

# Fundamentals of Astrodynamics and Applications 4<sup>th</sup> Ed

## Consolidated Errata

June 18, 2019

This listing is an on-going document of corrections and clarifications encountered in the book. I appreciate any comments and questions you find. I use RHS for “right hand side” when referring to equations and N/A for not applicable. You may reach me at: [dvallado@agi.com](mailto:dvallado@agi.com) or [davallado@gmail.com](mailto:davallado@gmail.com). Changes in equations are sometimes indicated by circles. I have tried to indicate changes that were present in previous editions as I know many of you have those copies. For many corrections in the 2<sup>nd</sup> edition, the first and second printings had identical pages, unless otherwise noted with the first printing pages being in parentheses. The exact description may differ, but it should get you close enough.

**Page xiv**, Algorithm 1: The cross reference should say pg 63, not 71.

**Page 14**, Equation 1-1: (3<sup>rd</sup> pg 14, 2<sup>nd</sup> pg 14, 1<sup>st</sup> pg 11) The radius values should all be vectors. Fig 1-4 should show the radii as vectors also.

**Page 53**, Fig 2-4: (3<sup>rd</sup> pg 61, 2<sup>nd</sup> pg 61, 1<sup>st</sup> pg 220) The turning angle should be 130.76 deg and  $\varphi_S$  should be divided by 2 in the figure. Note that the turning angle extends past the page to the satellite asymptote.

**Page 59**, Para after Eq 2-41: (3<sup>rd</sup> pg 67, 2<sup>nd</sup> pg 67, 1<sup>st</sup> pg 226) The text should read hyperbolic [co]sine.

**Page 65, 71, 75**, Alg 2, 1st equation, Alg 4: (3<sup>rd</sup> pg 73, 79, 2<sup>nd</sup> pg 73, 79, 1<sup>st</sup> pg 232, 237) The top line should be  $-\pi < M < 0$  or  $\pi < M < 2\pi$ .

**Page 85**, Eq 2-66 and the unnumbered equation afterwards: (3<sup>rd</sup> pg 93, 2<sup>nd</sup> pg 93, 1<sup>st</sup> pg 253) The parabolic  $\dot{f}$  term should be negative, the numerator of  $g$  should be  $p^2\{\Delta B - BB_o(B_o^3 - B^3)\}$ , and the  $\dot{H}$  term should be positive.

**Page 107**, Fig 2-19: (3<sup>rd</sup> pg 115, 2<sup>nd</sup> pg 115, 1<sup>st</sup> pg 142) The units for Mean motion should be (rev/day<sup>2</sup>/2) and for Mean motion second derivative (rev/day<sup>3</sup>/6). The Mean motion second derivative should have a negative sign in the box before the 0 exponent. The superscripted values were missing. The checksum for the first line should be 9 and the check sum for the second line should be 6.

**Page 109**, SEZ/ECI matrix at the bottom of the page. (3<sup>rd</sup> pg 117) The matrix should be

$$\begin{bmatrix} \cos \alpha \sin \delta & \sin \alpha \sin \delta & -\cos \delta \\ -\sin \alpha & \cos \alpha & 0 \\ \cos \delta \cos \alpha & \sin \alpha \cos \delta & \sin \delta \end{bmatrix}$$

**Page 110**, 2<sup>nd</sup> equation: (3<sup>rd</sup> pg 118) The velocity equation should be

$$v \begin{bmatrix} -\cos(\alpha) \sin(\delta) \cos(\beta) \cos(\phi_{fpav}) - \sin(\alpha) \sin(\beta) \cos(\phi_{fpav}) + \cos(\alpha) \cos(\delta) \sin(\phi_{fpav}) \\ -\sin(\alpha) \sin(\delta) \cos(\beta) \sin(\phi_{fpav}) + \cos(\alpha) \sin(\beta) \cos(\phi_{fpav}) + \sin(\alpha) \cos(\delta) \sin(\phi_{fpav}) \\ \cos(\alpha) \cos(\delta) \cos(\phi_{fpav}) + \sin(\delta) \cos(\phi_{fpav}) \end{bmatrix}$$

**Page 120**, Position and velocity vectors: (3<sup>rd</sup> pg 127-128, 2<sup>nd</sup> pg 126) the last 2 decimal places of the position and velocity vector components should be 68, 32, 19 and 79, 40, and 10.

**Page 147**, Last sentence: “MS ascension” should be “right ascension”.

**Page 158**, First paragraph: (3<sup>rd</sup> pg 166, 2<sup>nd</sup> pg 163, 1<sup>st</sup> pg 44) It should be just “clockwise”.

