Peer Reviewed, Open Access, Free Online Journal
Published monthly : ISSN: 2308-832X
Issue 9(18); September 2014

Original Article: GRADIOMETRIC SYSTEMS BASED ON THREE-COMPONENT VARIABLE-BASELINE MAGNETOMETER

Citation
Milovzorov G.V., Milovzorov D.G., Yasoveev V.Kh., Redkina T.A. Gradiometric Systems Based On Three-Component Variable-Baseline Magnetometer. *Italian Science Review*. 2014; 9(18). PP. 53-60.
Available at URL: http://www.ias-journal.org/archive/2014/september/Milovzorov.pdf

Authors
G.V. Milovzorov, Udmurt State University, Russia.
D.G. Milovzorov, department of electronics and biomedical technologies, Russia.
V.Kh. Yasoveev, Ufa State Aeronautic Technical University, Russia.
T.A. Redkina, Kalashnikov Izhevsk State Technical University, Russia.

Submitted: August 25, 2014; Accepted: September 5, 2014; Published: September 21, 2014

The article discusses issues related to the construction of the gradiometric systems based on the flux-gate transducers. The paper includes both structure and scheme of relative positions of three-component transmitters with flux-gate transducers. The text focuses on basic and generalized mathematical expressions for the two three-component flux-gate transmitters which comprise the gradiometric system.

Key words: gradiometer, magnetometer, three-component flux-gate transducer, three-component accelerometer transducer.

While studying magnetic fields in practical terms one may face a challenge to determine the gradient spatial distribution of the resultant vector or field strength. The list of similar tasks could be completed by a range of researches related to magnet field in core clearance and local inhomogeneities in polar area, estimation of ferromagnetic components' remanent magnetization, defectoscopy, search and finding of ferromagnetic items (weapons, ammunition supplies), concealed under clothing or in the baggage, and also search of ferromagnetic rocks in a near-surface zone of subsoil. Such objects have either their own magnetic field or distort homogeneous Earth's field. One way or another magnetic strength in a sensor element's zone would vary its value and direction. This is what should be identified as a property of a ferrous object. As regard to the target these tools are passive, i.e. they do not have any considerable effect on the target. [1-4].

Engineers involved in the studying of magnetic measurements would opt for flux-gate transducers that are considered to be the centerpiece while developing tools of this nature. It is caused by a number of advantages as compared to Hall transducer and inductive transducers:

- simple design and high reliability:
- low sensibility level, down to nT:
- considerable turn down;
- low-power discharge (mA);
- rapid response etc.

Flux-gate in its classical interpretation is regarded as a magnetic modulation measuring transmitter aimed to measure parameters of weak magnetic fields (magnetic induction or density) which include geomagnetic field in particular.

However regardless of the type of applied transducers traditional gradiometer scheme is introduced as two identical half-cells dispersed in particular distance indicated as the base of gradiometer L. Differential signal of transducers is in proportion to density gradient of the magnetic field in its basic direction. Direct measurements of gradients allow to improve accuracy of the obtained data in comparison with the results obtained due to differentiation of density distribution curve of the magnetic field (especially if we take into account highly nonhomogeneous fields). Thus, the main point of gradiometry measurements is to determine the value and the excess index of the density of the field under consideration at the given base.

While designing and developing similar tools special emphasis should be placed on providing invariancy of measuring transmitters when it comes to laminar geomagnetic field.

There are different alternatives of design and structural variations of gradiometers with flux-gate transducers. The preference of any given alternative depends on both particular gradiometry objective and a priori grounds that reveal the level of local distortion of magnetic field lines.

It is quite reasonable to use three-component flux-gate transmitters to complete difficult gradiometry tasks.

Deviation angle and sight angle transmitters; F_{ik} – flux-gate

The given arrangement of gradiometer allows to register density excess of the field under consideration in three projections $\Delta T_{i(i=x,y,z)}$, which provides control of full vector variations including both its value and direction.

