

A world map with a blue color scheme, showing continents and oceans. The map is centered on the Atlantic Ocean, with North and South America on the left and Europe and Africa on the right. The map has a grid of latitude and longitude lines.

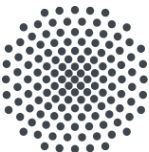
Transformation of first-, second-, and third-order potential gradients in different coordinates

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A circular logo composed of many small dots arranged in a grid pattern.

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- 1. Introduction**
- 2. Theory**
- 3. Validation**
- 4. Conclusions and outlook**

Introduction: Why coordinate transformation of potential gradients

- Potential fields (gravity & magnetism) are evaluated in different coordinate systems
- Physically meaningful comparison and interpretation of potential field data
- Three common 3D coordinate systems in the space:
 1. Cartesian coordinates (x, y, z)
 2. Cylindrical coordinates (r, λ, z)
 3. Spherical coordinates (λ, φ, ρ)
- Applications: gravimetry, magnetic survey in geodesy, geophysics, ...

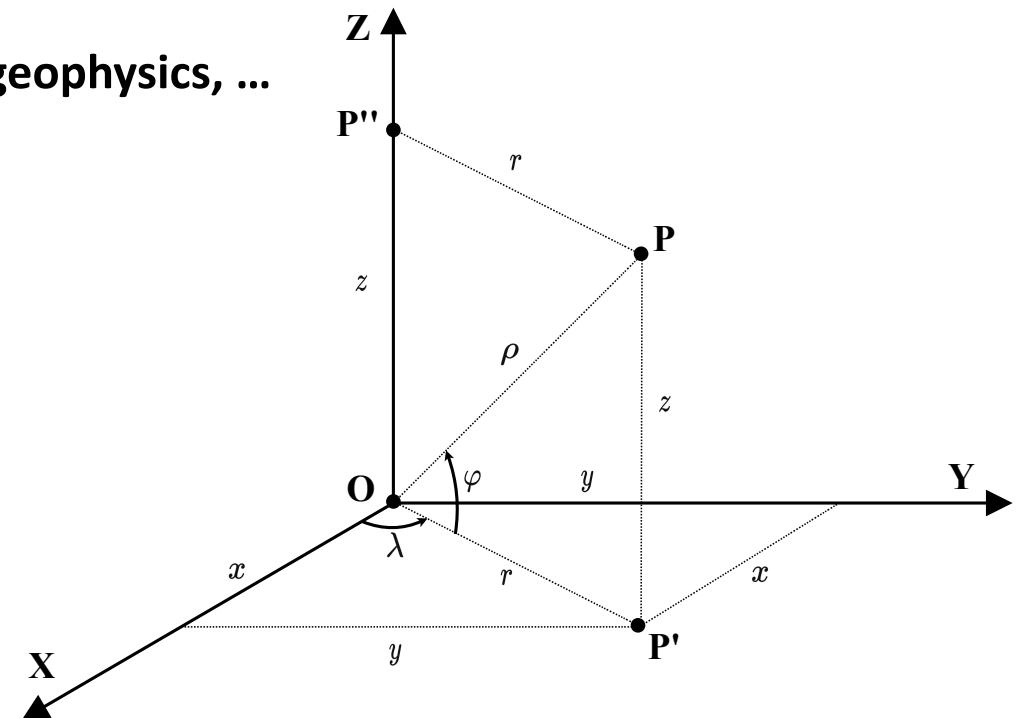


Fig. 1 Three coordinate systems

Introduction: Historical Development

- **Cartesian** $\leftrightarrow$ **Spherical** coordinates:
 - Moritz (1971) — 1st & 2nd order among rectangular Cartesian, spherical polar, and local rectangular coordinates
 - Koop (1993) — 1st & 2nd order between geocentric polar and local north-oriented coordinates
 - Casotto & Fantino (2009) — 1st-3rd order between global spherical equatorial and local Cartesian coordinates
- **Cylindrical** $\leftrightarrow$ **Cartesian** coordinates:
 - Rim & Li (2016), Asgharzadeh et al. (2018) — 1st & 2nd order between cylindrical and Cartesian coordinates
- **Other** coordinate transformations:
 - Moritz (1967), Reed (1973), Soler (1976), Koop (1993), Heck & Seitz (2007), Wild-Pfeiffer (2008), Du et al. (2015), Uieda et al. (2016), ...

