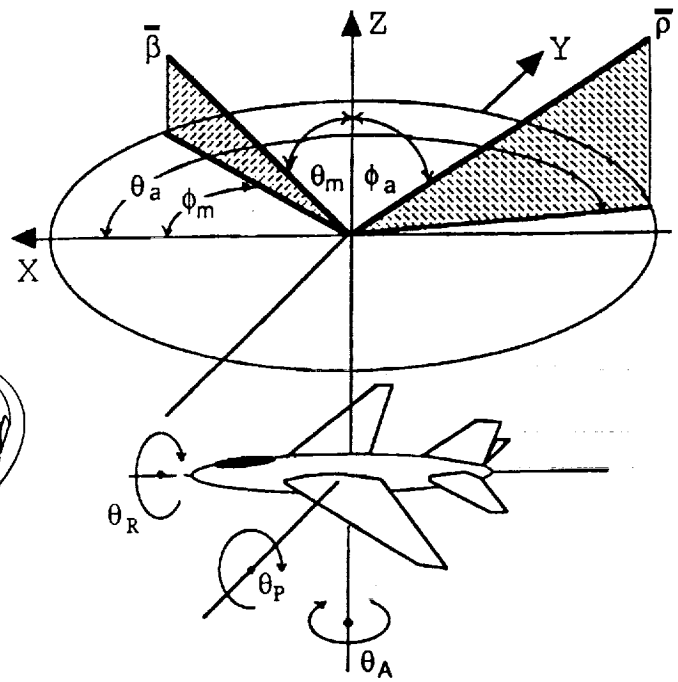**Figure 1**
Mechanically Steered High Gain
Satcom Antenna

Figure 2
Magnetic Field, Antenna Pointing, and Aircraft
Orientation Coordinates

Figure 2
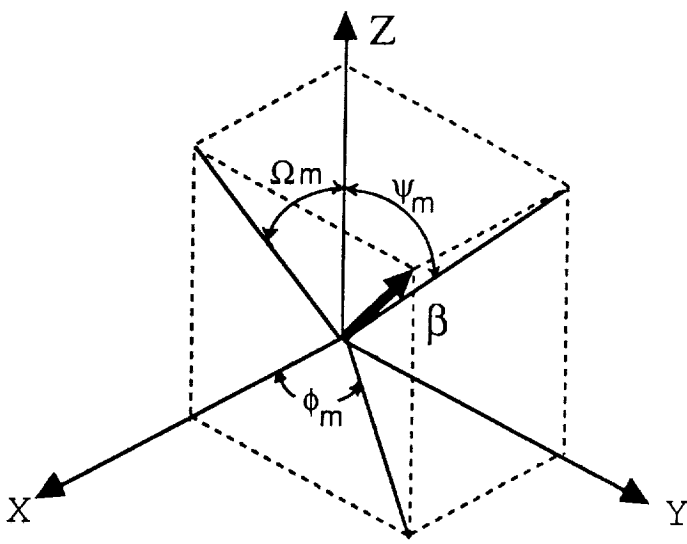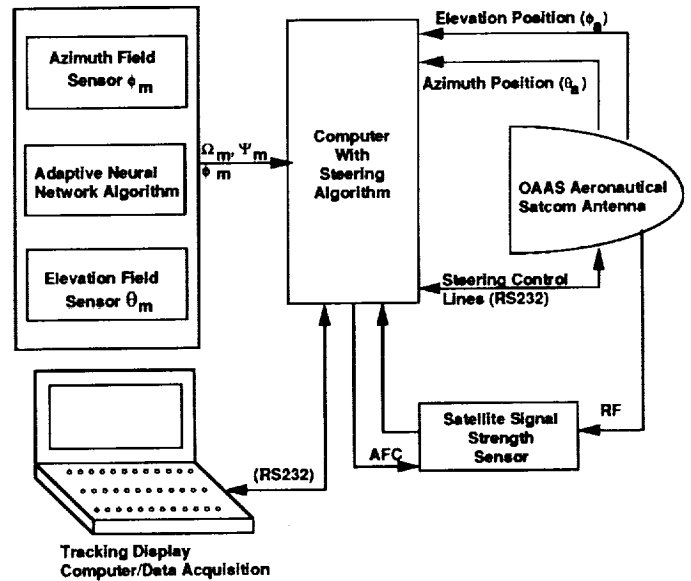**Resolution of the Magnetic Field Vector**

Figure 4
Experimental Set Up

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