The possibility to change gradiometer base enables us to improve its functional capabilities and to streamline the workflow according to parameters of the assumed subject of research.

The adequate choice of base L of the magnetometric gradiometer makes it possible to provide the search of local features in the environment of electromagnetic interference which could be observed in real conditions and as a result could lead to some smooth variation of external magnetic field. Reasonable length of the base L should be adjusted to the expected mass of subject of research and its dimensions. The base length could be considered reasonable if it is 1,5-2 times higher than the equivalent radius of the object of search.

Fig. 2 illustrates the scheme of the gradiometer with three-component flux-gate transmitters and a variable base.

F_{X1} e F_{X2}, F_{Y1} e F_{Y2}, F_{Z1} e F_{Z2} flux-gates are strictly parallel to each other in the space.

The given scheme has the following functional principle. A series of rectangular impulses having frequency level of about100 khz and amplitude of 2,5 V simultaneously flows to drive windings of three pairs of orthographic single-bar and single-inductor flux-gates F_{ik} (i = X, Y, Z; k = 1, 2). The impulses mentioned above flow through current-limiting resistors R_{ik} and blocking capacitors C_{ik}.

When the signal runs through drive windings it transforms into bipolar signal of irregular shape with trailing edge and this bipolar signal is supposed to go to the relevant signal conditioner SC_{ik}. External magnetic field action would lead to designature both in positive and negative phases due to redistribution of harmonic components quantitative relationship in gross spectrum of the signal that would be revealed through the variation of the trailing edge attenuation.

Accumulated impulses are integrated subsequently and considerably intensified impulse indexes are transformed into effective voltage. The amplifier gain has been sorted out so that valid signal would be in a range of -4,5V up to +4,5. Received signals would go to the input terminal of 24-bit quantity sigma-delta analog-to-digital converter (ADC) and then would be transformed into digital code.

Gradiometer scheme includes three component deviation angle and sight angle transmitter based on A_X, A_Y e A_Z, accelerometric transducers to provide unambiguous definition of required angular dimensions.

Microcontroller inquires analog-to-digital converter (ADC), calculates required parameters like angle of magnetic azimuth and angle of magnetic dip for both of three-component flux-gate transmitters (TFT-1 and TFT-2) (fig. 1) in accordance with mathematical support, and prints on the screen which makes it possible for users to register measurement results.

The problem of mathematic simulation of three-component flux-gate transducers reduces to the common problem of solid body dimensional orientation according to which three flat turns relative to the main basis axis $R_0(0X_0Y_0Z_0)$, connected with full vectors of magnetic field strength $\vec{T}$ and gravity acceleration (figure 3) are set sequentially.

Full intensity vector $\vec{T}$ is divided to vertical $\vec{Z}$ and horizontal $\vec{H}$ constituents interconnected by magnetic inclination angle υ.

Initially the main basis R_0 is oriented so that axis $0X_0$ is directed to the north of magnetic meridian and coincides with vector direction $\vec{H}$, and axis $0Z_0$ is directed on vector $\vec{g}$.

So, the general vector-matrix equitation, describing the main basis transformation R_0 to basis R_3 with the appropriate turns to azimuth angle α around the axis 0Z, to zenith angle θ around the axis 0Y, and to sight angle φ around the axis 0Z, is as follows (1).

Where, $\vec{T}_{R0}$ and $\vec{T}_{R3}$ – vector projection of geomagnetic field intensity $\vec{T}$ in basses R_0 and R_3 accordingly; Aφ, Aθ, Aα – cosine matrix, consistent with serial flat turns of the basis R_0 to Euler-Krylov angles φ, θ and α accordingly.

If we multiply the left and right parts of the equation (1) to the transposed matrix sequentially we will get the following equation (2).

Where, T_{X3}, T_{Y3}, T_{Z3} – vector projection of geomagnetic field intensity $\vec{T}$ in basis R_3.

