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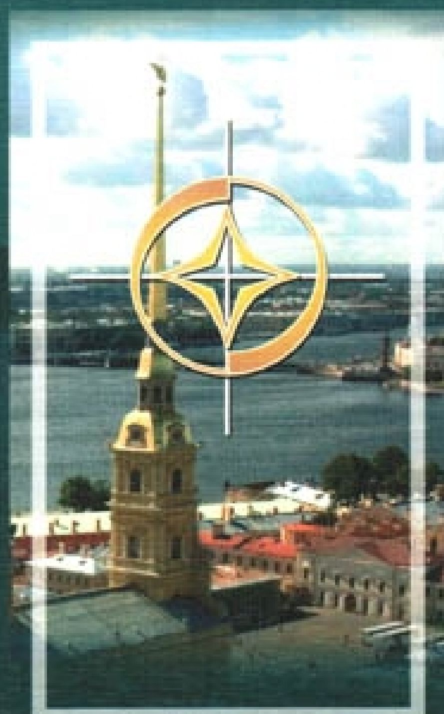

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LOW FREQUENCY ELECTROMAGNETIC SYSTEM OF RELATIVE NAVIGATION AND ORIENTATION

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Abstract

Key words: relative navigation, orientation, magnetic dipole, alternating magnetic field, airborne electromagnetics

A method of relative positioning of two moving objects is suggested. The method is based on measurements of parameters of alternating magnetic field by three-axial induction sensor (receiver) which is placed on one of the objects. Wire loops mounted on the second object are used to induce the field. Magnetic moments of these loops form a linearly independent vector system. The concept of the method is to find the parameters of the transmitter moments as parameters of magnetic dipoles with respect to receiver axes. Application of the method for a low frequency airborne electromagnetic survey system is described. One of the moving object is an aircraft, fixed-wing or helicopter, and the second is a towed bird with an induction sensor mounted inside. Two and three transmitters variants are considered. Results of flight test are given.

Introduction

Intensive development of airborne geophysical methods is associated with employment of new technologies in navigation tasks of surveying process. The most spectacular example is a new level of airborne gravimetry which was achieved after the Laboratory of Control and Navigation of Moscow State University under guidance of N.A. Parusnikov used tightly coupled inertial and satellite navigation systems [1].

A navigation task solution method under discussion is related to another branch of exploration geophysics – airborne electromagnetics (AEM). AEM use an alternating low frequency magnetic field (a few hundreds of Hertz), which is commonly created and measured by inductive methods.

A number of AEM systems were during more then 60 years long history of AEM development [2]. All these systems can be divided into two groups. The first one is represented by systems with rigid transmitter-receiver base. The second group includes all systems with loosely connected transmitter and receiver. The advantages of the first group are low dimensions and the primary field parameters stability with respect to receiver axes. The main disadvantage is necessity of the primary field compensation in a receiving point because it is 5-7 orders greater then the secondary field, which carries information about ground conductivity. In systems of the second group influence of the primary field can be essentially reduced by increasing the distance between the transmitter and the receiver. The main problem is that variations of the transmitter-receiver relative position lead to primary field variations in receiving point.

The most widely used AEM system in Russia is the one called EM-4H, which is a modification of DIP-A method (Dipole Inductive Profiling – Airborne) [5]. This system can be installed both on fixed-wing aircrafts (An-2 and An-3 were actually used) and on helicopters (Mi-8) [3,4]. EM-4H represents the second group. Design of the system is described below (Fig. 1).

A multi-turn loop is rigidly mounted on an aircraft fuselage, helicopter or fixed-wing. An alternating current, which is a sum of sinusoidal signals on four working frequencies, is induced in the loop. The tri-axial induction sensor is placed in a bird, which is towed by a flexible 70 meters long tow-cable. Each receiver axis is formed by two induction coils. All three pairs are mounted on cube sides to make all the sensitive centers coincident (Fig. 2). Along every axis amplitudes and phase shifts are measured on all working frequencies.

Modern approach in airborne electromagnetics data processing and interpretation requires measurement of a full response, i.e. both in-phase and quadrature components of the secondary field [6,7]. So the main purpose of an airborne EM survey system to measure response from the earth. To succeed it is necessary to solve the following tasks:

1) To calculate the primary field in the receiving point and to separate from the in-phase secondary field;
2) To exclude the transmitter and the receiver altitude variations.