Introduction: Four Gaps

1. No **general detailed expressions** for 1st-, 2nd-, and 3rd-order potential gradients transformations between any two coordinate systems
2. **Rotation matrix method** cannot easily produce 3rd-order gradient expressions, because 3D array cannot be uniquely represented as 2D rotation matrices
3. Only **partial** transformations among Cartesian, cylindrical, and spherical coordinates were derived; complete transformations still needed
4. Previously derived expressions were not all **validated** as correct

This work addresses all four gaps.

Theory: Direct Expansion method v.s. Rotation Matrix method

- **Rotation matrix method** — traditional approach
 - Works well for 1st and 2nd order
 - 3rd-order gradients are not easily captured by 2D rotation matrices
- **Direct expansion method** — this work's approach
 - Combines forward and inverse transformations into **one** general expression applicable to physical components of 1st, 2nd, & 3rd-order gradients
 - Expand summations directly using metric scale factors and Jacobian matrix components
 - Handles **forward & inverse** transformations uniformly
 - In principle, **arbitrary**-order potential gradients can be derived

Theory: First-order Potential Gradients

1st-order natural components: $V_{,p} = \frac{\partial u^{p'}}{\partial u^p} V_{,p'} \quad p, p' = 1, 2, 3 \quad V_{,p} = \frac{\partial V}{\partial u^p} \quad V_{,p'} = \frac{\partial V}{\partial u^{p'}}$

1st-order physical components:

$$V_{,p}^* = \frac{h_{p'}}{h_p} \frac{\partial u^{p'}}{\partial u^p} V_{,p'}^* = \frac{1}{h_p} \sum_{p'=1}^3 h_{p'} U_{p'p} V_{,p'}^*$$

h_p : metric scale factor

$U_{p'p}$: Jacobian Matrix

$$V_{,p}^* = \frac{1}{h_p} \left(h_1 U_{1p} V_{,1}^* + h_2 U_{2p} V_{,2}^* + h_3 U_{3p} V_{,3}^* \right)$$

Table 1 Metric scale factors of the Cartesian coordinates (x, y, z) , cylindrical coordinates (r, λ, z) , and spherical coordinates (λ, φ, ρ)

Name	Metric scale factor	Reference
Cartesian (x, y, z)	$h_1 = 1, h_2 = 1, \text{ and } h_3 = 1$	Eq. (47) in Casotto and Fantino (2009)
Cylindrical (r, λ, z)	$h_1 = 1, h_2 = r, \text{ and } h_3 = 1$	Eq. (3. 145) in Arfken et al. (2012)
Spherical (λ, φ, ρ)	$h_1 = \rho \cos \varphi, h_2 = \rho, \text{ and } h_3 = 1$	Eq. (38) in Casotto and Fantino (2009)

Theory: Second- and Third-order Potential Gradients

2nd-order physical components:

$$V_{;pq}^* = \frac{h_{p'}}{h_p} \frac{h_{q'}}{h_q} \frac{\partial u^{p'}}{\partial u^p} \frac{\partial u^{q'}}{\partial u^q} V_{;p'q'}^*$$

$$= \frac{1}{h_p h_q} \sum_{p'=1}^3 \sum_{q'=1}^3 h_{p'} h_{q'} U_{p'p} U_{q'q} V_{;p'q'}^*$$

$$V_{;pq}^* = \frac{1}{h_p h_q} \left[h_1^2 U_{1p} U_{1q} V_{;11}^* \right. \\ + h_1 h_2 (U_{1p} U_{2q} + U_{2p} U_{1q}) V_{;12}^* \\ + h_1 h_3 (U_{1p} U_{3q} + U_{3p} U_{1q}) V_{;13}^* \\ + h_2^2 U_{2p} U_{2q} V_{;22}^* \\ + h_2 h_3 (U_{2p} U_{3q} + U_{3p} U_{2q}) V_{;23}^* \\ \left. + h_3^2 U_{3p} U_{3q} V_{;33}^* \right]$$

