

# Appendix A

## Planetary Parameters

Characteristic parameters of the planets in the solar system

	$R$ [km]	$\mu$ [km <sup>3</sup> /s <sup>2</sup> ]	$a$ [10 <sup>6</sup> km]	$e$	$\langle r \rangle_t$ [10 <sup>6</sup> km]	$\langle v \rangle_t$ [km/s]
Sun	696,000	$1.327124400 \times 10^{11}$	–	–	–	–
Mercury	2440	$2.2032 \times 10^4$	57.90923	0.20564	59.134	46.362
Venus	6052	$3.24859 \times 10^5$	108.2096	0.00677	108.212	35.020
Earth	6378.136	$3.98600442 \times 10^5$	149.5984	0.01670	149.619	29.783
(Moon)	1737.5	$4902.801 \times 10^3$	0.384400	0.05540	0.38499	1.0175
Mars	3396.2	$4.282837 \times 10^4$	227.9443	0.09341	228.938	24.076
Jupiter	71,492	$1.2686534 \times 10^8$	778.338	0.04836	779.248	13.050
Saturn	60,268	$3.7931187 \times 10^7$	1426.64	0.05378	1428.70	9.6379
Uranus	25,559	$5.793939 \times 10^6$	2870.61	0.04725	2873.81	6.7955
Neptune	24,760	$6.836529 \times 10^6$	4498.40	0.00860	4498.57	5.4315
Pluto	1151	871	5906.43	0.24883	6089.28	4.6659

$R$  = equatorial planet radius,  $\langle r \rangle_t$  = time-averaged orbit radius,  $\langle v \rangle_t$  = time-averaged orbital velocity. The values hold for the year 2010. An underscore for  $R$  indicates uncertainties, for  $a$ ,  $e$ , and  $\langle r \rangle_t$  that this digit changes within a decade

## A.1 Mean Orbit Radius

### A.1.1 Titius–Bode Law

The orbit radii of the solar planets can be expressed empirically and approximately by the famous Titius–Bode law

$$\langle r \rangle = 0.4 + 0.3 \cdot 2^n \text{ [AU] Titius–Bode law}$$

with

- Mercury:  $n = -\infty$
- Venus:  $n = 0$
- Earth:  $n = 1$
- Mars:  $n = 2$
- Asteroid belt:  $n = 3$
- Jupiter:  $n = 4$
- Saturn:  $n = 5$
- Uranus:  $n = 6$

$$1AU = 149.597870700 \times 10^6 \text{ km (exactly)}$$

### A.1.2 Average over True Anomaly

$$\langle r \rangle_\theta = a(1 - e^2) \frac{1}{\pi} \int_0^\pi \frac{d\theta}{1 + e \cos \theta}$$

Since

$$\begin{aligned} \frac{1}{\pi} \int_0^\pi \frac{d\theta}{1 + e \cos \theta} &= \frac{2}{\pi\sqrt{1 - e^2}} \arctan \left( \sqrt{\frac{1 - e}{1 + e}} \cdot \tan \frac{\theta}{2} \right) \Big|_0^\pi = \frac{2}{\pi\sqrt{1 - e^2}} \left( \frac{\pi}{2} - 0 \right) \\ &= \frac{1}{\sqrt{1 - e^2}} \end{aligned}$$

then

$$\langle r \rangle_\theta = a\sqrt{1 - e^2} = b \quad (b = \text{semi-minor axis}) \quad (\text{A.1})$$

### A.1.3 Time Average

$$\langle r \rangle_t = a(1 - e^2) \frac{2}{T} \int_0^{T/2} \frac{dt}{1 + e \cos \theta} = a(1 - e^2) \frac{2}{T} \int_0^\pi \frac{dt/d\theta}{1 + e \cos \theta} d\theta$$

Since

$$\frac{dt}{d\theta} = \frac{r^2}{h} = \frac{a^2(1 - e^2)^2}{(1 + e \cos \theta)^2 \sqrt{\mu a(1 - e^2)}}$$

and

$$T = 2\pi \sqrt{\frac{a^3}{\mu}}$$

it follows that

$$\langle r \rangle_t = a(1 - e^2)^{5/2} \frac{1}{\pi} \int_0^\pi \frac{d\theta}{(1 + e \cos \theta)^3}$$

From Problem 7.6 we get

$$\begin{aligned} (1 - e^2)^{5/2} \int \frac{d\theta}{(1 + e \cdot \cos \theta)^3} &= \int (1 - e \cdot \cos E)^2 dE \\ &= \left(1 + \frac{e^2}{2}\right) E - 2e \sin E + \frac{e^2}{4} \sin 2E \end{aligned}$$

and hence finally

$$\langle r \rangle_t = a \left(1 + \frac{e^2}{2}\right) \quad (\text{A.2})$$

## A.2 Mean Orbital Velocity

Denote by

$$K(x) = \int_0^{\pi/2} \frac{dt}{\sqrt{1 - x^2 \sin^2 t}} = \frac{\pi}{2} \left[ 1 + \left(\frac{1}{2}\right)^2 x^2 + \left(\frac{1 \cdot 3}{2 \cdot 4}\right)^2 x^4 + \left(\frac{1 \cdot 3 \cdot 5}{2 \cdot 4 \cdot 6}\right)^2 x^6 + \dots \right]$$

the *complete elliptic integral of the first kind* and by

$$\begin{aligned} E(x) &= \int_0^{\pi/2} \sqrt{1 - x^2 \sin^2 t} \cdot dt \\ &= \frac{\pi}{2} \left[ 1 - \left(\frac{1}{2}\right)^2 x^2 - \left(\frac{1 \cdot 3}{2 \cdot 4}\right)^2 \frac{x^4}{3} + \left(\frac{1 \cdot 3 \cdot 5}{2 \cdot 4 \cdot 6}\right)^2 \frac{x^6}{5} + \dots \right] \end{aligned}$$

the *complete elliptic integral of the second kind*.