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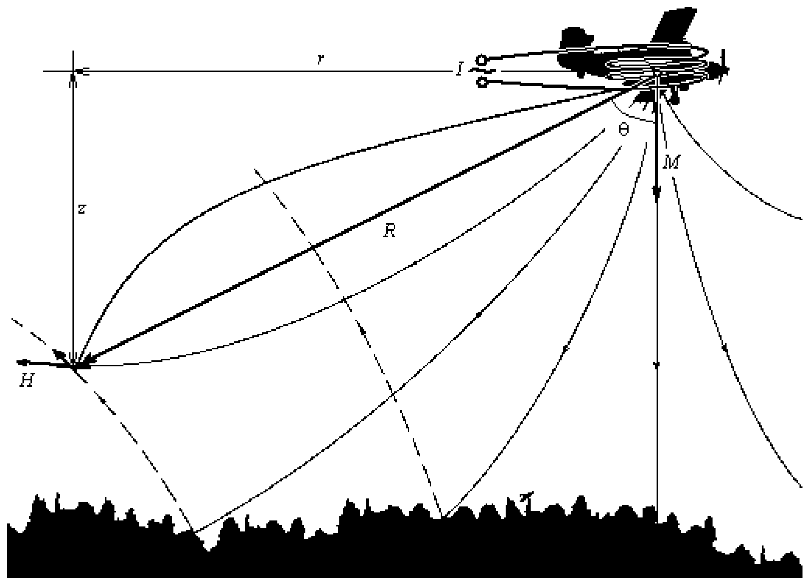

Fig. 1. Airborne Electromagnetics

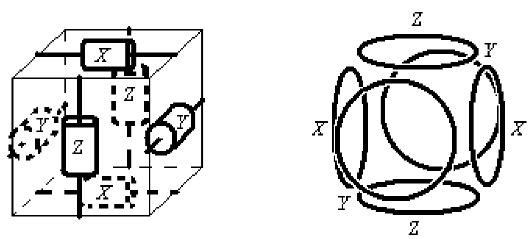

Fig. 2. EM-4H receiver (left) and GEOTEM receiver scheme (right).

In order to meet system technical requirements needed for response measurements angles of transmitter-receiver relative orientation must be known with as precise as one degree. For qualitative interpretation from 10 to 50 centimeters inaccuracy, depending on environmental conditions, is allowed for distance detection between the transmitter and the receiver. Airborne EM is used for conductive objects detections, and the higher ground conductivity is explored the higher precision of navigation solution is required [8].

The first approach to the navigation task solution the authors considered was one with employment of satellite and inertial navigation tools. In this case it is necessary to install satellite navigation systems both in the aircraft and in the bird, as well as inertial blocks, which could detect parameters of relative orientation of the transmitter and the receiver. Disadvantage is that this way leads to serious modification of the bird and the receiver.

Besides an analysis brought out that such systems are unable to provide the accuracy of distance measurement comparable with the field detection one. The sense is that the wire loop field for given geometry parameters is equivalent to the field of magnetic dipole with magnetic moment M, $|M| = ISn$, I is the current magnitude, S – loop square, n – number of turns in the loop. And this field is described by the following relations [9]:

$$H_r = 3\,|M| \cos\theta \sin\theta / 4\pi|R|^3, \quad H_\varphi = 0, \quad H_z = |M|\,(3\cos^2\theta - 1)/4\pi|R|^3. \qquad (1)$$

(1) is the expression for magnetic field strength vector components in cylindrical coordinate system in (r, φ, z) point, z axis is directed along the moment vector M, the origin of coordinates is in the dipole point, θ = arctg r/z, $R^2 = r^2 + z^2$ (Fig. 1). Here and further magnetic permeability of air is supposed to be equal to the magnetic permeability of free space, modern induction sensors sensitivity allows this assumption. From (1) H decreases as cube of distance, that's why

$$H(|R| + \Delta R) = H(|R|) + \Delta H, \quad \Delta H \sim 3\,\Delta R/|R|.$$

For example, EM-4H system has $|R| \sim 70$ m, that's why 1 cm error leads to an error of primary field calculation $\sim 4\cdot10^{-4}$, whereas the field measurements accuracy is up to $1\cdot10^{-4}$. But to detect even with 1 cm accuracy the transmitting center position of the 40-60 squared meters loop seems to be an unfeasible task.