**Page 173**, Algorithm 13: (3<sup>rd</sup> pg 180, 2<sup>nd</sup> pg 178) The equation for  $b$  should be corrected as follows:

$$b = R_{\oplus} \sqrt{(1 - e_b^2)} \text{SIGN}(r_K) = r_b$$

**Page 182-184**, Alg 14, discussion, and Ex 3-4: (3<sup>rd</sup> pg 189-190, 2<sup>nd</sup> pg 186-188, 1<sup>st</sup> pg 67-68) The 61 sec comment should be replaced with: “The usual method to display time when a leap second occurs, in HMS format, is 23:59:60.000”. The formula should be changed as follows. The 86400\* sec is 86401 in days with the leap second.

$$\frac{h3600 + \min60 + s}{86400^*}$$

**Page 193**, Eq 3-52: (3<sup>rd</sup> pg 199) The last term should be “-” instead of “+” (TDB<sub>0</sub>).

**Page 208**, Fig 3-26: The IAU 1976 precession matrix elements should be reversed and of opposite sign.

**Page 213**, Last para: (3<sup>rd</sup> pg 219, 2<sup>nd</sup> pg 212) The summation should go from 0 - 4, not 0 - 5.

**Page 216**, Eq 3-67: (3<sup>rd</sup> pg 221) The constant should be -0.000 029 956T<sup>4</sup>.

**Page 220**, Ex 3-14: (3<sup>rd</sup> pg 225, 2<sup>nd</sup> pg 217) The problem statement needs to add “LOD = 0.001 556 3 s”. The multipliers on the planetary nutation equations should be  $T_{TT}$ .

**Page 225**, Eq 3-82: (3<sup>rd</sup> pg 230, 2<sup>nd</sup> pg 210, 1<sup>st</sup> correct) The equations actually were from 1996 values and are thus a little different. They should be as follows:

$$\begin{aligned} M_{\odot} &= 134.962\,981\,39^{\circ} + (1325r + 198.867\,398\,1)T_{TT} + 0.008\,697\,2T_{TT}^2 + 1.78 \times 10^{-5}T_{TT}^3 \\ M_{\ominus} &= 357.527\,723\,33^{\circ} + (99r + 359.050\,340\,0)T_{TT} - 0.000\,160\,3T_{TT}^2 - 3.3 \times 10^{-6}T_{TT}^3 \\ u_{M_{\odot}} &= 93.271\,910\,28^{\circ} + (1342r + 82.017\,538\,1)T_{TT} - 0.003\,682\,5T_{TT}^2 + 3.1 \times 10^{-6}T_{TT}^3 \\ D_{\odot} &= 297.850\,363\,06^{\circ} + (1236r + 307.111\,480\,0)T_{TT} - 0.001\,914\,2T_{TT}^2 + 5.3 \times 10^{-6}T_{TT}^3 \\ \Omega_{\odot} &= 125.044\,522\,22^{\circ} - (5r + 134.136\,260\,8)T_{TT} + 0.002\,070\,8T_{TT}^2 + 2.2 \times 10^{-6}T_{TT}^3 \end{aligned}$$

**Page 226**, Sentence after Eq 3-86: The end should say “the equation after Eq. (3-72)”.

**Page 232**, Text of table 3-6: The velocity units should be “m/s”, not “mm/s”.

**Page 244**, bottom equation: (3<sup>rd</sup> pg 250, 2<sup>nd</sup> pg 238 (236)) The equation should be as follows:

$$\rho = \frac{c|(t_{s-rec}) - (t_{trans})| + |(t_{rec}) - (t_{s-trans})|}{2}$$

**Page 277-281**, Sun algorithm: (3<sup>rd</sup> pg 279-283, 2<sup>nd</sup> pg 265-269 (263-267), 1<sup>st</sup> 181-184) The equations should be made identical to the Almanac version, which is TOD, not MOD. The development shows where the equations come from, but the accuracy is slightly better using the truncated terms from the Almanac. It changes the example problem slightly, and this is evident in the Matlab approach which has been updated.

**Page 284**, first paragraph of text after the example: (3<sup>rd</sup> pg 287, 2<sup>nd</sup> pg 273 (271)) The “and 3000 m in altitude” can be deleted because it is not needed for the problem.

**Page 288-289**, Eq for magnitude of the Moon: (3<sup>rd</sup> pg 290-291, 2<sup>nd</sup> pg 276-277 (274-275), 1<sup>st</sup> 187-188) The numerator should be  $R_{\oplus}$ , not “1”. this will give km for units.