3rd-order physical components:

$$V_{;pqs}^* = \frac{h_{p'}}{h_p} \frac{h_{q'}}{h_q} \frac{h_{s'}}{h_s} \frac{\partial u^{p'}}{\partial u^p} \frac{\partial u^{q'}}{\partial u^q} \frac{\partial u^{s'}}{\partial u^s} V_{;p'q's'}^* = \frac{1}{h_p h_q h_s} \sum_{p'=1}^3 \sum_{q'=1}^3 \sum_{s'=1}^3 h_{p'} h_{q'} h_{s'} U_{p'p} U_{q'q} U_{s's} V_{;p'q's'}^*$$

$$V_{;pqs}^* = \frac{1}{h_p h_q h_s} \left[h_1^3 U_{1p} U_{1q} U_{1s} V_{;111}^* \right. \\ + h_1^2 h_2 (U_{1p} U_{1q} U_{2s} + U_{1p} U_{2q} U_{1s} + U_{2p} U_{1q} U_{1s}) V_{;112}^* \\ + h_1^2 h_3 (U_{1p} U_{1q} U_{3s} + U_{1p} U_{3q} U_{1s} + U_{3p} U_{1q} U_{1s}) V_{;113}^* \\ + h_1 h_2 h_3 (U_{1p} U_{2q} U_{3s} + U_{1p} U_{3q} U_{2s} + U_{2p} U_{1q} U_{3s} \\ + U_{2p} U_{3q} U_{1s} + U_{3p} U_{1q} U_{2s} + U_{3p} U_{2q} U_{1s}) V_{;123}^* \\ + h_1 h_2^2 (U_{1p} U_{2q} U_{2s} + U_{2p} U_{1q} U_{2s} + U_{2p} U_{2q} U_{1s}) V_{;221}^* \\ + h_2^3 U_{2p} U_{2q} U_{2s} V_{;222}^* \\ + h_2^2 h_3 (U_{2p} U_{2q} U_{3s} + U_{2p} U_{3q} U_{2s} + U_{3p} U_{2q} U_{2s}) V_{;223}^* \\ + h_1 h_3^2 (U_{1p} U_{3q} U_{3s} + U_{3p} U_{1q} U_{3s} + U_{3p} U_{3q} U_{1s}) V_{;331}^* \\ + h_2 h_3^2 (U_{2p} U_{3q} U_{3s} + U_{3p} U_{2q} U_{3s} + U_{3p} U_{3q} U_{2s}) V_{;332}^* \\ \left. + h_3^3 U_{3p} U_{3q} U_{3s} V_{;333}^* \right]$$

Theory: Coordinate Transformations among Three Coordinates

1. Cartesian → Cylindrical

$$r = \sqrt{x^2 + y^2}$$
$$\lambda = \arctan(y/x)$$
$$z = z$$

3. Cylindrical → Spherical

$$\lambda = \lambda$$
$$\varphi = \arctan(z/r)$$
$$\rho = \sqrt{r^2 + z^2}$$

5. Spherical → Cartesian

$$x = \rho \cos \varphi \cos \lambda$$
$$y = \rho \cos \varphi \sin \lambda$$
$$z = \rho \sin \varphi$$

2. Cylindrical → Cartesian

$$x = r \cos \lambda$$
$$y = r \sin \lambda$$
$$z = z$$

4. Spherical → Cylindrical

$$r = \rho \cos \varphi$$
$$\lambda = \lambda$$
$$z = \rho \sin \varphi$$

6. Cartesian → Spherical

$$\lambda = \arctan(y/x)$$
$$\varphi = \arcsin(z/\sqrt{x^2 + y^2 + z^2})$$
$$\rho = \sqrt{x^2 + y^2 + z^2}$$

