formulation of fluctuation loss remains for further study.

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Conversion of Earth-Centered Earth-Fixed Coordinates to Geodetic Coordinates

The transformations between Earth-centered Earth-fixed (ECEF) coordinates and geodetic coordinates are required in many applications, for example, in NAVSTAR/GPS navigation and geodesy. The transformation from ECEF coordinates to geodetic coordinates is usually carried out by approximation methods in practice, and the exact transformation methods are not used frequently. In this paper, several exact transformation formulas from ECEF coordinates to geodetic coordinates are reviewed, and compared with the approximation methods in complexity and in sensitivity to computer round-off error. The relationship among some exact transformation solutions and the approaches are pointed out.

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I. INTRODUCTION

The transformations between Earth-centered Earth-fixed (ECEF) coordinates and geodetic coordinates are required in many applications, for example, in NAVSTAR/GPS navigation geodesy. The exact transformation from geodetic coordinates to ECEF coordinates is well known [1, 2], but the exact inverse transformation (from ECEF to geodetic) is not so well known, and the approximation methods [2–4] are prevailing. The quest for a both mathematically exact and practically simple and stable transformation formula has never stopped.

There are several different exact transformation formulas found so far. Paul [5] seems to be the first to provide an exact analytic transformation formula. Heikkinen [6] presented the first exact analytical formula free of singularities. Barbee [7] gave a simple transformation formula. Borkowski [8, 9] developed a concise formula. The latest entry is made by Zhu [10], whose formula is also free of singularities.

In Section II, the exact transformation formulas from ECEF coordinates to geodetic coordinates are reviewed. In Section III, the relations between these formulas are pointed out and an algorithm analogous to a known one is given explicitly. The results of comparison with approximation algorithms in complexity and sensitivity to computer round-off error are presented in Section IV. And conclusions are drawn in the last section.

II. EXACT CONVERSIONS OF ECEF TO GEODETIC COORDINATES

The ECEF coordinates (x,y,z) of point P can be determined from its geodetic coordinates (ϕ,λ,h) by the following algorithm [5]:

$$x = (R+h)\cos\phi\cos\lambda$$
$$y = (R+h)\cos\phi\sin\lambda$$
$$z = (R+h-e^2R)\sin\phi$$

where

$$R = a/(1-e^2\sin^2\phi)^{1/2}.$$

Here,

ϕ is the geodetic latitude (positive North),
λ is the geodetic longitude (measured east from the Greenwich meridian),
h is the altitude normal to ellipsoid,

a is the ellipsoidal equatorial radius ($a =$ 6378.137 km for model WGS-84),
e is the eccentricity of ellipsoid ($e^2 = 0.00669437999$ for model WGS-84),
b is the ellipsoidal polar radius ($b = a\sqrt{1-e^2}$).

Now consider the transformation from ECEF coordinates to geodetic coordinates. The geodetic longitude λ can be determined in four quadrants by the identity

$$\lambda = 2\arctan[(\sqrt{x^2+y^2} - x)/y]$$

which can be implemented by the built-in function $\operatorname{atan2}(y,x)$ in computer programming languages. Now our attention can be concentrated on the meridian plane of point $P(r,z)$ to find out the latitude ϕ and height h from r and z, where $r = \sqrt{x^2+y^2}$. By taking a linear transform of $\tan\phi = (\zeta + z/2)/r$, and solving a quartic equation in ζ, Paul [5] derived the following algorithm

$$\alpha = (r^2 + a^2e^4)/(1-e^2)$$

$$\beta = (r^2 - a^2e^4)/(1-e^2)$$

$$q = 1 + 13.5z^2(\alpha^2 - \beta^2)/(z^2+\beta)^2$$

$$p = \sqrt[3]{q + \sqrt{q^2-1}}$$

$$t = (z^2+\beta)(p+p^{-1})/12 - \beta/6 + z^2/12$$

$$\phi = \arctan\left(\left(z/2 + \sqrt{t} + \sqrt{z^2/4 - \beta/2 - t + \alpha z/(4\sqrt{t})}\right)/r\right)$$

$$h = r/\cos\phi - R.$$

As pointed out by Paul [5], when z/a is sufficiently small, the expression for ϕ should be replaced by

$$\phi = \arctan((\alpha+\beta+\gamma)z/(2\beta r) - \gamma(\alpha+\gamma)^2z^3/(4\beta^4 r))$$

where $\gamma = \sqrt{\alpha^2 - \beta^2}$.