The second approach was proposed by Richard S. Smith [10] and is used for AEM systems GEOTEM, MEGATEM, TEMPEST, Fugro Airborne company (Canada). All the mentioned systems are the analogs of EM-4H in terms of geometry. The receiver (Fig. 2) is towed in a bird using 120 meters length tow-cable. The receiver measures decaying time of currents induced in the Earth by short current impulse in a loop mounted on a fixed-wing aircraft. This electromagnetic method is called the transient EM method (Time domain).

The main idea of the navigation task solution is as follows. Suppose the primary field is induced by magnetic dipole. Then the magnetic field vector components in any point are described by relations (1) in the dipole coordinate system. Suppose also the magnitude of dipole moment is known. Then, using these relations parameters R, θ can be found if both vectors M and H are given in the same coordinate system.

The advantages of this approach are evident. The receiver position is detected with respect to the loop transmitting center and exactly this parameters is used for interpretation. The weak point is absence of receiver attitude information with respect to vector M. While all the systems like GEOTEM use attitude heading reference systems mounted on aircrafts for detection of the transmitter orientation parameters, the orientation task for receiver still wasn't solved. The solution used is to assume stability of the receiver axes. This approach leads to necessity of receiver data averaging in order to remove induction coils evolutions influence. This affects negatively on spatial resolution of AEM method.

So, the transmitter-receiver relative navigation task obviously is the actual one for airborne EM. The accuracy of relative positioning equal to the one of alternating magnetic field components measurements allows to avoid system limitations associated with non-rigid fixing of the receiver, while it's sensitivity remains inaccessible for the systems with rigid base.

In this work to solve the navigation task under consideration a following method is described. It is suggested to measure the parameters of field induced by two or three loops mounted on an aircraft. At the same time, the induced magnetic moments to be a linearly independent vector system is of importance.

Three dipoles system

In arbitrary Cartesian coordinate system relations (1) for magnetic dipole field components can be represented in a more convenient vector form:

$$H = (3\, e_R\, e_R^{\,T} - E)\, M/4\pi|R|^3 = \Omega(R)\, M. \tag{2}$$

R is a transmitter-receiver radius-vector, e_R is a unit vector aligned with R, M is an inducing dipole magnetic moment vector, $e_R\, e_R^{\,T}$ is a dyadic product, i.e. a matrix formed by the pairwise product of the e_R components. From the relation (2) it is follows that the matrix $\Omega(R)$ specifies a connection between the field and the dipole moment. This matrix depends only on radius-vector R.

The most important properties of matrix $\Omega(R)$ are following. First, matrix $\Omega(R)$ is non-singular wherever it is defined, i.e. everywhere except point $R = 0$. Therefore the inversed matrix can be found everywhere:

$$\Theta(R) = [\Omega(R)]^{-1} = (3\, e_R\, e_R^{\,T} - 2E)\cdot 2\pi|R|^3, \quad M = \Theta(R)\, H. \tag{3}$$

Second, if the e_R direction is fixed then only the absolute value of vector H changes as $1/|R|^3$ when $|R|$ changes. Obviously the inversed matrix (3) has the same property.

Suppose that the amplitude of the inducing dipole $|M|$ is known and vector H components are measured in some coordinate system. Then for each direction of vector e_R there is only one point where the transmitting dipole induces the field measured. And equation (3) defines the direction of the moment vector uniquely. The distance to this point can be found from following formula:

$$R = (|M|/|(3\, e_R\, e_R^{\,T} - 2E)\cdot 2\pi H|)^{1/3}. \tag{4}$$

Equation (4) describes a closed convex centrally symmetric surface Σ, which is a locus of possible dipole positions. This surface is close to the surface of an ellipsoid with principal axes proportional, correspondingly, to $2^{1/3}$, 1, 1, and is a revolution surface around the vector H direction (Fig. 3).