From the equation (2) one can see the system of transcendent equation of constraints (3).

To solve the equation system (3) the following standard mathematic expressions for two three-component flux-gate transducers are used (4), (5).

Here, T_{X1}, T_{Y1}, T_{Z1} e T_{X2}, T_{Y2}, T_{Z2} – measured vector projections of geomagnetic field intensity of the first TFP-1 and second TFP-2 three-component flux-gate transducers in basis R_3 accordingly; T_1 and T_2 – modules of full geomagnetic field intensity vectors, measured by the first and second transducers.

To provide measuring transducer invariance with regard to the external laminar geomagnetic field it is necessary to take into account the deviation angle of ferroprobe sensitive axis from the basis axis $R_3(0X_3Y_3Z_3)$, shown in Figure 4.

In this case the system of vector-matrix equation for projections $T_{R3i(i=X,\ Y,\ Z)}$ of basis R3, measured by one three-component flux-gate transducer with ferroprobe $F_{i(i=X,\ Y,\ Z)}$ is as follows (6).

Where,

$A_{\delta_X(Y)}$, $A_{\chi(Z)}$, $A_{\delta_Y(X)}$, $A_{\gamma(Z)}$, $A_{\sigma_1(X)}$ и $A_{\sigma_2(Y)}$ – cosine matrix, corresponding to the additional flat turns of basis $R_3(0X_3Y_3Z_3)$.

The factums $A_{\delta i}\cdot A_{\delta j}$ in the system (6) will be:

$$A_{\delta_X(Y)}\cdot A_{\chi(Z)}=\begin{Vmatrix}\cos\delta_X\cos\chi & \cos\delta_X\sin\chi & -\sin\delta_X\\ -\sin\chi & \cos\chi & 0\\ \sin\delta_X\cos\chi & \sin\delta_X\sin\chi & \cos\delta_X\end{Vmatrix},$$

$$A_{\delta_Y(X)}\cdot A_{\gamma(Z)}=\begin{Vmatrix}\cos\gamma & \sin\gamma & 0\\ -\cos\delta_Y\sin\gamma & \cos\delta_Y\cos\gamma & \sin\delta_Y\\ \sin\delta_Y\sin\gamma & -\sin\delta_Y\cos\gamma & \cos\delta_Y\end{Vmatrix},$$

$$A_{\sigma_1(X)}\cdot A_{\sigma_2(Y)}=\begin{Vmatrix}\cos\sigma_2 & 0 & -\sin\sigma_2\\ \sin\sigma_1\sin\sigma_2 & \cos\sigma_1 & \sin\sigma_1\cos\sigma_2\\ \cos\sigma_1\sin\sigma_2 & -\sin\sigma_1 & \cos\sigma_1\cos\sigma_2\end{Vmatrix}.$$

Having made the appropriate transformations, the system (6) may be represented in the form of the three equation system with three unknowns x, y and z (7).

Where, $t_{i(i=X,Y,Z)} = \frac{T_{R3i(i=X,Y,Z)}}{|T|}$ – adjusted values of measured vector projections of geomagnetic field intensity $\vec{T}$ (8).

Having solved the equation system (7) in regard to x, y, z with measured $t_{i(i=X,\ Y,\ Z)}$, θ , φ and known parameters {A,…,M} (8), unknown angles α_1, υ_1, α_2, υ_2 of two three-component flux-gate transducers are defined as follows (9), (10).

where a_1 and b_1 – numerator and denominator of the first equation (9), a_2 and b_2 – numerator and denominator of the first equation (10).

Deduced expressions (9) and (10) are the extended static mathematic expressions TFTA-1 and TFTA-2.