Heikkinen [6] established a quartic equation in r_0, the r-coordinate of the subpoint P_0 on the surface of the ellipsoid and found a solution without singularities on the equatorial plane. Heikkinen's formula is

$$e'^2 = (a^2-b^2)/b^2$$

$$F = 54b^2z^2$$

$$G = r^2 + (1-e^2)z^2 - e^2(a^2-b^2)$$

$$c = e^4Fr^2/G^3$$

$$s = \sqrt[3]{1 + c + \sqrt{c^2+2c}}$$

$$P = \frac{F}{3(s+1/s+1)^2G^2}$$

$$Q = \sqrt{1+2e^4P}$$

$$r_0 = -\frac{Pe^2r}{1+Q} + \sqrt{\frac{a^2}{2}\left(1+\frac{1}{Q}\right) - \frac{P(1-e^2)z^2}{Q(1+Q)} - \frac{Pr^2}{2}}$$

$$U = \sqrt{(r-e^2r_0)^2 + z^2}$$

$$V = \sqrt{(r-e^2r_0)^2 + (1-e^2)z^2}$$

$$z_0 = \frac{b^2z}{aV}$$

$$h = U\left(1 - \frac{b^2}{aV}\right)$$

$$\phi = \arctan((z + e'^2z_0)/r).$$

Barbee [7] presented another exact algebraic solution. He, in effect, took a transformation of $\tan\phi = at/(b\sqrt{1-t^2})$ and solved a quartic equation in t. Although Barbee made the assumption that the point to be transformed be above the surface of the Earth, the formula he derived is valid for any point more than 43 km away from the center of the Earth. His formula can be written as

$$A = b|z|/(a^2-b^2)$$

$$B = ar/(a^2-b^2)$$

$$P = (A^2+B^2-1)/3$$

$$S = 2A^2B^2$$

$$Q = P^3 + S$$

$$D = \sqrt{(2Q-S)S}$$

$$v = \sqrt[3]{Q+D} + \sqrt[3]{Q-D} + P$$

$$U = \sqrt{v - B^2 + 1}$$

$$t = \left(\sqrt{A^2 - B^2 + 1 - v + 2A(B^2+1)/U} + U - A\right)/2$$

$$\phi = \operatorname{sign}(z)\arctan[at/(b\sqrt{1-t^2})]$$

$$h = (|z|/t - b)\sqrt{1 - e^2(1-t^2)}.$$

A new procedure was developed by Borkowski [8, 9]. By taking a trigonometric transform of $\tan\phi = a(1-t^2)/(bt)$ and solving a quartic equation in t, Borkowski derived his algorithm, which deals only with the nonnegative z. To deal with negative z, the expressions of E and F in the algorithm has to be interchanged. As noted by Borkowski, the results must be symmetric about the equatorial plane. Therefore, the Borkowski's algorithm can be modified to handle points on both hemispheres. The modified Borkowski's formula is

$$E = [b|z| - (a^2 - b^2)]/(ar)$$

$$F = [b|z| + (a^2 - b^2)]/(ar)$$

$$P = (4/3)(EF + 1)$$

$$Q = 2(E^2 - F^2)$$

$$D = P^3 + Q^2$$

$$v = -\sqrt[3]{\sqrt{D} + Q} + \sqrt[3]{\sqrt{D} - Q}$$

$$G = (\sqrt{E^2 + v} + E)/2$$

$$t = \sqrt{G^2 + (F - vG)/(2G - E)} - G$$

$$\phi = \operatorname{sign}(z)\arctan[a(1 - t^2)/(2bt)]$$

$$h = (r - at)\cos\phi + (|z| - b)|\sin\phi|.$$

Recently, Levin [11] took a rational parametric approach to arrive at a quartic equation, which is similar to the one Borkowski solved. Hsu [12] also studied this problem, and his approach is roughly the same as the Hedgley's approach [13]. What is common to the three algorithms by Hedgley, Levin, and Hsu is that their objectives are to provide closed-form solutions to achieve exact transformation of the coordinates, instead of providing a set of exact transformation formulas. They all stopped at a quartic equation which can be solved, though Levin [11] realized that the equation can be easily solved.