### A.2.1 Average over True Anomaly

$$\langle v \rangle_\theta = \frac{\mu}{h} \frac{1}{\pi} \int_0^\pi \sqrt{1 + 2e \cos \theta + e^2} \cdot d\theta = \sqrt{\frac{\mu}{a}} \sqrt{\frac{1+e}{1-e}} \frac{2}{\pi} E\left(\frac{2\sqrt{e}}{1+e}\right)$$

From this it follows that

$$\langle v \rangle_\theta = \sqrt{\frac{\mu}{a}} \left[ 1 + \frac{3}{4}e^2 + \frac{33}{64}e^4 + O(e^6) \right] \quad @ \quad e \rightarrow 0 \quad (\text{A.3})$$

## A.2.2 Time Average

$$\langle v \rangle_t = \frac{\mu}{hT} \int_0^{T/2} \sqrt{1 + 2e \cos \theta + e^2} \cdot dt = \frac{\mu}{hT} \int_0^\pi \sqrt{1 + 2e \cos \theta + e^2} \frac{dt}{d\theta} d\theta$$

From this it follows that

$$\langle v \rangle_t = \sqrt{\frac{\mu}{a}} (1 - e^2) \cdot \frac{1}{\pi} \int_0^\pi \frac{\sqrt{1 + 2e \cos \theta + e^2}}{(1 + e \cos \theta)^2} d\theta$$

$$\int_0^\pi \frac{\sqrt{1 + 2e \cos \theta + e^2}}{(1 + e \cos \theta)^2} d\theta = \frac{1}{(1 - e^2)} \left[ (1 - e)K \left( \frac{2\sqrt{e}}{1 + e} \right) + (1 + e)E \left( \frac{2\sqrt{e}}{1 + e} \right) \right]$$

hence

$$\langle v \rangle_t = \sqrt{\frac{\mu}{a}} \cdot \frac{1}{\pi} \left[ (1 - e)K \left( \frac{2\sqrt{e}}{1 + e} \right) + (1 + e)E \left( \frac{2\sqrt{e}}{1 + e} \right) \right]$$

and therefore

$$\langle v \rangle_t = \sqrt{\frac{\mu}{a}} \left[ 1 - \frac{1}{4}e^2 - \frac{3}{64}e^4 - O(e^6) \right] \quad @ \quad e \rightarrow 0 \quad (\text{A.4})$$

# Appendix B

## Approximate Analytical Solution for Uneven Staging

Let

$v_{*,i}$  arbitrary

$\varepsilon_i$  arbitrary

We define

$$v_{*,i} = v_* + \Delta v_{*,i} =: v_*(1 + \delta_i)$$

and

$$\varepsilon_i = \varepsilon + \Delta \varepsilon_i =: \varepsilon(1 + \Delta_i)$$

with arithmetic means

$$v_* := \frac{1}{n} \sum_i v_{*,i}$$

$$\varepsilon := \frac{1}{n} \sum_i \varepsilon_i$$

implying

$$\sum_i \delta_i = 0, \quad \sum_i \Delta_i = 0$$

Assuming  $\delta_i \ll 1$  and  $\Delta_i \ll 1$  we derive from Eq. (3.2.4)

$$\frac{\Delta v}{v_*} = \sum_{i=1}^n (1 + \delta_i) \ln \left[ \frac{1}{\varepsilon_i} \left( 1 - \frac{\alpha}{v_{*,i}} \right) \right]$$

$$= - \sum_{i=1}^n (1 + \delta_i) \ln \varepsilon_i + \sum_{i=1}^n (1 + \delta_i) \ln \left( 1 - \frac{\alpha}{v_{*,i}} \right)$$

Expanding  $\ln(1 - \alpha/v_{*,i})$  for  $v_{*,i} = v_*(1 + \delta_i)$  we get

$$\begin{aligned} \ln\left(1 - \frac{\alpha}{v_{*,i}}\right) &\approx \ln\left[\left(1 - \frac{\alpha}{v_*}\right)\left(1 + \frac{\alpha\delta_i}{v_* - \alpha}\right)\right] \\ &\approx \ln\left(1 - \frac{\alpha}{v_*}\right) + \frac{\alpha\delta_i}{v_* - \alpha} - \frac{1}{2}\left(\frac{\alpha\delta_i}{v_* - \alpha}\right)^2 + O(\delta_i^3) \end{aligned} \quad @ \frac{\alpha\delta_i}{v_* - \alpha} \ll 1$$

With  $\sum_i \delta_i = 0$  we get

$$\frac{\Delta v}{v_*} \approx \sum_i (1 + \delta_i) \ln\left[\frac{1}{\varepsilon_i} \left(1 - \frac{\alpha}{v_*}\right)\right] - \frac{1}{2} \left(\frac{\alpha}{v_* - \alpha}\right)^2 \sum_{i=1}^n \delta_i^2 + O\left(\sum_{i=1}^n \delta_i^3\right)$$

Due to

$$\sum_i (1 + \delta_i) \ln\left[\frac{1}{\varepsilon_i} \left(1 - \frac{\alpha}{v_*}\right)\right] = - \sum_i \delta_i \ln \varepsilon_i + \sum_i \ln\left[\frac{1}{\varepsilon_i} \left(1 - \frac{\alpha}{v_*}\right)\right]$$

and

$$\sum_i \delta_i \ln \varepsilon_i = \sum_i \delta_i [\ln \varepsilon + \ln(1 + \Delta_i)] = \sum_i \delta_i \Delta_i - \frac{1}{2} \sum_i \delta_i \Delta_i^2$$

and

$$\sum_i \ln\left[\frac{1}{\varepsilon_i} \left(1 - \frac{\alpha}{v_*}\right)\right] = n \ln \frac{1}{\varepsilon} \left(1 - \frac{\alpha}{v_*}\right)$$

follows

$$\frac{\Delta v}{v_*} \approx n \ln \frac{1}{\varepsilon} \left(1 - \frac{\alpha}{v_*}\right) - nC$$

where

$$C := \frac{1}{n} \sum_i \delta_i \left[ \Delta_i + \frac{1}{2} \left(\frac{\alpha}{v_* - \alpha}\right)^2 \delta_i + O(\delta_i^2) + O(\Delta_i^2) \right]$$

from which follows

$$\frac{\alpha}{v_*} \approx 1 - \frac{\Delta v}{\varepsilon e^{nv_*}} + C \approx 1 - \frac{\Delta v}{\varepsilon e^{nv_*}} \quad (\text{B.1})$$

Because of  $\frac{\alpha\delta_i}{v_* - \alpha} \ll 1$  we find from Eq. (B.1) the constraint  $\exp\left(-\frac{\Delta v}{nv_*}\right) \ll \min_{i=1,n}\left(\frac{\bar{\varepsilon}}{\delta_i}\right)$   
 From Eq. (B.1) we determine the quantity  $C$  as

$$C = \frac{1}{n} \sum_i \frac{\Delta v_{*,i}}{v_*} \left[ \frac{\Delta \varepsilon_i}{\varepsilon_i} + \frac{1}{2} \left( 1 - \frac{1}{\bar{\varepsilon}} e^{-\frac{\Delta v}{nv_*}} \right)^2 \frac{\Delta v_{*,i}}{v_*} + O\left[(\Delta \varepsilon_i)^2\right] + O\left[(\Delta v_{*,i})^2\right] \right] \quad (\text{B.2})$$