To estimate the approximation degree of the base (4), (5) and extended (9), (10) mathematic expressions, and to compare the received errors, it is necessary to use a computational experiment - computer simulation. Simulation results for one three-component flux-gate transducer are shown in Figures 5, 6. The simulation was carried out by using equal values of small angle parameters $\delta_{i(i=X,\ Y)}$, χ, γ e $\sigma_{j(j=1,\ 2)}$, that were 1, 2, 3 degrees.

The accelometric transducers errors, in order to simplify a problem, are not taken into account, because they are sufficiently small.

Outcome analysis of the computational experiment shows that the calculation of azimuth according to the base mathematic expression (4) is rather inaccurate, and the error with defined θ, φ, $\delta_{i(i=X,\ Y)}$, χ, γ and $\sigma_{j(j=1,\ 2)}$ is about 16 degrees. The error according to the extended expression (9) is rather small, about 10^{-14} degrees.

In absence of magnetic gradient with the distance L, expressions (9) and (10) will be equal, and with the magnetic gradient the increments will be as follows:

Δα = α2 – α1; Δυ = υ2 – υ1; ΔT = T2 – T1.

While developing and creating such kind of equipment it is necessary to pay special attention to providing the invariance of measuring transducers with regard to external laminar geomagnetic field.

It can be achieved by the fact that half-elements – ferroprobes must be equal, namely, output signals should have equal transformation coefficients, that correspond to the rate of static characteristics, and sensitive axes must be strictly parallel.

Thus, the given gradiometer scheme (Fig.1), while measuring the induction resultant or field intensity, allows to define at the base distance L not only the full vector increment ΔT, but also angular increments in horizontal plane Δα and in vertical plane Δυ. Moreover, the Δυ parameter determination does not depend on spatial attitude of gradiometer body.

References:

1. Ljubimov V.V. 1998. Diagnostic magnetometers for electromagnetic monitoring in urban area and modern methods and means of individual mass visualization of its results.
2. Shcherbakov G.N. 1998. Detection in concealment environments. For criminalistics, archeology, engineering development and antiterrorism protection.
3. Afanasiev Y. V. 1986. Ferroprobes.
4. Milovzorov D.G., Loginova T.M. 2009. Gradiometric transmitters with flux-gate transducers. Measurement, control, informational support. Papers for the ninth international scientific and technical conference. p. 51-53.

Fig. 1. Relative positions of three-component transmitters with flux-gate transducers: TFT – three-component flux-gate transmitters

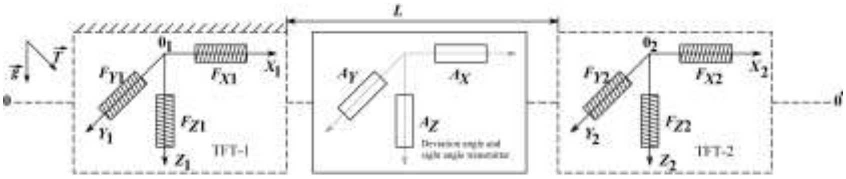


Fig. 2. Functional chart of the magnetometric gradiometer with three-component flux-gate transmitters