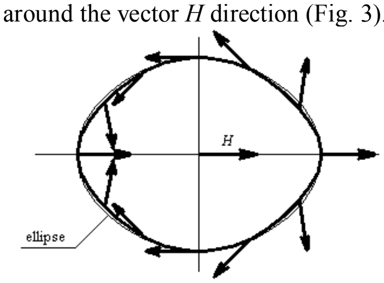

Fig. 3. A locus of possible positions of dipole M.

Should be noted that in case of periodical induction $M \cos \omega t$ the relations (1)-(4) are correct for the amplitudes of magnetic moment and magnetic field strength..

Consider now two dipoles placed in one point with moment vectors M_1, M_2 pointed to essentially different directions. This situation is possible if transmitting centers of loops mounted in different planes are coincident. Dealing with transient (time-domain) EM systems, such as GEOTEM, it is necessary to have a time shift between signals in two loops. For frequency-domain systems, such as EM-4H, it is enough to have different signal spectra in different loops. It allows separation of two dipoles fields in a receiving point.

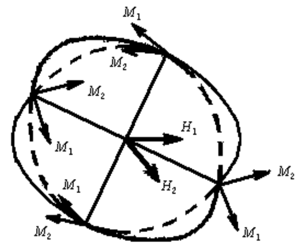

Fig. 4. Intersection of two surfaces.

Assuming the inducing moments amplitudes known one can find the two surfaces intersection line, which is the locus of possible dipoles position (Fig. 4). And if the third moment vector M_3 is linearly independent from both vectors M_1, M_2 then the surface associated with it in general case gives an intersection consisting of only eight points.

Consider a special case when M_1, M_2, M_3 form the right set of vectors. Suppose the receiver is placed in point S inside the octant I, formed by positive directions of dipole moments. Then vectors H_1, H_2, H_3 gives eight points O_{I}, O_{II},...,O_{VIII} and each of them defines three moment vectors uniquely (Fig. 5). But only for point O_{I} point S belongs to the octant I.

Due to linearity of the relations (2), (3) any three vectors can be chosen as the basis, not only moments vectors but also any linear combination of them. Thus arbitrary dipoles configuration can be converted to the previous case.

Dipole moments should be estimated for the method described. For this purpose the loop currents are measured and the geometry parameters of the loops are estimated during the initial calibration of the system.

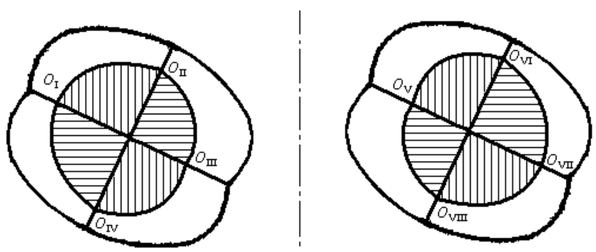

Fig. 5. Three surfaces intersection, top and bottom view.

Angular information usage

The method described has some limitations for practical usage. Calibration errors essentially affect the amplitude relations of system signals. Instability of loops geometry also has a negative effect [8]. At the same time all these factors have notable reduced influence on the angles. Considering the relation between amplitude and distance in expressions (2), (3) direction cosines of radius-vector can be calculated first and its length can be obtained using only that of H vectors, which will be used in EM survey data processing. To solve the problem in this formulation the values of angles between moment vectors are used.

Consider the two dimensional case first. Let the point O be an initial point of two orthogonal dipoles. Suppose the receiving point S is in the plane of the moment vectors M_1, M_2. The angle α between the field vectors H_1, H_2 is related with angle θ between the moment vector M_1 and the radius-vector R by the following equation:

$$3 \sin 2\theta = 4 \operatorname{ctg} \alpha, \tag{5}$$

which can be easily obtained from relations (1) for dipole field components.

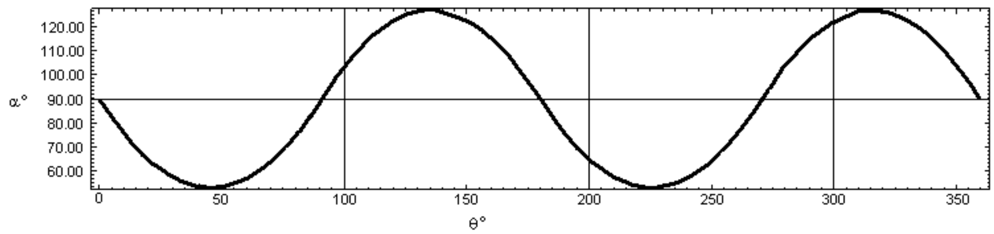

Fig. 6. $\alpha(\theta)$ chart.