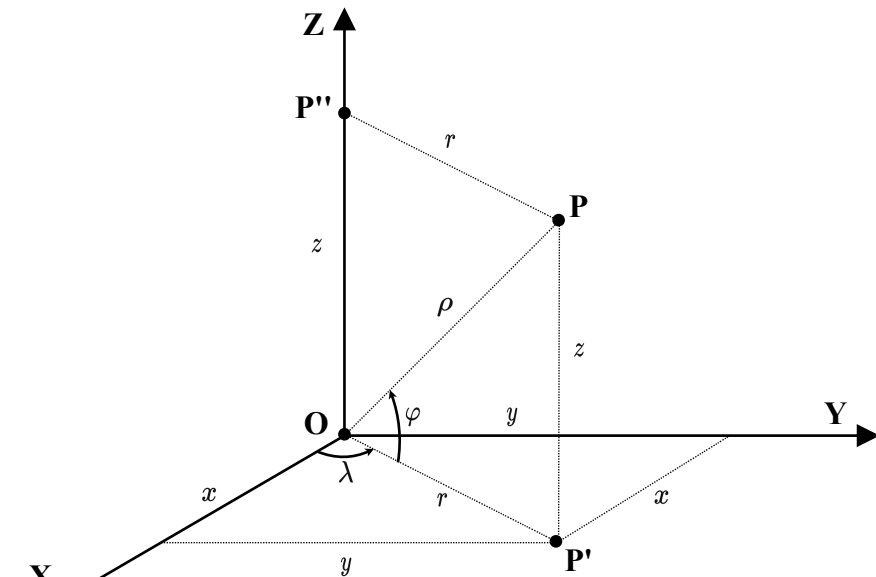


Fig. 1 Three coordinate systems

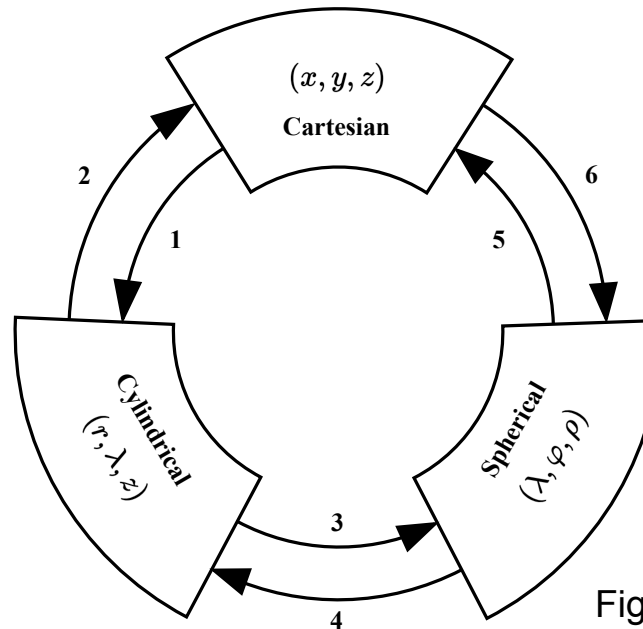


Fig. 2 Coordinate transformations

Theory: Jacobian Matrix for Cartesian $\leftrightarrow$ Cylindrical

Jacobian Matrix for Cartesian $\rightarrow$ Cylindrical

$$U_{pq} = \frac{\partial(x, y, z)}{\partial(r, \lambda, z)} = \begin{pmatrix} \cos \lambda & -r \sin \lambda & 0 \\ \sin \lambda & r \cos \lambda & 0 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} \frac{x}{\sqrt{x^2 + y^2}} & -y & 0 \\ \frac{y}{\sqrt{x^2 + y^2}} & x & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Jacobian Matrix for Cylindrical $\rightarrow$ Cartesian

$$U_{pq} = \frac{\partial(r, \lambda, z)}{\partial(x, y, z)} = \left(\frac{\partial(x, y, z)}{\partial(r, \lambda, z)} \right)^{-1} = \begin{pmatrix} \frac{x}{\sqrt{x^2 + y^2}} & \frac{y}{\sqrt{x^2 + y^2}} & 0 \\ -\frac{y}{x^2 + y^2} & \frac{x}{x^2 + y^2} & 0 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} \cos \lambda & \sin \lambda & 0 \\ -\frac{\sin \lambda}{r} & \frac{\cos \lambda}{r} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Theory: Jacobian Matrix for Cylindrical $\leftrightarrow$ Spherical