Zhu [10] derived another set of closed-form formulas which is, fortunately, different from the above algorithms, though the approach is similar to the approaches which Hedgley and Hsu took. Zhu constructed a quartic equation in an indeterminate t in the process of finding height h. It turns out that this is equivalent to taking a transform of $\tan\phi = z(t + l)/(r(t - l))$. The Zhu's formula is

$$l = e^2/2, \qquad m = (r/a)^2, \qquad n = [(1 - e^2)z/b]^2$$

$$i = -(2l^2 + m + n)/2, \qquad k = l^2(l^2 - m - n)$$

$$q = (m + n - 4l^2)^3/216 + mnl^2$$

$$D = \sqrt{(2q - mnl^2)mnl^2}$$

$$\beta = i/3 - \sqrt[3]{q + D} - \sqrt[3]{q - D}$$

$$t = \sqrt{\sqrt{\beta^2 - k} - (\beta + i)/2} - \operatorname{sign}(m - n)\sqrt{(\beta - i)/2}$$

$$r_0 = r/(t + l), \qquad z_0 = (1 - e^2)z/(t - l)$$

$$\phi = \arctan[z_0/((1 - e^2)r_0)]$$

$$h = \operatorname{sign}(t - 1 + l)\sqrt{(r - r_0)^2 + (z - z_0)^2}.$$

One more square root has been added in this algorithm to remove the singularities when $ar = b|z|$.

III. RELATIONSHIP OF THE ALGORITHMS

All of the algorithms given above can be derived from two distinct sets of basic relations, respectively. The first basic relation [14] is

$$r - z/\tan\phi = (a^2 - b^2)/\sqrt{a^2 + (b\tan\phi)^2}$$

and the second basic relation [6] is

$$z - z_0 = \frac{a^2 z_0}{b^2 r_0}(r - r_0), \qquad \frac{r_0^2}{a^2} + \frac{z_0^2}{b^2} = 1.$$

Paul [5] solved the first basic relation directly in $\tan\phi$ by taking a linear transform of $\tan\phi = (\zeta + z/2)/r$ and Borkowski [8, 9] constructed a quartic equation in t from the first basic relation by taking a trigonometric transform of $\tan\phi = a(1 - t^2)/(2bt)$. Heikkinen [6] based his algorithm completely on the second basic relation. Zhu's formula [10] can be derived either from the first basic relation by taking a bilinear transform of $\tan\phi = z(t + l)/(r(t - l))$ or from the second by taking a transform of $r_0 = r/(t + l)$ and $z_0 = (1 - e^2)z/(t - l)$. Zhu's approach can be related to Paul's approach by the transform $\zeta = z/2 + ze^2/(t - e^2/2)$.

As noted by Borkowski [8], t in his transform is equal to $\tan(\pi/4 - \psi/2)$, where ψ is the eccentric latitude, and a new algorithm exactly analogous to his algorithm can be obtained by constructing a quartic equation in $t = \tan(\psi/2)$ through the trigonometric transform $\tan\phi = 2at/(b(1 - t^2))$. This quartic equation is the same as the one arrived at by Levin [11], who used a parametric representation of $r_0 = a(1 - t^2)/(1 + t^2)$ and $z_0 = 2bt/(1 + t^2)$. We can write this new algorithm as follows.

$$E = [ar + (a^2 - b^2)]/(b|z|)$$

$$F = [ar - (a^2 - b^2)]/(b|z|)$$

$$P = (4/3)(EF + 1)$$

$$Q = 2(E^2 - F^2)$$

$$D = P^3 + Q^2$$

$$v = -\sqrt[3]{\sqrt{D}+Q} + \sqrt[3]{\sqrt{D}-Q}$$

$$G = (\sqrt{E^2+v} + E)/2$$

$$t = \sqrt{G^2 + (F - vG)/(2G - E)} - G$$

$$\phi = \mathrm{sign}(z)\arctan[2at/(b(1-t^2))]$$

$$h = (r-a)\cos\phi + (|z| - bt)|\sin\phi|.$$

The structure of this algorithm is virtually the same as its counterpart, except that z and r are interchanged, as well as a and b. Their computational complexities are exactly the same, and their sensitivity to computer round-off error are similar. The only thing one has to notice is that the singularities has moved from the pole to the equatorial plane.

Note that the roles played by r_0 and z_0 in the second basic relation are symmetric, and therefore, an algorithm analogous to the Heikkinen's can be obtained by constructing a quartic equation in z_0. This is equivalent to taking the transform of $r_0 = a\sqrt{1-t^2}$ and $z_0 = bt$, which happens to be the one Barbee [7] used to derive his formula. Therefore, Barbee's algorithm is analogous to Heikkinen's, no matter how different they appear in formulation.

In fact, more algorithms analogous to the above ones can be obtained through similar transformation of the transforms mentioned above or taking the inverse of the indeterminate in the quartic equation. It is hard to see that any algorithm obtained in such a way can significantly reduce the complexity.