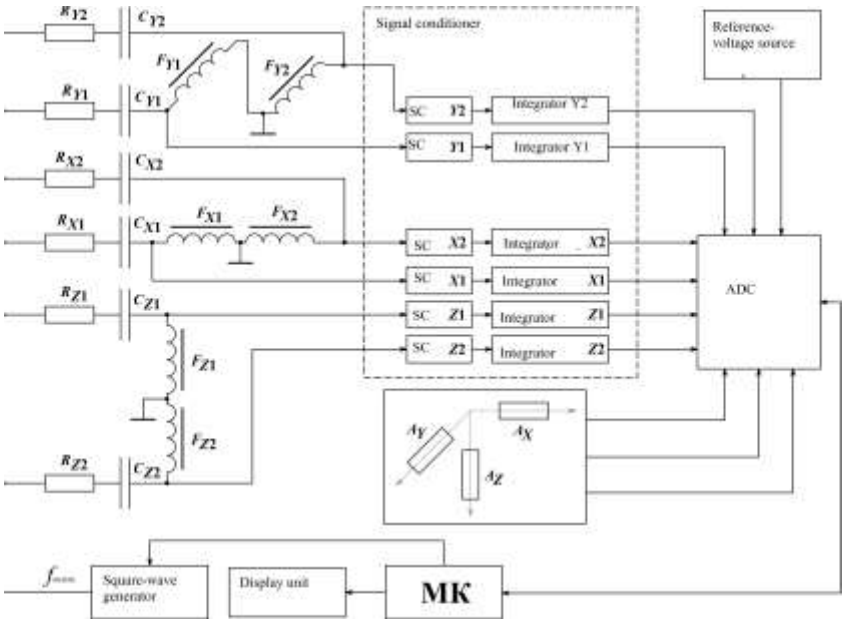


Fig 3. Main basis $R_0(0X_0Y_0Z_0)$

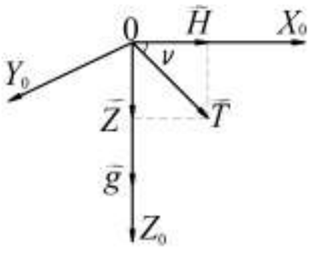


Fig. 4. The deviation angle of ferroprobe sensitive axis from the basis axis $R_3(0X_3Y_3Z_3)$

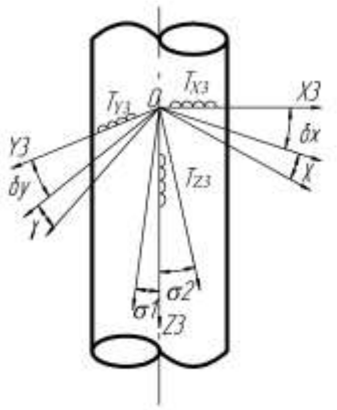


Fig. 5. Allocation of errors $|\Delta\alpha|$ over the range α with $\theta = 60°$, $\varphi = 210°$ according to the base mathematic expression (4)

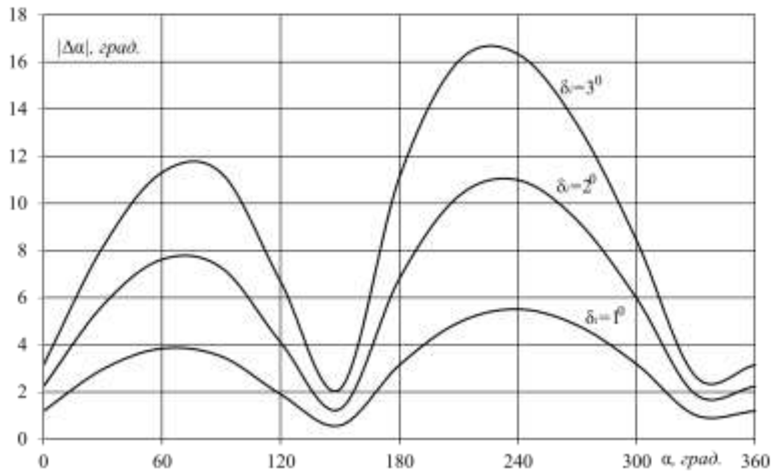
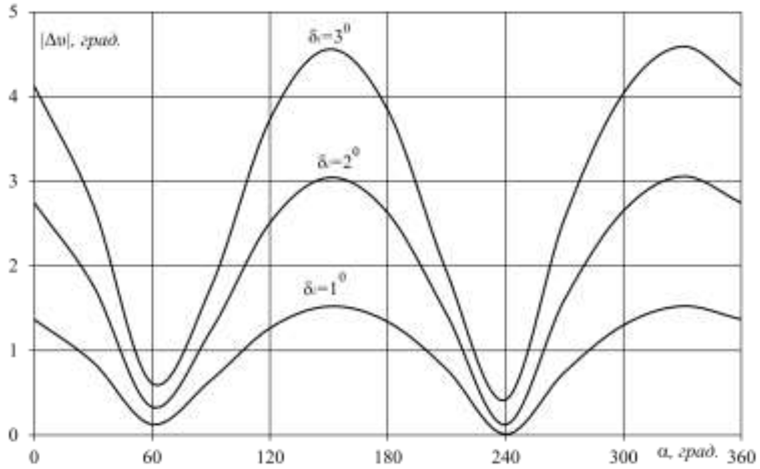