We therefore find a solution equivalent to Eq. (3.3.7) with the substitution

$$\frac{\Delta v}{nv_*} \rightarrow \frac{\Delta v}{nv_*} + C$$

Applying this substitution rule we find the solutions equivalent to Eqs. (3.3.8) and (3.3.9)

$$\lambda_*^{1/n} = \frac{e^{-\Delta v/nv_* - C} - \bar{\varepsilon}}{1 - \varepsilon} \quad @ \quad \exp\left(-\frac{\Delta v}{nv_*}\right) \ll \min_{i=1,n}\left(\frac{\bar{\varepsilon}}{\delta_i}\right) \quad (\text{B.3})$$

and

$$\Delta v = -nv_* \left\{ \ln \left[ \lambda_*^{1/n} (\overline{1 - \varepsilon}) + \bar{\varepsilon} \right] + C' \right\} \quad (\text{B.4})$$

From Eq. (B.3) follows

$$e^{-\Delta v/nv_*} \approx \lambda_*^{1/n} (\overline{1 - \varepsilon}) + \bar{\varepsilon} \ll \min_{i=1,n}\left(\frac{\bar{\varepsilon}}{\delta_i}\right)$$

from which we obtain

$$C' = \frac{1}{n} \sum_i \frac{\Delta v_{*,i}}{v_*} \left[ \frac{\Delta \varepsilon_i}{\varepsilon_i} + \frac{\lambda_*^{2/n}}{2} \left( \frac{\overline{1 - \varepsilon}}{\bar{\varepsilon}} \right)^2 \frac{\Delta v_{*,i}}{v_*} + O\left[(\Delta \varepsilon_i)^2\right] + O\left[(\Delta v_{*,i})^2\right] \right] \quad (\text{B.5})$$

With Eq. (B.1) inserted into Eq. (3.2.3), and with  $e^{-C/nv_*} \approx 1 - C/nv_*$  we find after some elementary calculations

$$\lambda_{i,opt} = \frac{e^{-\Delta v/nv_* - C'} - \bar{\varepsilon}}{\frac{\bar{\varepsilon}}{\varepsilon_i} - e^{-\Delta v/nv_* - C'}} = \frac{\lambda_*^{1/n} + K}{\frac{\bar{\varepsilon}}{\varepsilon_i} \frac{1 - \varepsilon_i}{1 - \varepsilon} - \lambda_*^{1/n} - K} \quad (\text{B.6})$$

with  $K = \left( \lambda_*^{1/n} + \frac{\bar{\varepsilon}}{1 - \varepsilon} \right) C'$ .

# References

- Anderson, J.D.: Hypersonic and High-Temperature Gas Dynamics. AIAA Education Series (2006). ISBN 1-56347-780-7
- Anderson, J.D.: Fundamentals of Aerodynamics (5th SI unit edn). McGraw-Hill (2011). ISBN 13: 9780073398105
- Barth, H.: Conrad Haas—Raketenpionier und Humanist. Johannis Reeg Verlag (2005). ISBN 3-937320-55-5
- Bate, R.R., Mueller, D., White, J.E.: Fundamentals of Astrodynamics. Dover Publications (1971). ISBN 0-486-60061-0
- Battin, R.H.: Astronautical Guidance. McGraw-Hill, New York (1964)
- Battin, R.H.: An Introduction to the Mathematics and Methods of Astrodynamics. AIAA Education Series (1987). ISBN 0-930403-25-8
- Berlin, P.: Satellite Platform Design. Department of Space Science of the Universities Luleå and Umeå (2005). ISBN 91-631-4917-6, orders by email to berlin@space@cs.com
- Berlin, P.: Geostationary Applications Satellite. Cambridge University Press (1988). ISBN 0-521-33525-6
- Bertin, J.J.: Hypersonic Aerothermodynamics. AIAA Education Series, Washington, DC (1994). ISBN 1-56347-036-5
- Beutler, G.: Methods of Celestial Mechanics I: Physical Mathematical and Numerical Principles. Springer, Berlin (2005). ISBN 3-540-40749-9
- Beutler, G.: Methods of Celestial Mechanics II: Application to Planetary System, Geodynamics and Satellite Geodesy. Springer, Berlin (2005). ISBN 3-540-40750-2
- Brandenberger, R.H., Vafa, C.: Superstrings in the Early Universe. Nucl. Phys. B **316**, 391 (1989)
- Brankin, R., et al.: Algorithm 670: a Runge-Kutta-Nyström code. ACM Trans. Math. Softw. **15**(1), 31–40 (1989)
- Brown, C.D.: Elements of Spacecraft Design. AIAA Education Series (2002). ISBN 1-56347-524-3
- Campan, G., Alby, F., Gautier, H.: Station-keeping techniques for geostationary satellites. In: Carrou, J.-P. (ed.) Spaceflight Dynamics, Part II. CNES/CÉPADUÈS (1995). ISBN 2-85428-377-5
- Chao, C.-C.: Applied Orbit Perturbation and Maintenance. Aerospace Press (2005). ISBN 1-884989-17-9
- Chapman, D.R.: An approximate analytical method for studying entry into planetary atmospheres. NASA TR R-11 (1959)
- Chapman, D.R.: Tables of Z Functions for Atmospheric Entry Analysis. NASA TR R-106 (1961)
- Chobotov, V.A. (ed.) Orbital Mechanics, 3rd edn. AIAA Education Series (2002). ISBN 1-56347-537-5
- Cook, G.E.: Perturbations of near-circular orbits by the gravitational potential. Planet. Space Sci. **14**(5), 433–444 (1966)