Analyzing eqution (5) it can be lightly seen that the angle θ is well defined in vicinity of $\pi n/2$, and poor defined in vicinity of $\pi/4 + \pi n/2$, $n = 0,1,2,3$ (Fig. 6). For all possible orientations of the dipole moments M_1, M_2 with respect to the receiver axis one can obtain vectors of field for dipoles

$$M_1' = M_1 \cos\varphi - M_2 \sin\varphi\,,\quad M_2' = M_1 \sin\varphi + M_2 \sin\varphi \;\Rightarrow$$
$$H_1' = H_1 \cos\varphi - H_2 \sin\varphi\,,\quad H_2' = H_1 \sin\varphi + H_2 \sin\varphi$$

for any value of φ, including the case when the vector M_1' coincident with the direction of radius-vector R. This method is acceptable when there is no possibility to install three inducing dipoles. In this case lateral deviations can not be estimated, but these deviations don't involve essential variations of the secondary field.

Suppose we have set of three orthogonal dipoles M_1, M_2, M_3 and vector M_1 is directed to the receiver. Then the angle ψ can be taken so that the vector H_3' is orthogonal to the pair H_1, H_2':

$$H_2' = H_2 \cos\psi - H_3 \sin\psi\,,\quad H_3' = H_2 \sin\psi + H_3 \sin\psi \;\Rightarrow\; H_3'^T H_1 = H_3'^T H_2' = 0.$$

In this case the receiver is placed in the plane of vectors M_1, M_2' and we come to the two dimensional case. Further the distance to the main dipole can be found using formula (4).

To solve the problem in this formulation the angles between inducing dipole vectors and the value of the main moment M_1 are measured during initial calibration.

Flight tests results

Airborne electromagnetic system EM-4H is well adapted for the described method of navigation task solution because the additional dipoles are already used for compensation of induced polarization of aircraft [11]: induced field vector is associated with conductive parts of fuselage and is stable in axis of aircraft, so it can be represented by linear combination of inducing dipoles. In case of An-2, An-3 fixed-wing aircrafts main magnetic dipole moment is directed downwards and the moment of one additional dipole is directed along the fuselage. Dipole moment vectors are orthogonal (Fig. 7). In case of Mi-8 helicopter there are two additional dipoles with moments in horizontal plane mounted symmetrically with respect to the longitudinal axis of the helicopter. Each additional dipole is formed by two solenoidal coils (Fig. 8). The sum and the difference of additional moment vectors with the main loop moment vector give the set of three orthogonal vectors.

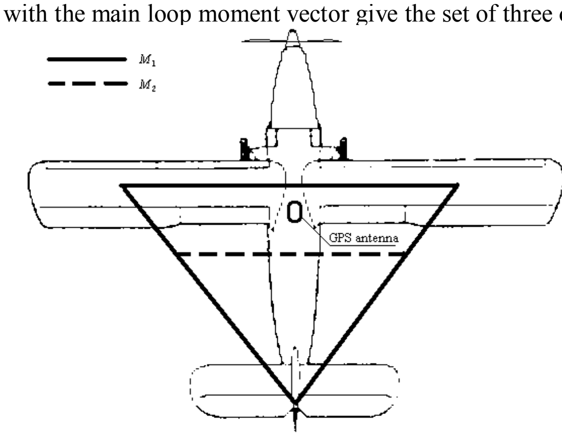

Fig. 7. Loops scheme for installation in An-3, An-2.