Jacobian Matrix for Cylindrical $\rightarrow$ Spherical

$$U_{pq} = \frac{\partial(r, \lambda, z)}{\partial(\lambda, \varphi, \rho)} = \begin{pmatrix} 0 & -\rho \sin \varphi & \cos \varphi \\ 1 & 0 & 0 \\ 0 & \rho \cos \varphi & \sin \varphi \end{pmatrix} = \begin{pmatrix} 0 & -z & \frac{r}{\sqrt{r^2 + z^2}} \\ 1 & 0 & 0 \\ 0 & r & \frac{z}{\sqrt{r^2 + z^2}} \end{pmatrix}$$

Jacobian Matrix for Spherical $\rightarrow$ Cylindrical

$$U_{pq} = \frac{\partial(\lambda, \varphi, \rho)}{\partial(r, \lambda, z)} = \left(\frac{\partial(r, \lambda, z)}{\partial(\lambda, \varphi, \rho)} \right)^{-1} = \begin{pmatrix} 0 & 1 & 0 \\ -\frac{z}{r^2 + z^2} & 0 & \frac{r}{r^2 + z^2} \\ \frac{r}{\sqrt{r^2 + z^2}} & 0 & \frac{z}{\sqrt{r^2 + z^2}} \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ -\frac{\sin \varphi}{\rho} & 0 & \frac{\cos \varphi}{\rho} \\ \cos \varphi & 0 & \sin \varphi \end{pmatrix}$$

Theory: Jacobian Matrix for Spherical $\leftrightarrow$ Cartesian

Jacobian Matrix for Spherical $\rightarrow$ Cartesian

$$U_{pq} = \frac{\partial(\lambda, \varphi, \rho)}{\partial(x, y, z)} = \begin{pmatrix} -\frac{y}{x^2 + y^2} & \frac{x}{x^2 + y^2} & 0 \\ -\frac{xz}{(x^2 + y^2 + z^2)\sqrt{x^2 + y^2}} & -\frac{yz}{(x^2 + y^2 + z^2)\sqrt{x^2 + y^2}} & \frac{\sqrt{x^2 + y^2}}{x^2 + y^2 + z^2} \\ \frac{x}{\sqrt{x^2 + y^2 + z^2}} & \frac{y}{\sqrt{x^2 + y^2 + z^2}} & \frac{z}{\sqrt{x^2 + y^2 + z^2}} \end{pmatrix} = \begin{pmatrix} -\frac{\sin \lambda}{\rho \cos \varphi} & \frac{\cos \lambda}{\rho \cos \varphi} & 0 \\ -\frac{\sin \varphi \cos \lambda}{\rho} & -\frac{\sin \varphi \sin \lambda}{\rho} & \frac{\cos \varphi}{\rho} \\ \cos \varphi \cos \lambda & \cos \varphi \sin \lambda & \sin \varphi \end{pmatrix}$$

Jacobian Matrix for Cartesian $\rightarrow$ Spherical

$$U_{pq} = \frac{\partial(x, y, z)}{\partial(\lambda, \varphi, \rho)} = \left(\frac{\partial(\lambda, \varphi, \rho)}{\partial(x, y, z)} \right)^{-1} = \begin{pmatrix} -\rho \cos \varphi \sin \lambda & -\rho \sin \varphi \cos \lambda & \cos \varphi \cos \lambda \\ \rho \cos \varphi \cos \lambda & -\rho \sin \varphi \sin \lambda & \cos \varphi \sin \lambda \\ 0 & \rho \cos \varphi & \sin \varphi \end{pmatrix} = \begin{pmatrix} -y & -\frac{xz}{\sqrt{x^2 + y^2}} & \frac{x}{\sqrt{x^2 + y^2 + z^2}} \\ x & -\frac{yz}{\sqrt{x^2 + y^2}} & \frac{y}{\sqrt{x^2 + y^2 + z^2}} \\ 0 & \sqrt{x^2 + y^2} & \frac{z}{\sqrt{x^2 + y^2 + z^2}} \end{pmatrix}$$

Theory: 1st-, 2nd-, and 3rd-order Physcial Components Formulas

After substituting the Jacobian matrices and metric scale factors into general formulas, **detailed formulas among Cartesian, cylindrical, and spherical coordinates** are obtained; see Tables 3-15 of Deng & Sneeuw (2026).