Fig. 6. Allocation of errors |Δυ| over the range α with θ = 60°,
φ = 210° according to the base mathematic expression (4)



$$\vec{T}_{R3} = A_{\varphi(Z)} A_{\theta(Y)} A_{\alpha(Z)} \vec{T}_{R0} \qquad (1)$$

$$A_{\alpha(Z)} \begin{Vmatrix} T\cos v \\ 0 \\ T\sin v \end{Vmatrix} = A^{T}_{\theta(Y)} A^{T}_{\varphi(Z)} \begin{Vmatrix} T_{X3} \\ T_{Y3} \\ T_{Z3} \end{Vmatrix} \qquad (2)$$

$$\left.\begin{aligned} & T_{X3}\cos\theta\cos\varphi - T_{Y3}\cos\theta\sin\varphi + T_{Z3}\sin\theta = \cos\alpha\cos v\cdot T \\ & T_{X3}\sin\varphi + T_{Y3}\cos\varphi = -\sin\alpha\cos v\cdot T \\ & -T_{X3}\sin\theta\cos\varphi + T_{Y3}\sin\theta\sin\varphi + T_{Z3}\cos\theta = \sin v\cdot T \end{aligned}\right\} \qquad (3)$$

$$\left.\begin{aligned} & \alpha_1 = \operatorname{arctg}\frac{-(T_{X1}\sin\varphi + T_{Y1}\cos\varphi)}{\cos\theta(T_{X1}\cos\varphi - T_{Y1}\sin\varphi) + T_{Z1}\sin\theta} \\ & v_1 = \operatorname{arctg}\frac{\sin\theta(-T_{X1}\cos\varphi + T_{Y1}\sin\varphi) + T_{Z1}\cos\theta}{\sqrt{[\cos\theta(T_{X1}\cos\varphi - T_{Y1}\sin\varphi) + T_{Z1}\sin\theta]^2 + [T_{X1}\sin\varphi + T_{Y1}\cos\varphi]^2}} \\ & T_1 = \sqrt{T_{X1}^2 + T_{Y1}^2 + T_{Z1}^2} \end{aligned}\right\} \qquad (4)$$

$$\left.\begin{aligned} & \alpha_2 = \operatorname{arctg}\frac{-(T_{X2}\sin\varphi + T_{Y2}\cos\varphi)}{\cos\theta(T_{X2}\cos\varphi - T_{Y2}\sin\varphi) + T_{Z2}\sin\theta} \\ & v_2 = \operatorname{arctg}\frac{\sin\theta(-T_{X2}\cos\varphi + T_{Y2}\sin\varphi) + T_{Z2}\cos\theta}{\sqrt{[\cos\theta(T_{X2}\cos\varphi - T_{Y2}\sin\varphi) + T_{Z2}\sin\theta]^2 + [T_{X2}\sin\varphi + T_{Y2}\cos\varphi]^2}} \\ & T_2 = \sqrt{T_{X2}^2 + T_{Y2}^2 + T_{Z2}^2} \end{aligned}\right\} \qquad (5)$$