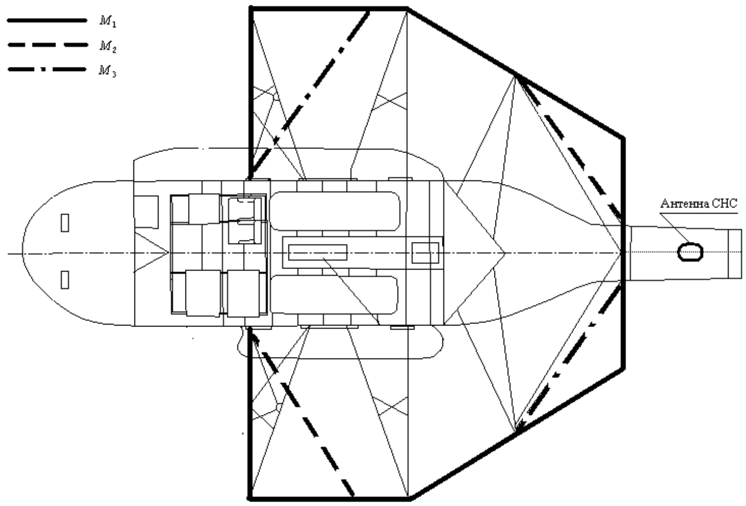

Fig. 8. Loops scheme for installation in Mi-8.

For accuracy analysis and for initial calibration the relative differential mode solution of the Satellite Navigation System (SNS) was used. One SNS receiver was installed in the aircraft and another one in the bird (Fig. 9). Both receivers measured L1 signals of GPS satellites.

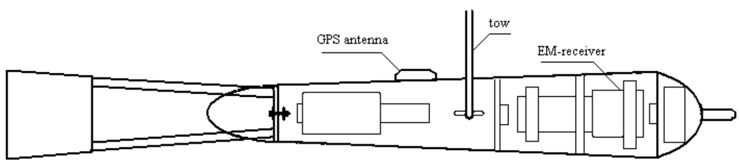

Fig. 9. The towed bird.

The Figure 10 represents the results of the flight test on the Mi-8 helicopter. For the better estimation of the method capabilities the bird was disturbed by special attachment on the tail. This led to the bird angular evolutions with period of about four seconds. Here and further the x-axis represents the distance along the aircraft's path.

The upper chart shows the distance in meters measured by three methods: R_{GPS} — using SNS differential mode, R_{EM} — electromagnetic method, using three dipoles, R_{Sm} — electromagnetic method suggested by Richard S. Smith for the GEOTEM like systems, using one dipole [10]. The misalignment of R_{EM} and R_{Sm} is due to evolutions of receiver axes with respect to inducing dipoles.

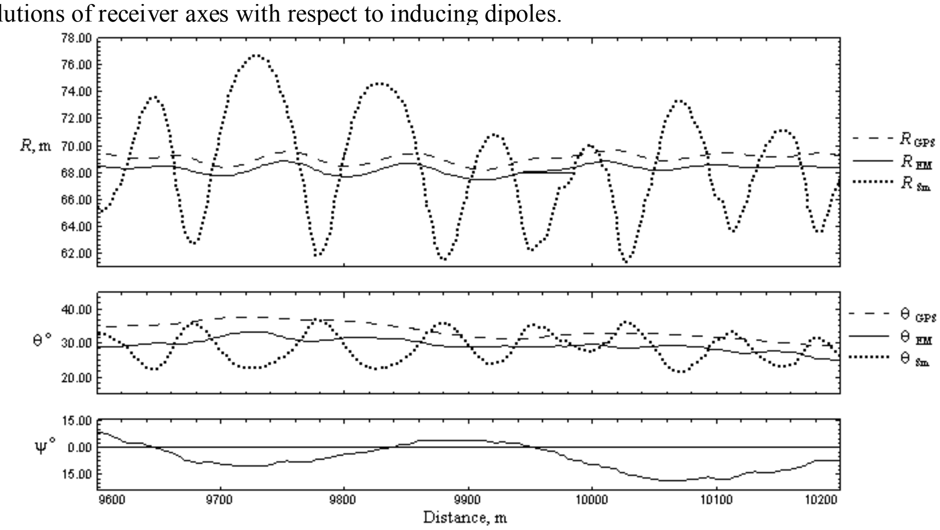

Fig. 10. Distance and angles measurements for Mi-8 helicopter.

The middle chart represents the angle measured in vertical plane: θ_{GPS} — the angle between the radius-vector R and local vertical line measured by SNS in differential mode, θ_{EM} — the angle between the radius-vector R and the moment vector M_1, measured using three dipoles, θ_{Sm} — the angle between the radius-vector R and the moment vector M_1, measured using one dipole. All angles are measured in degrees.