Table 9 Expressions for physical components of first-, second-, and third-order potential gradients from spherical coordinates (V_α^* , $V_{\alpha\beta}^*$, and $V_{\alpha\beta\gamma}^*$ with $\alpha, \beta, \gamma = \lambda, \varphi, \rho$) to cylindrical coordinates (V_a^* , V_{ab}^* , and V_{abc}^* with $a, b, c = r, \lambda, z$) represented by the algebraic form of r, z

Expression

$$V_r^* = (-zV_\varphi^* + rV_\rho^*)/\sqrt{r^2 + z^2}$$

$$V_\lambda^* = V_\lambda^*$$

$$V_z^* = (rV_\varphi^* + zV_\rho^*)/\sqrt{r^2 + z^2}$$

$$V_{rr}^* = (z^2V_{\varphi\varphi}^* - 2rzV_{\varphi\rho}^* + r^2V_{\rho\rho}^*)/(r^2 + z^2)$$

$$V_{r\lambda}^* = (-zV_{\lambda\varphi}^* + rV_{\lambda\rho}^*)/\sqrt{r^2 + z^2}$$

$$V_{rz}^* = [-rzV_{\varphi\varphi}^* + (r^2 - z^2)V_{\varphi\rho}^* + rzV_{\rho\rho}^*]/(r^2 + z^2)$$

$$V_{\lambda\lambda}^* = V_{\lambda\lambda}^*$$

$$V_{\lambda z}^* = (rV_{\lambda\varphi}^* + zV_{\lambda\rho}^*)/\sqrt{r^2 + z^2}$$

$$V_{zz}^* = (r^2V_{\varphi\varphi}^* + 2rzV_{\varphi\rho}^* + z^2V_{\rho\rho}^*)/(r^2 + z^2)$$

$$V_{rrr}^* = (-z^3V_{\varphi\varphi\varphi}^* + 3rz^2V_{\varphi\varphi\rho}^* - 3r^2zV_{\rho\rho\varphi}^* + r^3V_{\rho\rho\rho}^*)/(r^2 + z^2)^{3/2}$$

$$V_{rr\lambda}^* = (-2rzV_{\lambda\varphi\rho}^* + z^2V_{\varphi\varphi\lambda}^* + r^2V_{\rho\rho\lambda}^*)/(r^2 + z^2)$$

$$V_{rrz}^* = [rz^2V_{\varphi\varphi\varphi}^* + z(z^2 - 2r^2)V_{\varphi\varphi\rho}^* + r(r^2 - 2z^2)V_{\rho\rho\varphi}^* + r^2zV_{\rho\rho\rho}^*]/(r^2 + z^2)^{3/2}$$

$$V_{r\lambda z}^* = [(r^2 - z^2)V_{\lambda\varphi\rho}^* - rzV_{\varphi\varphi\lambda}^* + rzV_{\rho\rho\lambda}^*]/(r^2 + z^2)$$

$$V_{\lambda\lambda r}^* = (-zV_{\lambda\lambda\varphi}^* + rV_{\lambda\lambda\rho}^*)/\sqrt{r^2 + z^2}$$

$$V_{\lambda\lambda\lambda}^* = V_{\lambda\lambda\lambda}^*$$

$$V_{\lambda\lambda z}^* = (rV_{\lambda\lambda\varphi}^* + zV_{\lambda\lambda\rho}^*)/\sqrt{r^2 + z^2}$$

$$V_{zzr}^* = [-r^2zV_{\varphi\varphi\varphi}^* + r(r^2 - 2z^2)V_{\varphi\varphi\rho}^* + z(2r^2 - z^2)V_{\rho\rho\varphi}^* + rz^2V_{\rho\rho\rho}^*]/(r^2 + z^2)^{3/2}$$

$$V_{zz\lambda}^* = (2rzV_{\lambda\varphi\rho}^* + r^2V_{\varphi\varphi\lambda}^* + z^2V_{\rho\rho\lambda}^*)/(r^2 + z^2)$$

$$V_{zzz}^* = (r^3V_{\varphi\varphi\varphi}^* + 3r^2zV_{\varphi\varphi\rho}^* + 3rz^2V_{\rho\rho\varphi}^* + z^3V_{\rho\rho\rho}^*)/(r^2 + z^2)^{3/2}$$

Validation I: Laplace's Equation

Laplace's equation can confirm the correctness of involved physical components of 2nd- and 3rd-order potential gradients.