**Page 298**, Example 5-5: (3<sup>rd</sup> pg 300, 2<sup>nd</sup> pg 286 (284), 1<sup>st</sup> 190-192) The “TU’s” should be replaced by “day”. This causes several calculations to be different.

$$\begin{aligned}\dot{r}_{XYZ} &= -4.075\,931 \hat{X} - 3.578\,308 \hat{Y} + 0.105\,970 \hat{Z} \text{ AU} \\ \dot{r}_{XYZ(J2000)}, \dot{v}_{XYZ(J2000)} &= \mathbf{ROT1}(-\epsilon) \dot{r}_{XYZ} \dot{v}_{XYZ} \\ \dot{r}_{XYZ(J2000)} &= -4.075\,931 \hat{I} - 3.325\,169 \hat{J} - 1.326\,186 \hat{K} \text{ AU} \\ &= -609,750,543 \hat{I} - 497,438,245 \hat{J} - 198,394,607 \hat{K} \text{ km} \\ \dot{v}_{XYZ(J2000)} &= 0.004\,889 \hat{I} - 0.004\,846 \hat{J} - 0.002\,197 \hat{K} \text{ AU/day} \\ &= 8.46560 \hat{I} - 8.39137 \hat{J} - 3.80323 \hat{K} \text{ km/s}\end{aligned}$$

**Page 299**, Last Eq: (3<sup>rd</sup> pg 301, 2<sup>nd</sup> pg 287 (285)) The umbra and penumbra equations should not have the “=” sign before the answer in degrees.

**Page 362-364**, Eq 6-38, Algorithm 44, and Ex 6-8 and Ex 6-9: (3<sup>rd</sup> pg 363-366, 2<sup>nd</sup> pg 348-352 (346-350), 1<sup>st</sup> 318-321) The equation should be  $\vartheta = \pi - \alpha_L$  in each. In Ex 6-8, the target is “in front of” the interceptor,  $\omega_{tgt} = 0.000\,438$  rad/s, the phasing value is “smaller” than the original orbit, and the interceptor enters a “lower” orbit. In Ex 6-9, the target is “in front of” the interceptor,  $\omega_{tgt} = 0.000\,072\,9$  rad/s,  $\omega_{int} = 0.000\,438$  rad/s, and the target satellite begins “in front of” the interceptor.

**Page 369**, Ex 6-10: (3<sup>rd</sup> pg 371, 2<sup>nd</sup> pg 357 (355), 1<sup>st</sup> 326)  $\omega_{tgt} = 0.000\,072\,9$  rad/s, and  $\omega_{int} = 0.001\,045\,7$  rad/s,

**Page 386**, Eq 6-55: (3<sup>rd</sup> pg 388, 2<sup>nd</sup> pg 373 (371), 1<sup>st</sup> 342) The two summations should be divided, not multiplied.

**Page 388**, Ex 6-13  $v_{acc}$  equation: (3<sup>rd</sup> pg 388, 2<sup>nd</sup> pg 374 (372)) The  $v_{acc}$  equation should be  $0.75 (6578.136) / (845.0472)$ . (remove the “1/”)

**Page 414-416**, Alg 49 and 50 (3<sup>rd</sup> pg 412-416, 2<sup>nd</sup> pg 397-399(395-397), 1<sup>st</sup> pg 366-368) There have been several updates to match the final form given in Vallado and Alfano. 2014. Curvilinear Coordinate Transformation for Relative Motion. 118 (3):253-271, *Celestial Mechanics and Dynamical Astronomy* and the few errata in (2016) 125:263–264.

**Page 432**, Last equation: (3<sup>rd</sup> pg 428, 2<sup>nd</sup> pg 412 (410) 1<sup>st</sup> 386) The position vector in the velocity equation should have no subscripts. It’s simply the position vector at the beginning of the equation.

**Page 445**, 2<sup>nd</sup> Eq after ELSE: (3<sup>rd</sup> pg 441, 2<sup>nd</sup> pg 425 (423), 1<sup>st</sup> 399) The denominator should be changed as follows:

$$e \sin(\nu_2) = \frac{\cos(\Delta\nu_{32})e \cos(\nu_2) - e \cos(\nu_3)}{\sin(\Delta\nu_{32})}$$

**Page 473, 475**, After 2<sup>nd</sup> para, and in Alg 56: (3<sup>rd</sup> pg 471, 2<sup>nd</sup> pg 454 (452), 1<sup>st</sup> 428) Add the following para and equation:

To find the minimum time with  $a_{min}$  new values of  $\alpha_e$  and  $\beta_e$  are required. Prussing and Conway (1992, 72) show the result.

$$\alpha_{min} = \pi \quad \sin\left(\frac{\beta_{min}}{2}\right) = \sqrt{\frac{s-c}{s}}$$

Change the  $\alpha_e$  and  $\beta_e$  subscripts to “min” in Alg. 56.