- Cornelisse, J.W., Schöyer, H.F.R., Wakker, K.F.: *Rocket Propulsion and Spaceflight Dynamics*. Pitman Publishing Ltd. (1979). ISBN 0-273-01141-3
- Curtis, H.D.: *Orbital Mechanics for Engineering Students*. Elsevier (2005). ISBN 0-7506-6169-0
- Danby, J.M.A.: *Fundamentals of Celestial Mechanics*, 2nd edn. Willmann-Bell (2003). ISBN 0-943396-20-4
- Deser, S., Jackiw, R., 'tHooft, G.: Three-dimensional Einstein gravity: dynamics of flat space. *Ann. Phys.* **152**, 220–235 (1984)
- Efroimsky, M.: Gauge freedom in astrodynamics. In: Gurfil, P. (ed.) *Modern Astrodynamics*. Elsevier (2006). ISBN 9780123735621
- Esmaelzadeh, R., Ghadiri, H.: Appropriate starter for solving the Kepler's Equation. *Int. J. Comput. Appl.* **89**(7), 31–38 (2014)
- Escobal, P.R.: *Methods of Orbit Determination*. Krieger Publishing (1965). ISBN 0-88275-319-3
- Fehse, W.: *Automated Rendezvous and Docking of Spacecraft*. Cambridge University Press (2003). ISBN 0-521-82492-3
- Fortescue, P., Stark, J., Swinerd, G.: *Spacecraft Systems Engineering*, 3rd edn. Wiley (2003). ISBN 0-470-85102-3
- Goodman, J.L.: History of Space Shuttle Rendezvous and Proximity Operations. *J. Spacecraft Rockets* **43**(5), 944–959 (2006)
- Griffin, M.D., French, J.R.: *Space Vehicle Design*, 2nd edn. AIAA Education Series (2004). ISBN 1-56347-539-1-90-8
- Groves, G.V.: Motion of a satellite in the earth's gravitational field. *Proc. Royal Soc. London* **254** (1276), 48–65 (1960)
- Gurfil, P.: Nonlinear feedback control of low-thrust orbital transfer in a central gravitational field. *Acta Astronaut.* **60**, 631–648 (2007)
- Gurzadyan, G.A.: *Theory of Interplanetary Flights*. Gordon and Breach (1996). ISBN 2-919875-15-9
- Guthmann, A.: *Einführung in die Himmelsmechanik und Ephemeridenrechnung*. In: Spektrum Akademischer Verlag, 2nd edn (2000). ISBN 3-8274-0574-2
- Hale, F.J.: *Introduction into Space Flight*. Prentice-Hall (1994). ISBN 0-13-481912-8
- Hankey, W.L.: *Re-Entry Aerodynamics*. AIAA Education Series (1988). ISBN 0-930403-33-9
- Hastings, D., Garrett, H.: *Spacecraft-Environment Interactions*. Cambridge University Press (1996). ISBN 0-521-47128-1
- Herrick, S.: *Astrodynamics—Orbit Determination, Space Navigation, Celestial Dynamics*, vol. 1. Van Nostrand Reinhold Company, London (1971). ISBN 978-0442033705
- Herrick, S.: *Astrodynamics—Orbit Correction, Perturbation Theory, Integration*, vol. 2. Van Nostrand Reinhold Company, London (1972). ISBN 978-0442033712
- Hill, P.G., Peterson, R.: *Mechanics and Thermodynamics of Propulsion*, 2nd edn. Addison-Wesley (1992). ISBN 0-201-14659-2
- Hirschel, E.H.: *Basics of Aerothermodynamics*. Springer (2004). ISBN-10: 3540221328
- Hughes, P.C.: *Spacecraft Attitude Dynamics*. Wiley (1986). ISBN 0-471-81842-9
- Humble, R.W., Henry, G.N., Larson W.J.: *Space Propulsion Analysis and Design*. McGraw-Hill (1995). ISBN 0-07-031320-2
- Jochim, E.F.M.: *Satellitenbewegung, Band IV* (2013, vol. IV). ISSN 1434-8454
- Johnson, N.L.: A new look at the GEO and near-GEO regimes: operations, disposals, and debris. *Acta Astronaut.* **80**, 82–88 (2012)
- Kaplan, M.H.: *Modern Spacecraft Dynamics and Control*. Wiley (1976). ISBN 0-471-45703-5
- Kaula, W.M.: *Theory of Satellite Geodesy*. Waltham (1966). ISBN 0-486-41465-5
- Kemble, S.: *Interplanetary Mission Analysis and Design*. Springer (2006). ISBN 3-540-29913-0
- King-Hele, D.: *Theory of Satellite Orbits in an Atmosphere*. Springer (1987). ISBN 0216922526
- Koon, W.S., Lo, M.W., Marsden, J.E., Ross, S.D.: Heteroclinic connections between periodic orbits and resonance transitions in celestial mechanics. *Chaos* **10**(2), 427–469 (2000)
- Larson, W.J., Wertz, J.R.: *Space Mission Analysis and Design*, 3rd edn. Microcosm Press (1999). ISBN 1-881883-10-8