IV. COMPARISONS

One common feature of those exact conversion algorithms is that they are reduced to solving some quartic equation and therefore, as it seems, at least one cubic root operation is required. In fact, the number of cubic root operations can be reduced to just one for each algorithm. This can be seen from the fact that if

$$v^3 + 3Pv + 2Q = 0$$

is the associated cubic equation, a real root of the cubic equation is given by

$$v = -\sqrt[3]{Q+\sqrt{D}} - \sqrt[3]{Q-\sqrt{D}}$$
$$= -\sqrt[3]{Q+\sqrt{D}} + P/\sqrt[3]{Q+\sqrt{D}}$$

where $D = P^3 + Q^2$.

TABLE I
Comparison of Arithmetic Operations

Algorithms	cubic roots	trigo-metric	square roots	mul/div	add/sub
Paul	1	2	4	22	18
Heikkinen	1	1	5	32	18
Barbee	1	1	5	18	20
Borkowski	1	3	3	20	20
Zhu	1	1	5	23	20
†Olson	0	1	3	29	23
†Borkowski	0	10	2	21	12

† denotes approximation algorithms

Except for a few singular points, all of the exact transformation formulas found so far are valid for all of the points $P(r,z)$ such that $(ar)^2 + (bz)^2 \geq (a^2 - b^2)^2$, which includes all the points 43 km $(= (a^2 - b^2)/b)$ away from the Earth center.

Let's consider the operations needed to carry out these algorithms. The operations between constants are not counted. Since the computation of longitude λ and $r = \sqrt{x^2+y^2}$ are common to all of the algorithms, the operations for them (and thus for r^2) are not counted in the result. Table I is the result of comparison in complexity with the approximation algorithms by Olson [4] and Borkowski [9], whose algorithms are among the best approximation algorithms. The exact transformation algorithms usually require one cubic root and two square root operations more than Olson's algorithm, and this does not pose a great burden to modern computing technology.

Now compare the accuracies of these exact formulas with computer round-off errors. The programs are coded in C language running on an IBM compatible personal computer with double precision (16 decimals). For the purpose of comparison, the exact transformation from geodetic to ECEF coordinates (backward transformation) is also used in the computer program. It certainly introduces a certain amount of error into the final result. Since this error is common to all the exact formulas to be examined, it could not affect the qualitative conclusions drawn from the result. More than one million points are considered; for height, h takes a point for every 10 km from $-6{,}300$ km to 30,000 km (from the core of the Earth to geostationary orbit); and for latitude, ϕ takes a point every half a degree for the whole range $[-90, 90]$. Two approximation algorithms [4, 9] are used for comparison. The range of heights for the approximation algorithms is starting from $-5{,}000$ km since they introduce very large conversion errors when the heights get below $-5{,}000$ km. The result is shown in Table II. Since most applications of these formulas are near the surface of the Earth, let's look at the points with smaller height now. For height, h takes a point for every 100 m from -10 km to 100 km and for latitude, ϕ takes a point every one-tenth deg for the whole range $[-90, 90]$. Since the algorithms by Paul and

TABLE II
Comparison of Accuracy of Algorithms for Displacement

Algorithms	Average error $\times 10^{-9}$m	max. error $\times 10^{-9}$m	maximal point height (km)	lat. (degree)
Paul	54896.	47217730	29830	-0.5
Heikkinen	1.1	10.5	27710	-57.5
Barbee	20680600	2.3m	29950	-10.0
Borkowski	3.2	288.	29570	-89.5
Zhu	0.9	632.	-3330	-45.5
†Olson	186.	61914.	-5000	-74.5
†Borkowski	4.8	1577.	-5000	-45.0

† denotes approximation algorithms

TABLE III
Comparison of Accuracy of Algorithms Near the Earth Surface

Algorithms	Average Error $\times 10^{-9}$m	max. error $\times 10^{-9}$m	maximal point height (km)	lat. (degree)
Paul	2622.	1553605	93.9	-0.5
Heikkinen	0.6	2.9	7.1	-25.1
Barbee	334052	9847893	69.6	-10.1
Borkowski	1.5	332.	99.1	-89.9
Zhu	0.7	7408.	0.0	-45.3
†Olson	4.7	30.	100.	-89.9
†Borkowski	0.6	3.	-7.5	-68.2

† denotes approximation algorithms

Barbee produce larger and larger transformation errors when the points are near the equator plane, the points with latitude less than 0.5 deg are not considered for Paul's algorithm and the points with latitude less than 10 deg are not considered for Barbee's algorithm. See Table III.