**Page 489**, 3<sup>rd</sup> full para (3<sup>rd</sup> pg 486, 2<sup>nd</sup> pg 461(460), 1<sup>st</sup> pg 436) The reference is for pgs 231-236, not 193-198.

**Page 496, Alg 59:** (3<sup>rd</sup> pg 493, 2<sup>nd</sup> pg 468 (466), 1<sup>st</sup> 443) If  $a > 0.0$ , calculate the minimum values first, then find the subscripted  $e$  values.

$$\alpha_{min} = \pi \quad \text{SIN}\left(\frac{\beta_{min}}{2}\right) = \sqrt{\frac{s-c}{s}}$$

IF  $\Delta v > \pi$

$$\beta_{min} = -\beta_{min}$$

$$a_{min} = \frac{s}{2}$$

$$t_{min} = \sqrt{\frac{a_{min}^3}{\mu}} \{ \alpha_{min} - \beta_{min} + \text{SIN}(\beta_{min}) \}$$

$$\text{SIN}\left(\frac{\alpha_e}{2}\right) = \sqrt{\frac{s}{2a}}$$

$$\text{SIN}\left(\frac{\beta_e}{2}\right) = \sqrt{\frac{s-c}{2a}}$$

The  $K(U)$  “ $n$ ” coefficients should also be corrected as:

$$n = 0, 1, 2, \dots \text{IF } 2n \text{ even}$$

$$c_U = \frac{2(3n+1)(6n-1)}{9(4n-1)(4n+1)}$$

$$n = 0, 1, 2, \dots \text{IF } 2n+1 \text{ odd}$$

$$c_U = \frac{2(3n+2)(6n+1)}{9(4n+1)(4n+3)}$$

**Page 542, 544, Eq 8-15, Eq 8-17:** (3<sup>rd</sup> pg 541, 2<sup>nd</sup> pg 516 (513), 1<sup>st</sup> 490). In Eq 8-15, the “2” is not needed outside the summation. Inside the summation, there should be a  $(2-\delta_k)$  term defined as “ $k$ ” was in Eq 8-22. In Eq 8-17, the  $(2-\delta_k)$  term should be inside the integral. All three equations should use the  $\delta_k$  parameter for consistency.

**Page 550, Eq 8-27:** (3<sup>rd</sup> pg 548, 2<sup>nd</sup> pg 524 (521), 1<sup>st</sup> 497) The final terms should be components of the position vector as follows:

$$a_I = \left\{ \frac{1}{r} \frac{\partial U}{\partial r} - \frac{r_K}{r^2 \sqrt{r_I^2 + r_J^2}} \frac{\partial U}{\partial \phi_{gc_{sat}}} \right\} r_I - \left\{ \frac{1}{r_I^2 + r_J^2} \frac{\partial U}{\partial \lambda_{sat}} \right\} r_J - \frac{\mu r_I}{r^3}$$

$$a_J = \left\{ \frac{1}{r} \frac{\partial U}{\partial r} - \frac{r_K}{r^2 \sqrt{r_I^2 + r_J^2}} \frac{\partial U}{\partial \phi_{gc_{sat}}} \right\} r_J + \left\{ \frac{1}{r_I^2 + r_J^2} \frac{\partial U}{\partial \lambda_{sat}} \right\} r_I - \frac{\mu r_J}{r^3}$$

$$a_K = \frac{1}{r} \frac{\partial U}{\partial r} r_K + \frac{\sqrt{r_I^2 + r_J^2}}{r^2} \frac{\partial U}{\partial \phi_{gc_{sat}}} - \frac{\mu r_K}{r^3}$$

**Page 559, Next to last Eq:** (3<sup>rd</sup> pg 557) The final  $Kp_4$  and  $ap_4$  terms should be divided by 6.

**Page 575, Eq 8-35 and Eq 8-36:** (3<sup>rd</sup> pg 571, 2<sup>nd</sup> pg 543 (540), 1<sup>st</sup> 515) The first equation denominators should be magnitudes, not vectors. In Eq 8-36, the subscript on the first term in the parentheses should be  $\oplus 3$ , not  $\oplus \text{sat}$ .

**Page 589**, Eq 8-50: (3<sup>rd</sup> pg 587, 2<sup>nd</sup> pg 550 (546), 1<sup>st</sup> 524) The  $F_{thrust}$  equation should have a “g” before “ $I_{sp}$ ”.