- Ledermann, W., Lloyd, E., Vaijda, S., Alexander, C.: Handbook of Applicable Mathematics, Supplement. Wiley (1990). ISBN 978-0471918257
- Liu, J.J.F., Alford, R.L.: Semianalytic theory for a closed-earth artificial satellite. *J. Guidance Control* **3**(4), 304–311 (1980)
- Loh, W.H.T.: Re-entry and Planetary Entry: Physics and Technology, vol. I: Dynamics, Physics, Radiation, Heat, Transfer and Ablation, and vol. II: Advanced Concepts, Experiments, Guidance-Control and Technology. Springer, New York (1968)
- Martin, J.J.: Atmospheric Reentry—An Introduction to its Science and Engineering. Prentice-Hall (1966)
- Messerschmid, E., Fasoulas, S.: Raumfahrtsysteme. Springer (2000). ISBN 3-540-66803-9
- Micheau, P.: Orbit Control Techniques for Low Earth Orbiting (LEO) Satellites. In: Carrou, J.-P. Spaceflight Dynamics, Part I. CNES/CÉPADUÈS (1995). ISBN 2-85428-376-7
- Montenbruck, O., Gill, E.: Satellite Orbits—Models, Methods, Applications. Springer, Berlin (2000). ISBN 3-540-67280-X
- Murray, C.D., Dermott, S.F.: Solar Systems Dynamics. Cambridge University Press (1999). ISBN 0-521-57295-9
- Noton, M.: Spacecraft Navigation and Guidance. Springer (1998). ISBN 3-540-76248-5
- Perozzi, E., Ferraz-Mello, S.: Space Manifold Dynamics. Springer (2010). ISBN 978-1441903471
- Pisacane, V.L.: Fundamentals of Space Systems, 2nd edn. Oxford University Press (2005). ISBN 0-19-516205-6
- Pollard, H.: Celestial Mechanics, (The Carus Mathematical Monographs, no. 18). Mathematical Association of America (1976). ISBN-13: 978-0883850190
- Prussing, J.E., Conway, B.A.: Orbital Mechanics. Oxford University Press (1993). ISBN 0-19-507834-9
- Rao, G.V.R.: Exhaust nozzle contour for optimum thrust. *Jet Propul.* **28**, 377 (1958)
- Rao, A.V.: Trajectory optimization. In: Blockley, R., Shyy, W. Encyclopedia of Aerospace Engineering. Wiley (2010). ISBN 978-0-470-68665-2
- Reif, F.: Fundamentals of Statistical and Thermal Physics. McGraw-Hill (1965). ISBN 0070518009
- Reimann, P.: Brownian motors: noisy transport far from equilibrium. *Phys. R.* **361**, 57–265 (2002)
- Regan, F.J.: Re-Entry Vehicle Dynamics. AIAA Education Series (1984). ISBN 0-915928-78-7
- Richardson, D.L.: Analytical construction of periodic orbits about the collinear points. *Celest. Mech.* **22**, 241–253 (1980)
- Roy, A.E.: Orbital Motion, 4th edn. Institute of Physics Publishing (2005). ISBN 0-7503-1015-4
- Ruppe, H.O.: Introduction to Astronautics, vol. 1. Academic Press (1966)
- Schaub, H., Junkins, J.L.: Analytical Mechanics of Space Systems. AIAA Education Series (2003). ISBN 1-56347-563-4
- Sellers, J.J.: Understanding Space, 3rd edn. McGraw-Hill (2005). ISBN 0-07-340775-5
- Shapiro, B.E.: Phase plane analysis and observed frozen orbit for the Topex/Poseidon mission. In: 6th International Space Conference of Pacific Basin Societies (1995)
- Szebehely, V.: Theory of Orbits—The Restricted Problem of Three Bodies. Academic Press, New York (1967)
- Sidi, Marcel J.: Spacecraft Dynamics and Control. Cambridge University Press (1997). ISBN 0-521-55072-6
- Soop, E.M.: Handbook of Geostationary Orbits. Kluwer Academic Publisher (1994). ISBN 0-792-33054-4
- Steiner, W., Schagerl, M.: Raumflugmechanik. Springer (2004). ISBN 3-540-20761-9
- Sutton, G.P., Biblarz O.: Rocket Propulsion Elements, 7th edn. Wiley (2001). ISBN 0-471-32642-9
- Tapley, B.C., Schulz, B.E., Born, G.H.: Statistical Orbit Determination. Academic Press, New York (2004). ISBN 0126836302
- Tegmark, M.: On the dimensionality of spacetime. *Class. Quantum Grav.* **14**, L69–L75 (1997)
- Thomson, W.T.: Introduction to Space Dynamics. Dover Books (1986). ISBN 0-486-65113-4

- Tribble, A.C.: *The Space Environment—Implications for Spacecraft Design*. Princeton University Press (2003). ISBN 0-691-10299-6
- Turner, M.J.L.: *Rocket and Spacecraft Propulsion*, 2nd edn. Springer (2006). ISBN 3540221905
- Vallado, D.A.: *Fundamentals of Astrodynamics and Applications*, 3rd edn. McGraw Hill (2007). ISBN 978-1-881883-14-2
- Vinh, N.X., Busemann, A., Culp, R.D.: *Hypersonic and Planetary Entry Flight Mechanics*. Ann Arbor University of Michigan Press (1980). ISBN 0-472-09304-5
- Volk, O.: Miscellanea from the History of Celestial Mechanics. *Celest. Mech.* **14**, 365–382 (1976)
- Walter, U.: Relativistic rocket and space flight. *Acta Astronaut.* **59**, 453–516 (2006)
- Westmoreland, S.: A note on relativistic rocketry. *Acta Astronaut.* **67**, 1248–1251 (2010)
- Wiesel, W.E.: *Spaceflight Dynamics*. McGraw Hill (1997). ISBN 0-07-070110-5
- Zhong, W., Gurfil, P.: Mean orbital elements estimation for autonomous satellite guidance and orbit control. *J. Guidance Control Dyn.* **36**, 1624–1641 (2013)
- Zoby, E.V.: Approximate heating analysis for the windward symmetry plane of shuttle-like bodies at angle of attack. In: Horton, T.E. (ed.) *Thermodynamics of Atmospheric Entry*, vol. 82. Progress in the Astronautics and Aeronautics, AIAA, pp. 521–528 (1982)

# Index

## Directions for Use

- Compound terms that are set expressions (Example: characteristic velocity ( $c^*$ )) are listed as such, otherwise they are listed by their superordinate term (Example: “departure velocity” is listed as “velocity, departure”). In case of doubt, cross references are provided.
- Only significant page references are listed.
- Page references that are definitions or are essential in terms of important results are printed in **bold**.
- Braces {...} mean a.k.a. ...

## A

- absorption coefficient. *see* {absorptivity}
- absorptivity, xxxiii, 736, **746–748**, 750, 756, 762, 765, 778, 790
- spectral, 746, 747
- total, 747
- acceleration, xxx, xxxi, xxxiii, 24–26, 33, 34, 105–111, 146, 173, 176, 178, **182**, 422, 423, **444**, 483, 484, 489, 520, 662, 727.
- see also* deceleration
- constant, 33, 34
- drag, **483–484**, 487, 489. *see also* {drag}
- Earth’s mean gravitational, **173**, 174
- gravitational, xxxi, 122, **173**, 174, 341, 727
- ion, 107
- perturbational, 555, **557–559**, 570, 573, 606, 607, 610, 617, 621, 622, 624, 633–635
- proper, xxxiii, **26**
- residual, 341
- acceleration voltage, 108, 111, 115
- adiabatic flow theory, 430
- adiabatic process, 79
- access area, 597, **680–681**
- addition theorem, 562, 753
- aerobraking, 404, 428, 645
- aerocapture, 404, 434, 471, 645
- aerodynamic pressure, 157, 447
- maximum, 157. *see also* {Max q}
- aerothermodynamics, 428–431. *see also* heat flux
- aiming radius, **222**. *see* {impact parameter}
- albedo, 735, 737, **761–763**, 769, 777, 778, 782, 785, 793–795
- altitude, xxxi, xxxiv, 121–123, 125–129, 140, 431
- critical (deceleration), **451**, 459, **462**, **463**, 469, 471, 479, **480**
- dimensionless (variable), xxxiv, **443**, 451, 459
- maximum heating, 452, 481
- reflection, **466**, 476, 469, 471
- resonance, 611
- altitude variable (dimensionless), xxxiv, **443**