The lower chart shows the angle ψ of lateral deviations of the bird from the longitudinal plane of the helicopter, in degrees.

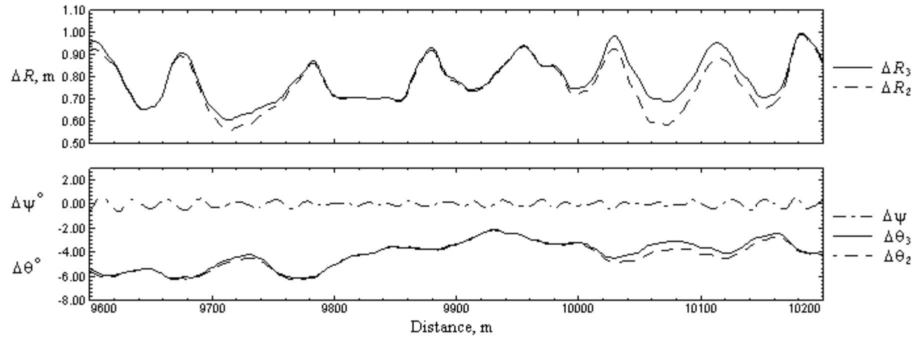

Fig. 11. Differences of the measured distances and angles for Mi-8 helicopter.

The upper chart of the Figure 11 represents the difference between the distances measured by electromagnetic method and by SNS, in meters. The constant component (about 80 cm) is due to SNS antennas shift and initial calibration errors. ΔR_3 fluctuations with amplitude about 10-15 cm are the forced by angular evolutions of the bird and as a result by angular deviations of the receiver with respect to the SNS antenna, which is located in approximately 1.5 m off the receiver. The dashed line ΔR_2 corresponds to the distance calculated without reference to the lateral deviations, i.e. using fild measurements of two dipoles only. The difference between ΔR_2 and ΔR_3 is less then 10 cm for lateral deviations up to 15 degrees.

The lower chart shows the difference between $\Delta\theta_2$ and $\Delta\theta_3$ calculated in by the similar way, in degrees. Here $\Delta\theta$ fluctuations in the range from -4 to -6 degrees is mainly the result of helicopter pitch evolutions. The difference between $\Delta\theta_2$ and $\Delta\theta_3$ is less then 0.7 degree.

The high frequency component of the angle of lateral deviations $\Delta\psi$ is represented on the same chart, in degrees. Fluctuations with the period of about one second and amplitude under 0.5 degree are due to addition dipoles attachment features. Only their signals are used in ψ calculation in case of Mi-8 installation. The reason is that additional loops mounted on the head part of the fuselage (Fig. 8) haven't got a rigid framework and therefor airflow changes their geometry.

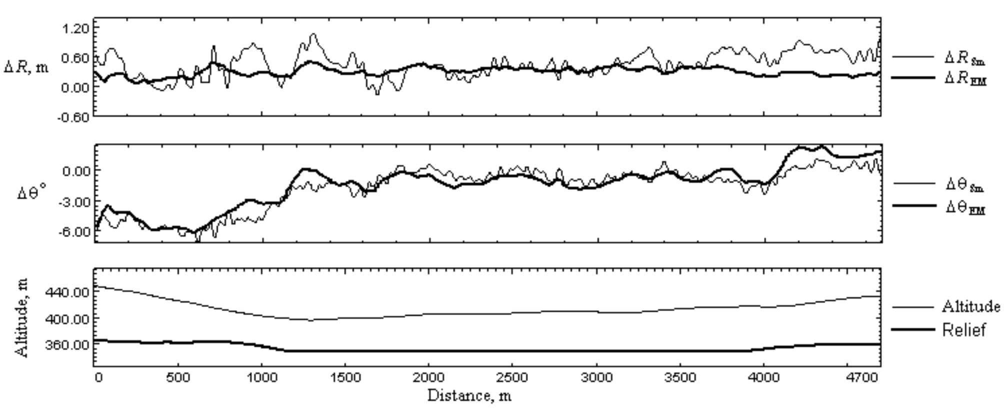

Fig. 12. Differences of the measured distances and angles for An-2 fixed-wing aircraft.