**Page 600**, Last paragraph: (3<sup>rd</sup> pg 596, 2<sup>nd</sup> pg 559) “verification” should be “validation”.

**Page 626**, 2<sup>nd</sup> equation: (3<sup>rd</sup> pg 622, 2<sup>nd</sup> pg 584 (582), 1<sup>st</sup> 557) The Mean anomaly rate should have a “n” as the first term on the RHS.

**Page 635**, first equation: (3<sup>rd</sup> pg 631, 2<sup>nd</sup> pg 593 (591), 1<sup>st</sup> 566) The  $F_s$  term should have a  $\text{SIN}(\nu)$  as well.

**Page 636**, first unnumbered equation: (3<sup>rd</sup> pg 632, 2<sup>nd</sup> pg 594 (592), 1<sup>st</sup> 567) The brackets should be as follows:

$$\frac{dv}{dt} = \frac{h}{r^2} + \frac{1}{eh} \left\{ p \cos(\nu) F_R - (p+r) \text{SIN}(\nu) F_S \right\}$$

**Page 709**, last line of SP radial rate term: (3<sup>rd</sup> pg 705) The term should be  $(1+\text{ecos}(\nu))^2$ .

**Page 751**, Center equation and text: (3<sup>rd</sup> pg 745, 2<sup>nd</sup> pg 694 (692), 1<sup>st</sup> 672) The text should be changed as follows

“For  $N$  unique sensor and observation type combinations,”

and

“Note that  $\mathbf{W}$  contains the weights (as appropriate) for each measurement. For example, if one sensor records right ascension-declination, and another records range azimuth and elevation, and each sensor produces 1 measurement, the  $\mathbf{W}$  matrix would be  $5 \times 5$ . If each sensor took 6 measurements, the  $\mathbf{W}$  matrix would be  $30 \times 30$ ! In practice, we accumulate measurements so the size of the  $\mathbf{W}$  matrix is much smaller. In the example above, the  $\mathbf{W}$  matrix would still be just  $5 \times 5$  for all 6 measurements.”

The equation should read  $w_i = \frac{1}{\sigma_{Ad}^2} = w_A \quad i = 1 \dots N$ .

**Page 752**, 3rd and 4th equations: (3<sup>rd</sup> pg 746, 2<sup>nd</sup> pg 695 (693)) The  $y_c$  equation should be  $y_c = -0.0216 + 0.0162x_o$ . The coefficients should be  $\alpha = -0.0216 \pm 0.1520$        $\beta = 0.0162 \pm 0.0285$ .

**Page 796**, Eq 10-35: The expression should be

$$\sigma_l^2 = \frac{\mu^2(l-1)^2}{R_{\oplus}^4} \left[ \sum_{m=0}^N (\sigma_c(\bar{C}_{l,m})^2 + \sigma_s(\bar{S}_{l,m})^2) + \sum_{m=N+1}^{N_{max}} (\bar{C}_{l,m}^2 + \bar{S}_{l,m}^2) \right]$$

**Page 802-803**, last equation and top equation (803): (3<sup>rd</sup> pg 793, 2<sup>nd</sup> pg 743 (740)) The azimuth numerator and denominator are switched. Both terms in the numerator of the 3,3 matrix position should be squared.

**Page 810**, footnote equation: (3<sup>rd</sup> pg 801, 2<sup>nd</sup> pg 750) The  $\Delta t$  should be squared.

**Page 865**, first equation: (3<sup>rd</sup> pg 854, 2<sup>nd</sup> pg 788 (784), 1<sup>st</sup> 760) The semimajor axis should be “7178.1363” instead of “1.12532”.

**Page 898-899**, Eq 11-44: (3<sup>rd</sup> pg 887, 2<sup>nd</sup> pg 819 (815), 1<sup>st</sup> 791) The second negative sign from the left should be “+”. Top of 899, the Danielson reference should be from 2003.

**Page 961**, Ex 12-8: (3<sup>rd</sup> pg 44, 2<sup>nd</sup> pg 44 (44), 1<sup>st</sup> 126) The last sentence should be “came within about 340,000 km of Jupiter—certainly far enough out to avoid encountering the atmosphere. This is close to the actual value due to some approximations used in this example.”.

**Page 972**, second equation: (3<sup>rd</sup> pg 44, 2<sup>nd</sup> pg 44 (44), 1<sup>st</sup> 126) The first terms should be  $1/2 - u^*$ .

**Page 1060**, FreeFlyer line in table: (3<sup>rd</sup> pg 1013, 2<sup>nd</sup> pg 928 (922)) Some updated information should be as follows:

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FreeFlyer	ai-solutions	Complete graphical displays and user interface. Batch Least Squares, KF, UKF, and SRIF OD
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