Cartesian coordinates:

$$V_{xx}^* + V_{yy}^* + V_{zz}^* = 0, \quad V_{xxx}^* + V_{yyx}^* + V_{zzx}^* = 0, \quad V_{xxy}^* + V_{yyy}^* + V_{zzy}^* = 0, \quad V_{xxz}^* + V_{yyz}^* + V_{zzz}^* = 0$$

Cylindrical coordinates:

$$V_{rr}^* + V_{\lambda\lambda}^* + V_{zz}^* = 0, \quad V_{rrr}^* + V_{\lambda\lambda r}^* + V_{zzr}^* = 0, \quad V_{rr\lambda}^* + V_{\lambda\lambda\lambda}^* + V_{zz\lambda}^* = 0, \quad V_{rrz}^* + V_{\lambda\lambda z}^* + V_{zzz}^* = 0$$

Spherical coordinates:

$$V_{\lambda\lambda}^* + V_{\varphi\varphi}^* + V_{\rho\rho}^* = 0, \quad V_{\lambda\lambda\lambda}^* + V_{\varphi\varphi\lambda}^* + V_{\rho\rho\lambda}^* = 0, \quad V_{\lambda\lambda\varphi}^* + V_{\varphi\varphi\varphi}^* + V_{\rho\rho\varphi}^* = 0, \quad V_{\lambda\lambda\rho}^* + V_{\varphi\varphi\rho}^* + V_{\rho\rho\rho}^* = 0$$

If these sums are zero, the corresponding transformed expressions are verified as correct.

Validation II: Transformation Cycle Method

Principle: Potential gradients become themselves after a closed-loop transformation cycle among three coordinates.

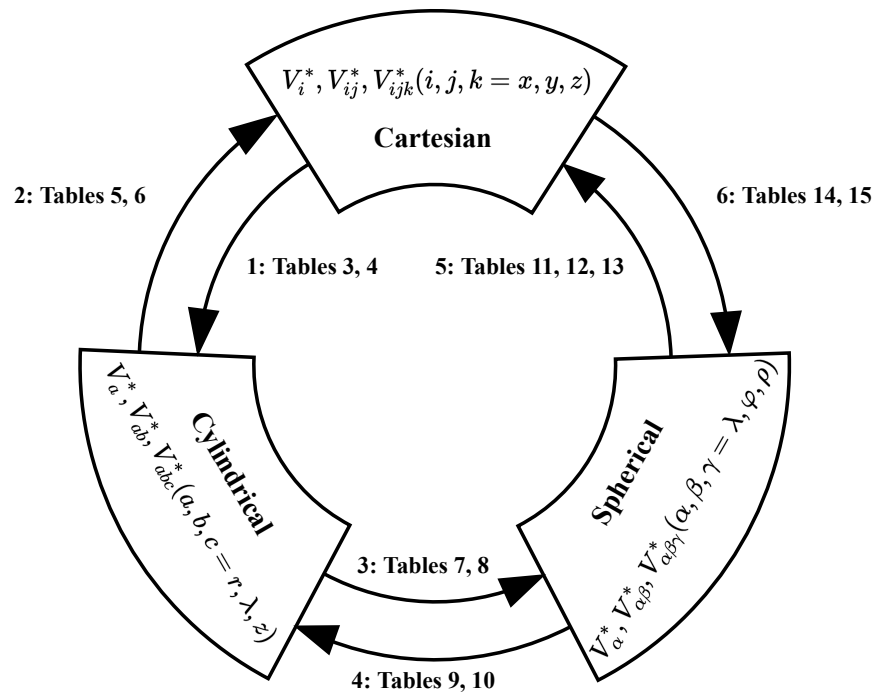


Table 2 Relations among the represented forms, cycles with different routes, and tables for physical components of first-, second-, and third-order potential gradients in Cartesian, cylindrical, and spherical coordinates in Fig. 3