The Figure 12 represents the results of flight test on the An-2 airplane with two dipoles. Standard towed bird was used. The upper chart shows the difference between the distances measured by electromagnetic methods and by SNS in differential mode, in meters. ΔR_{EM} corresponds the electromagnetic method with two dipoles, ΔR_{Sm} — the electromagnetic method with one dipoles. The middle chart represents the difference between the angles measured by electromagnetic methods and by SNS. $\Delta\theta_{EM}$ — for two dipoles method, $\Delta\theta_{Sm}$ — for one dipole method.

Should be noted that the flight was followed the terrain contours and the lower chart represents relief and altitude. The airplane is diving first 1000 meters and is pitching up the last 700 meters.

During the straight flight the amplitude of ΔR_{EM} fluctuations is about 5 cm, for ΔR_{Sm} — 20 см. During the dive ΔR_{EM} amplitude is 20 см, ΔR_{Sm} — 40 см. The character period of ΔR_{EM} fluctuations is about ten seconds, which corresponds with slow fluctuation of the bird on the 70 meters long tow. In case of ΔR_{Sm} a new component with 1.5 seconds period appears. It corresponds with the angular fluctuations of the receiver axes. The constant component is due to SNS antennas shift and initial calibration errors.

Diving and pitch up zones can be easily seen on the chart of $\Delta\theta$. In case of dive θ is 3-4 degrees smaller then in straight flight, in case of pitch up 2-3 degrees greater. In the chart of $\Delta\theta_{Sm}$ one can see a component associated with the receiver fluctuations. Its amplitude — 1-2 degree.

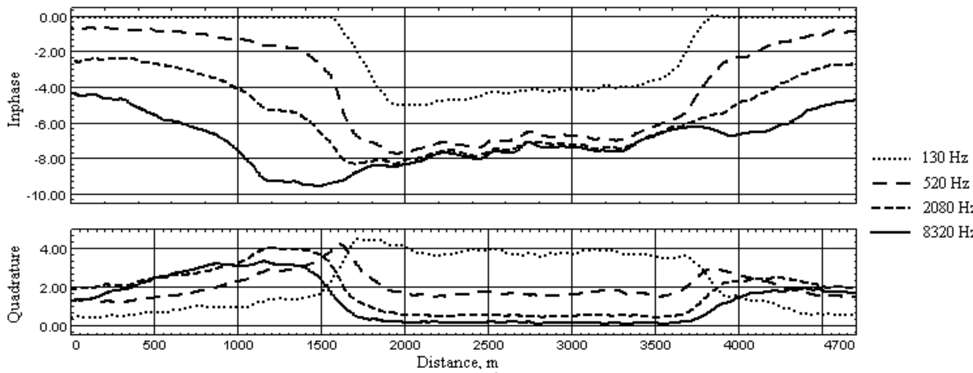

Fig. 13. Vertical projection of the response, in-phase and quadrature components.

The figure 13 shows the result of navigation parameters usage. The survey was flown over the salt lake Tus in Khakasiya. The resistivity of the ground there is approximately 100 Ohmm, the resistivity of the salt water is about 0.1 Ohmm. The achieved navigation solution allowed separation of the in-phase response from the primary field in both resistive and conductive environment (upper chart). It essentially simplify data interpretation. For example, for the frequency 2080 Hz the quadrature component of the signal has the same amplitude over ground and over lake (lower chart), while the in-phase component differs by almost one order.

Conclusions

The solution of the described navigation problem is of great practical importance. First the distance measurements are as accurate as for the Satellite Navigation System in differential mode. It was shown that the accuracy is limited by the geometry stability of the transmitter loops configuration and potentially can be better then 1 cm.

Second the angels of the relative orientation are measured with the accuracy better then one degree.

Third for the first time the full response measurement became available for systems of described type due to the presented navigation solution. EM-4H is the unique system with loose transmitter-receiver connection measuring both in-phase and quadrature components with accuracy about 1% for the averaging interval about 0.5 sec.

It was also shown that in case of airborne electromagnetics usage of two dipoles mounted in the vertical longitudinal is quit enough to measure navigation parameters.

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