$$\left.\begin{aligned}\vec{T}_{R3X} &= A_{\delta_X(Y)} \cdot A_{\chi(Z)} \cdot A_{\varphi(Z)} \cdot A_{\theta(Y)} \cdot A_{\alpha(Z)} \cdot \vec{T}_{R0} \\ \vec{T}_{R3Y} &= A_{\delta_Y(X)} \cdot A_{\gamma(Z)} \cdot A_{\varphi(Z)} \cdot A_{\theta(Y)} \cdot A_{\alpha(Z)} \cdot \vec{T}_{R0} \\ \vec{T}_{R3Z} &= A_{\sigma_1(X)} \cdot A_{\sigma_2(Y)} \cdot A_{\varphi(Z)} \cdot A_{\theta(Y)} \cdot A_{\alpha(Z)} \cdot \vec{T}_{R0}\end{aligned}\right\} \quad (6)$$

$$\left.\begin{aligned}t_X &= Ax + By + Cz \\ t_Y &= Dx + Ey + Fz \\ t_Z &= Kx + Ly + Mz\end{aligned}\right\} \quad (7)$$

$$\left.\begin{aligned}
A &= \cos\delta_X \cos\theta(\cos\chi\cos\varphi - \sin\chi\sin\varphi) - \sin\delta_X \sin\theta \\
B &= \cos\delta_X (\cos\chi\sin\varphi + \sin\chi\cos\varphi) \\
C &= \cos\delta_X \sin\theta(\sin\chi\sin\varphi - \cos\chi\cos\varphi) - \sin\delta_X \cos\theta \\
D &= -\cos\delta_Y \cos\theta(\sin\gamma\cos\varphi + \cos\gamma\sin\varphi) + \sin\delta_Y \sin\theta \\
E &= \cos\delta_Y (\cos\gamma\cos\varphi - \sin\gamma\sin\varphi) \\
F &= \cos\delta_Y \sin\theta(\sin\gamma\cos\varphi + \cos\gamma\sin\varphi) + \sin\delta_Y \cos\theta \\
K &= \cos\theta(\cos\sigma_1 \sin\sigma_2 \cos\varphi + \sin\sigma_1 \sin\varphi) + \\
&\quad + \cos\sigma_1 \cos\sigma_2 \sin\theta \\
L &= \cos\sigma_1 \sin\sigma_2 \sin\varphi - \sin\sigma_1 \cos\varphi \\
M &= -\sin\theta(\cos\sigma_1 \sin\sigma_2 \cos\varphi + \sin\sigma_1 \sin\varphi) + \\
&\quad + \cos\sigma_1 \cos\sigma_2 \cos\theta
\end{aligned}\right\} \quad (8)$$

$$\left.\begin{aligned}
\alpha_1 &= \operatorname{arctg} \frac{t_{X1}(DM - FK) + t_{Y1}(CK - MA) + t_{Z1}(FA - CD)}{t_{X1}(EM - FL) + t_{Y1}(LC - BM) + t_{Z1}(BF - CE)} \\
\upsilon_1 &= \operatorname{arctg} \frac{t_{X1}(DL - EK) + t_{Y1}(KB - LA) + t_{Z1}(AE - BD)}{\sqrt{a_1{}^2 + b_1{}^2}} \\
T_1 &= \sqrt{t_{X1}^2 + t_{Y1}^2 + t_{Z1}^2}
\end{aligned}\right\} \quad (9)$$

$$\left.\begin{aligned}
\alpha_2 &= \operatorname{arctg} \frac{t_{X2}(DM - FK) + t_{Y2}(CK - MA) + t_{Z2}(FA - CD)}{t_{X2}(EM - FL) + t_{Y2}(LC - BM) + t_{Z2}(BF - CE)} \\
\upsilon_2 &= \operatorname{arctg} \frac{t_{X2}(DL - EK) + t_{Y2}(KB - LA) + t_{Z2}(AE - BD)}{\sqrt{a_2{}^2 + b_2{}^2}} \\
T_2 &= \sqrt{t_{X2}^2 + t_{Y2}^2 + t_{Z2}^2}
\end{aligned}\right\} \quad (10)$$