As we can see from Table I and Table II, the average errors of the three exact transformation formulas by Heikkinen, Borkowski, and Zhu are on the order of 1 nm, which is also matched by the approximation algorithm by Borkowski. Although Zhu's algorithm is free of singularities, it produces its maximal errors when the latitudes are around ± 45 deg. This is one reason why its average error is even larger than that of the approximation algorithm by Borkowski. The results show that the exact transformation algorithms can also be used in practice.

V. CONCLUSIONS

The exact transformation formulas from ECEF coordinates to geodetic coordinates has been reviewed. The relationship among those transformation formulas has been pointed out. The exact transformation formulas has also been compared with some approximation algorithms in complexity and in transformation accuracy with computer round-off errors. Some of the exact transformation formulas introduce only negligible errors in practical coordinate transformation. They are not only important in theory, but can also be used in practice.

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Comparison of Monostatic and Bistatic Bearing Estimation Performance for Low RCS Targets

Bistatic radars, specifically forward-scatter radars, are proposed as an alternative to standard monostatic radars against targets whose radar cross sections (RCS) have been reduced by passive means. Forward-scatter radars operate by detecting echoes from a targets forward-scatter RCS, which is insensitive to effects of passive RCS reduction techniques. However, the performance of the forward-scatter radar is compromised when the angular separation between the interference, which propagates directly from the transmitter to the receiver, and the target return is less than the Rayleigh resolution limit of the receiving antenna. This research presents the results of a parametric study of the ability of a forward-scatter radar to detect and measure the bearing of a large target, whose RCS is reduced via passive means. Super-resolution array processing techniques, particularly root-MUSIC (multiple signal classification), are used to overcome the traditional limitations resulting from the Rayleigh resolution limit of the antenna. The study compares the received power and the bearing measurement accuracy of the forward-scatter radar to that of an "equivalent" monostatic radar system. The results indicate that forward-scatter radars enjoy advantages in detection and bearing measurement when the backscatter RCS of the target has been reduced and when the target is close to the baseline. The results also indicate that, through the use of super-resolution array processing, the capability of the forward-scatter radar to accurately measure the bearing of the target is dependent upon the amount of interference from the direct wave (i.e., the wave which propagates from the transmitter directly to the receiver) and the correlation between the direct wave and the target echo. Good bearing estimates can be achieved if the correlation coefficient is less than 0.95. Bearing measurements may be improved by suppressing the direct wave by either sidelobe control or null steering techniques.

I. INTRODUCTION

Standard monostatic radars operate by detecting echoes from the backscatter radar cross section (RCS) of a target. An increasingly popular countermeasure to this threat is to reduce the backscatter RCS of the target via passive techniques. Passive RCS reduction techniques use combinations of masking and shaping to reduce the backscatter RCS of a given target. Masking techniques reduce the RCS of the targets by absorbing the energy of the incoming electromagnetic wave. Shaping techniques reduce the targets RCS by scattering the incident electromagnetic wave in directions other than the direction of arrival.

An intrinsic physical characteristic of the scattering process at high frequencies is the insensitivity of the target's forward-scattering RCS to passive RCS reduction techniques. Instead, the peak of the forward-scattering RCS lobe remains at approximately $4\pi A^2/\lambda^2$ (where A is the shadow area of the target even though the monostatic cross section may have been reduced to extremely low values by passive means. It is our intent to investigate to what extent bistatic radars, specifically forward-scatter radars, can be used to exploit this particularly large "residual" cross section to detect, acquire, and track targets with low monostatic RCS.

Limitations inherent to the forward-scattered radar include 1) the narrowness of the forward-scatter lobe ($\lambda/\sqrt{A}$), and 2) the small angular separation between the interference from the stronger direct transmitted wave and the weaker target echo. This angular separation is generally less than the Rayleigh resolution limit of the receiving antenna. These are some of the reasons why forward-scatter radars have been considered only for very specialized applications. To our knowledge, no analysis addressing the performance of forward-scatter radars in detecting low monostatic RCS targets has been published.

A rudimentary parametric study is presented here of a forward-scatter radar, detecting a large target with a low monostatic RCS. Of the three potential discriminates, i.e., Doppler, time gating, and angular resolution, only the latter is employed. Specifically, in order to overcome the traditional limitations offered by the Rayleigh resolution limit of the receiving antenna, super-resolution array processing techniques are applied for target acquisition against a simplified target model, whose monostatic RCS is reduced via passive means. The results are compared with the performance of an "equivalent" monostatic radar system.

II. THE MODEL

This study is based on the scenario depicted in Fig. 1. Starting above the transmitter, the target is displaced along a line parallel to the baseline, the line segment connecting the transmitter and the receiver, until the target is above the receiver. The perpendicular distance between the target path and

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