- angle. *see also* orbital angles  
 bank, **xxxiv**, **141**, **438**, **477–479**, **485**, **486**.  
*see also* {roll angle}  
 beta. *see* beta angle  
 compound, **204**, **205**  
 deflection, **xxxiii**, **408–410**, **412**, **415**,  
**418–420**  
 dogleg, **205**, **206**. *see also* angle,  
 compound  
 entry, **431**, **438**, **442**, **454**, **458**, **459**,  
**464–465**, **467**, **470**, **472**, **483**. *see also*  
 initial flight path angle  
 flight path. *see* flight path angle  
 hour. *see* hour angle  
 initial kick, **156**. *see also* {pitch angle}  
 lead, **363**. *see also* angle, phase  
 nutation. *see* nutation angle  
 orbit. *see* orbit angle  
 phase, **359–361**, **363–364**, **394–395**, **533**, **536**  
 pitch, **xxxiv**, **156**, **157**, **649**  
 roll, **xxxiv**, **477**. *see also* {angle, bank}  
 steering, **4**, **145**, **147**, **155**, **161**. *see also*  
 {angle, thrust}, *see also* steering law  
 thrust, **xxxiii**, **145**, **147**, **155**, **158**, **159**, **162**.  
*see also* {angle, steering}. *see also*  
 {steering law}  
 transfer, **300**, **307**, **365**  
 velocity, **431**. *see* {angle, entry}
- angle of attack (AOA), **vii**, **xxv**, **xxxiii**, **143**,  
**144**, **431**, **438**, **445**, **447**, **455**, **477**, **479**,  
**483**, **485–487**, **489**, **490**
- angular elements. *see* orbital elements, angular
- angular frequency, **viii**, **xxxv**, **265**, **474**, **533**,  
**547**, **613**, **618**, **734**
- angular momentum, **xxx**, **xxxi**, **173**, **175**, **183**,  
**184**, **185**, **186**, **192**, **199**, **201**, **247**, **256**,  
**494**, **670**, **700–704**, **706**, **710–712**,  
**715–717**, **722–725**  
 conservation of, **175**. *see* conservation of  
 angular momentum  
 mass-specific, **xxx**, **183**
- angular velocity, **viii**, **xxxv**, **146**, **182**, **184**, **338**,  
**339**, **513**, **515**, **700**
- anomaly, **194**  
 eccentric, **xxx**, **204**, **211**, **212**, **215**, **225**  
 hyperbolic, **xxx**, **204**  
 mean, **xxx**, **196**, **204**, **226**  
 true, **xxxiv**, **194**, **195**, **200**, **204**, **276**, **289**,  
**798**. *see also* {orbit angle}  
 universal, **204**, **215**, **222**, **228**, **236**
- apoapsis, **xxvii**, **210**, **211**, **286**, **326**, **645**  
 change of, **286**. *see also* progression of line  
 of apsides
- apocenter, **210**. *see* {apoapsis}
- apogee, **210**, **597**. *see also* {apoapsis}
- apogee boost, **65**, **150**, **151**, **330**
- Apollo, **55–57**, **143**, **365**, **366**, **427**, **435**, **438**,  
**469–472**, **528**
- approach corridor, **361**, **371**, **372**
- approach ellipsoid, **361**, **367**
- approach hyperbola, **402**, **403**
- apse line, **210**, **597**, **696**. *see also* {line of  
 apsides}
- apsidal precession, **579**
- area-velocity equation, **80**
- argument of latitude. *see* latitude, argument of
- argument of periapsis, **xxix**, **xxxv**, **200**, **201**,  
**203**, **592**, **595**, **687**  
 change of, **287**
- arrival orbit. *see* orbit, arrival
- ascending node, **xxvi**, **xxix**, **xxxv**, **200**, **202**,  
**612**, **665**, **677**, **687**
- ascending node vector, **202**, **206**
- ascent (flight), **ix**, **149–163**  
 optimum, **153–154**, **162–163**. *see also*  
 trajectory, ascent  
 vertical, **42**, **43**
- ascent equations of motion, **147**, **149**
- ascent phases, **150**
- astronaut, **127**, **128**, **345**, **360**, **365**
- atmosphere, **xxxiv**, **xxxii**, **121–129**, **130–144**,  
**431**, **435**, **453**, **464**, **465**, **472–476**, **482**,  
**485–490**, **555**, **641–655**, **659**, **720**, **721**,  
**724**, **725**
- atmospheric (mass) density, **125–129**, **430**,  
**452**, **453**, **641–655**, **720**, **721**, **725**  
 master equation, **123**
- atmospheric models, **125–129**
- atomic oxygen, **140**, **765**
- attitude dynamics, **699–729**
- attitude kinematics, **711–717**
- B**
- ballistic capture, **423**, **525**, **543**. *see also*  
 planetary capture
- ballistic coefficient, **xxx**, **137**, **452**, **453**, **481**,  
**482**, **648–649**, **652–654**, **655**
- ballistic radiation coefficient, **622**
- ballistic reentry, **447–451**, **452–454**, **459**, **476**,  
**481**  
 near-ballistic, **459–465**
- bang-bang control, **162**
- bank angle. *see* angle, bank
- Barker's equation, **228**, **274**, **276**
- bank reversal, **485**, **486**
- barometric formula, **124–125**, **431**, **447**
- barycenter, **xxvii**, **179**, **529**, **664**. *see also*  
 {center of mass}