Represented form	Coordinate	Cycle	Table
Algebraic x, y, z	Cartesian	Routes 1 $\rightarrow$ 3 $\rightarrow$ 5	Table 3 $\rightarrow$ Table 7 $\rightarrow$ Tables 11, 12
	Cartesian	Routes 6 $\rightarrow$ 4 $\rightarrow$ 2	Table 14 $\rightarrow$ Table 9 $\rightarrow$ Table 5
	Cylindrical	Routes 3 $\rightarrow$ 5 $\rightarrow$ 1	Table 7 $\rightarrow$ Tables 11, 12 $\rightarrow$ Table 3
	Cylindrical	Routes 2 $\rightarrow$ 6 $\rightarrow$ 4	Table 5 $\rightarrow$ Table 14 $\rightarrow$ Table 9
	Spherical	Routes 5 $\rightarrow$ 1 $\rightarrow$ 3	Tables 11, 12 $\rightarrow$ Table 3 $\rightarrow$ Table 7
	Spherical	Routes 4 $\rightarrow$ 2 $\rightarrow$ 6	Table 9 $\rightarrow$ Table 5 $\rightarrow$ Table 14
Trigonometric λ, φ	Cartesian	Routes 1 $\rightarrow$ 3 $\rightarrow$ 5	Table 4 $\rightarrow$ Table 8 $\rightarrow$ Table 13
	Cartesian	Routes 6 $\rightarrow$ 4 $\rightarrow$ 2	Table 15 $\rightarrow$ Table 10 $\rightarrow$ Table 6
	Cylindrical	Routes 3 $\rightarrow$ 5 $\rightarrow$ 1	Table 8 $\rightarrow$ Table 13 $\rightarrow$ Table 4
	Cylindrical	Routes 2 $\rightarrow$ 6 $\rightarrow$ 4	Table 6 $\rightarrow$ Table 15 $\rightarrow$ Table 10
	Spherical	Routes 5 $\rightarrow$ 1 $\rightarrow$ 3	Table 13 $\rightarrow$ Table 4 $\rightarrow$ Table 8
	Spherical	Routes 4 $\rightarrow$ 2 $\rightarrow$ 6	Table 10 $\rightarrow$ Table 6 $\rightarrow$ Table 15

Fig. 3 Transformations of potential gradients

Conclusions and outlook

1. **General detailed expressions** for 1st-, 2nd-, and 3rd-order potential gradients transformations between any two coordinate systems are provided.
2. **Direct expansion method** (v.s. rotation matrix method) — systematic, general framework for all orders (1st, 2nd, and 3rd) between any two coordinates.
3. **Complete** transformations of 1st-, 2nd-, and 3rd-order potential gradients among Cartesian, cylindrical, and spherical coordinates are derived.
4. All derived expressions are **validated** as correct by the proposed transformation cycle method.
5. The derived expressions can be applied to the potential gradients transformations for **arbitrary** two different coordinates.



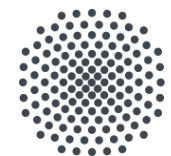
Deng & Sneeuw (2026) Self-consistent transformation of first-, second-, and third-order potential gradients among Cartesian, cylindrical, and spherical coordinates. *Journal of Geodesy*, 100(2):10. doi: [10.1007/s00190-025-02025-6](https://doi.org/10.1007/s00190-025-02025-6)

A world map with a blue color scheme, showing continents and oceans. The map is centered on the Atlantic Ocean, with North and South America on the left and Europe and Africa on the right.

Thank you for your attention!



Deng & Sneeuw (2026) Self-consistent transformation of first-, second-, and third-order potential gradients among Cartesian, cylindrical, and spherical coordinates. *Journal of Geodesy*, 100(2):10. doi: [10.1007/s00190-025-02025-6](https://doi.org/10.1007/s00190-025-02025-6)



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