- Battin's method (modified), **693–695**  
 berthing, **354, 374, 375**  
 beta angle, xxxiii, **596, 677, 678, 762, 763**  
 bi-elliptic transfer. *see* transfer, bielliptic  
 big O notation. *see* {Landau notation}  
 bi-parabolic transfer. *see* transfer, bi-parabolic  
 blackout phase, **487, 489, 490, 492**  
 body (reference) system, xxvii, **704, 705, 707, 709, 710, 718, 720, 724**  
 beginning of life (BOL), **736, 778, 788**  
 boost, **150, 280, 314, 315, 325**. *see also* {kick-burn}  
   apogee. *see* apogee boost  
 boost error, **373**. *see also* burn error  
 booster. *see* engine  
 boundary value problem (orbital), **298, 300, 301**  
 B-plane, **411, 415**  
 Bstar, **453, 482, 649, 653**  
 burn error, **323–324, 401, 402**  
 Burdet transformation, **257, 274**
- C**  
 capacitance, **737, 771, 783**  
 capsule (space), **143, 428, 429, 438, 442, 447, 464, 467, 468**. *see also* Soyuz capsule; Apollo  
 capture, **325, 354, 355, 371, 374, 375, 403, 404, 525, 543, 655**. *see also* aerocapture  
   ballistic. *see* ballistic capture  
   planetary. *see* planetary capture  
 capture orbit. *see* orbit, capture  
 center of mass, xxv, xxvii, **6, 141, 179, 341, 389, 447, 469, 493, 494, 503, 507, 661, 664, 727**. *see also* {barycenter}  
 chamber  
   design, **95–97**  
   pressure, **9–11, 13, 68, 85, 88–92, 102, 103**  
 Chapman's theory, **444**  
 characteristic length (chamber), xxxi, **96, 97, 102, 103, 125**  
 characteristic velocity  
   electric ( $v_e$ ), **116**  
   thermal ( $c^*$ ), xxx, **89, 90, 96, 116**  
 charge flow density, xxxi, **108, 109**  
 charge flux. *see* charge flow density  
 Child-Langmuir law, **109**  
 CIRA, **125, 129**  
 circle. *see* orbit, circular  
 circular orbit, **199, 208–210, 340–345, 380, 505, 507, 605, 629, 648–654, 655, 677–678**. *see also* geostationary orbit (GEO); orbit, commensurate  
   near-, **265, 266–269, 272, 321–323, 350–353, 589–595**  
   maneuvers in, **283, 285, 287–289**  
   transfer between, **292, 317–325, 363**.  
     *see also* transfer bi-elliptic; transfer, continuous thrust  
 circularization, **298, 319, 331, 381, 643, 646, 647, 655**  
 circularization time, **646, 647, 655**  
 circular restricted three-body problem (CR3BP). *see* three-body problem  
 Clohessy–Wiltshire equations, **341**. *see* {Hill's equations}  
 coasting phase, **150**  
 coefficient. *see* [...] coefficient  
 cold case (satellite), **788, 789, 795**  
 cold wall approximation, **430**  
 collinear configuration, xxxi, xxxiv, **500–506, 510, 551, 552**  
 collinear libration points, **500, 509, 510–512, 530, 552**  
 combustion chamber, xxxi, **9, 67, 68, 72, 73, 82, 85, 87, 90, 95, 96, 99, 101, 105**.  
   *see also* thrust chamber  
 combustion chamber design, **95–97**  
 combustion efficiency. *see* efficiency, combustion  
 combustion enthalpy, **23, 86, 87**  
 conductive coupling, **780–781**  
 conductor (thermal), **735, 737, 769, 771, 772, 774, 780**  
   conductive, **771, 772, 774, 792**  
   convective, **771**  
   radiative, **737, 771, 772, 774, 792**  
 configuration parameter, xxxiv, **504, 510, 511**  
 conic section, **192, 193**  
 conservation law, **27, 174–175, 256**  
 conservation of (total) angular momentum, **175, 183, 184, 256, 268, 494, 665, 718**  
 conservation of energy, **43, 73, 79–80, 174, 186, 190, 224, 256, 257, 291, 421, 423, 494, 517, 718**. *see also* vis-viva equation  
 conservation of (linear) momentum, **2–4, 17, 175, 190, 494**  
 conservation of mass, **74, 75, 80, 108**. *see also* continuity equation  
 conservative (force) field, **171–173, 187, 188, 574**. *see also* force, central  
 contact conductance, **737, 781**  
 continuity equation  
   charge, **108**  
   mass, **9–10, 74, 131**  
 convective coupling, **780–781**

- co-orbital objects, **551**. *see* orbit, tadpole; orbit, horseshoe
- Coordinated Universal Time (UTC), **674**
- coordinate system. *see* {reference frame}
- correction factor, **90, 743**
- discharge, **xxxiv, 22, 114**
- thrust, **23**
- velocity, **xxxiv, 22, 114**
- cosmic velocity
- first, **xxxiii, 209, 255, 430, 436, 443**
- second, **xxxiii, 227, 255, 434, 436, 469**
- coupling coefficient (thermal), **737, 769, 772, 780–782**. *see also* conductor
- Cowell's method, **494, 571, 574**
- CR3BP. *see* circular restricted three-body problem
- cycloid, **345–348, 351–352, 367–369**
- D**
- day, **673**
- sidereal. *see* sidereal day
- solar, **673**
- DeBra-Delp region, **733, 734**
- deceleration, **141, 178, 427, 438–441, 443–444, 446, 492, 642, 673**. *see also*
- acceleration
- centrifugal, **727**
- critical (peak), **xxvii, 427, 444, 451, 452, 453, 459, 461–465, 469, 471, 476, 479–480**
- maximum, **442, 452, 453, 459**
- peak, **427**
- declination, **677, 787**
- degrees of freedom (molecules), **xxxii, 70–72, 77, 81, 493, 494**
- rotational, **70**
- translatory, **70**
- vibrational, **70**
- delta- $v$  ( $\Delta v$ ), **xxx, 37, 38, 41, 42, 43–44, 54, 56, 163, 290, 301, 304, 316, 321, 322, 327, 328, 330, 333, 334, 340, 344, 357, 364, 367, 368, 370, 372, 373, 374, 380, 386, 403, 404, 418, 419, 422, 620, 621, 638, 639, 659**. *see also* {propulsion demand}
- flyby, **413–415**
- $\Delta$ DOR, **684–685**
- deorbit, **432–433, 435, 484, 491, 659**
- Descartes' rule of signs, **228, 274, 505, 532, 547**
- Detra and Hidalgo (heat flux model), **452, 481**
- diffuse radiator, **741–743, 749**
- diffuse reflection. *see* reflection, diffuse
- discharge correction factor. *see* correction factor, discharge
- discharge loss factor. *see* loss factor, discharge
- divergence loss factor. *see* loss factor, divergence
- docking, **353–354, 355, 374–375**
- dogleg maneuver. *see* maneuver, dogleg
- Doppler shift, **683, 684**
- double dip reentry, **471**
- draconic. *see* {draconitic}
- draconitic motion (mean), **582, 589, 602**
- draconitic period, **602, 603**
- drag, **xxvii, xxx, xxxiv, 6, 63, 101, 131–135, 135–136, 137–141, 143, 145, 153, 173, 287, 360, 404, 414, 431, 443, 445–446, 475, 477, 486, 489–490, 555, 557, 600, 641–655, 659, 682, 707, 720–721, 724, 725**
- skin friction, **135**
- drag coefficient, **xxx, 135–136, 137–141, 438, 697, 721, 725**
- reduced, **137, 153**
- drag acceleration, **483–484, 487, 489**
- drag force, **xxx, 141, 142, 145**
- drag loss, **63, 153–155, 157, 163**
- E**
- Earth-Mars transfer (transit), **316, 395, 397–498, 402**
- Earth-Moon system, **422, 425, 512, 513, 522–526, 547, 548**
- Earth-Moon transfer, **423**. *see also* Farquhar transfer orbit
- Earth's atmosphere. *see* atmosphere
- Earth's (polar) flattening, **562, 578, 580, 658**
- Earth's mean gravitational acceleration (g), **xxx, 141, 173, 174, 255, 341**
- Earth's gravity, **173**
- Earth's oblateness. *see* Earth's (polar) flattening
- Earth's rotation. *see* rotation, Earth's
- East-West drift, **620, 631**
- East-West station-keeping. *see* station keeping
- $\varepsilon$ -based transformation, **231–235, 236, 250**
- eccentric anomaly. *see* anomaly, eccentric
- eccentricity, **xxx, 191, 192, 194, 201, 203, 207, 210, 211, 214, 274, 288, 301, 305, 306, 308, 333, 340, 348, 391, 402, 413, 433, 591–593, 595, 596, 598–600, 608, 613, 622–632, 640, 645, 647, 655, 670, 691**
- eccentricity change, **284–285, 288, 624**
- eccentricity evolution, **627–629**
- eccentricity functions, **608, 614**
- eccentricity vector, **191, 194, 199, 201, 232, 274, 305, 591, 626–629, 631, 632, 670, 694, 695**

- eclipse, vii, 596, **677–680**, 786, 794, 795  
*E* ellipsoid, **718–719**. *see also* {Poincot ellipsoid}  
 effective [...]. *see* [...] effective  
 effective (projected) surface area, 557, 621, **739**, 724, 755, 762. *see also* {wetted area}  
 efficiency  
   combustion, **86**  
   energy, 28  
   energy conversion, xxxiv, **23**, 113  
   engine. *see* engine efficiency  
   external, **17**, 18, 19, **32**  
   internal, **17**, 19. *see* {engine efficiency (total)}  
   mechanical. *see* {rocket efficiency, external}  
   nozzle. *see* nozzle efficiency  
   rocket. *see* rocket efficiency  
   thermal. *see* thermal efficiency  
   thrust. *see* thruster efficiency  
   total rocket. *see* rocket efficiency, total  
 eigentime, xxxiv, **25**. *see also* {proper time}  
 Einstein field equations, 166  
 electric potential. *see* potential, electric  
 electric propulsion. *see* propulsion, electric  
 elements. *see* orbital elements  
 ellipse, 192, **193**, **210**, 233, 238, 271, 272, 272, 342, 348–350, 352–353, 432, 501, 507, 508, 630. *see also* transfer orbit  
   entry, 432  
   fundamental, **305–306**, 309  
   long/short path, **302**. *see also* transfer orbit, long/short  
   minimum energy, **303–305**, 306, 313, 320, 381  
   radial, **248**. *see* trajectory, radial elliptic  
 elliptic orbit. *see* orbit, elliptic; *see also* ellipse  
 emission coefficient. *see* {emissivity}  
 emissivity xxxiv, 428, 454, 482, **736**, **745–749**, 762, 790  
   spectral, **745**  
   total, **745**, **746**, 750  
 emittance. *see* {emissivity}  
 Encke's method, 573  
 end of life (EOL), 765, 778, 788  
 energy  
   characteristic, xxx, **223**, 391  
   internal (of a gas), xxxiii, **70–72**, 744  
   jet, **21**, **113**, 116  
   kinetic. *see* kinetic energy  
   mechanical (total), xxxiv, 7, 186. *see* {orbital energy}  
   orbital (specific), **186**, 189, 192, **198–199**, 209–210, 210, 222, 227, 315, 340, 428  
   potential. *see* potential energy  
   radiant, **736**, **738**  
   rotational, **188**, 517, 518, **705–706**, 710, 711, 719, 721–723, 725  
   total mechanical, xxxiv. *see* energy, orbital (specific)  
 energy conservation. *see* conservation of energy  
 energy conversion efficiency. *see* efficiency, energy conversion  
 energy dissipation, 718, **721–724**  
 energy supply system, 105  
 engine (thruster/propulsion/booster)  
   aerospike, 101  
   chemical, 5, 13, 17, 19, 23, 43, 87, 88, 98, 105, 106, 108, 110. *see also* engine, thermal  
   ion, 22, **105–119**, 334, 335  
   jet, vii, **7–14**  
   reaction, 7  
   rocket, **7**, **13–14**, 19  
   thermal, xiii, 14, 22, **67–104**, 105, 108, 110. *see also* propulsion, thermal  
 engine design, ix, 14, 88, 89, **95–103**  
 engine efficiency (total), **17**, 19, **21–23**, **87–88**, 113. *see also*  $I_{sp}$ ; exhaust velocity, effective  
 engine performance (ideal), **86–88**, 89, 93  
 engine performance parameters, **19–20**, **89–90**  
 engine thrust. *see* thrust, engine, thermal; thrust, engine, ion  
 enthalpy, xxxi, 23, 67, **70**, 73, 81, **86**, 87, 430  
 entry [...]. *see* {reentry [...]}  
 entry corridor, **434–435**, **471**  
   Space Shuttle, 428, **484**  
 entry interface, 127, **431–432**, 453–454, 469, 477, 482, 484  
 entry profiles, **433–441**, 442, 444. *see also* entry trajectories  
   ballistic, 447–454  
   lifting, 476–483  
   low lift (near-ballistic), 459–465  
   Space Shuttle, **484**  
 entry trajectory. *see* trajectory, entry  
 epicycle, **267–269**, 271, **548**  
 epicyclic motion, **268–271**, **548**  
 epoch, xxxiii, **194**, 203, **358**, 580, 664, **667**, 674, 675, 689  
   astronomical, 194  
   progression of, **579**, 580  
   standard, **194**, **358**, 664, **667**, 675

vernal equinox of, **664**. *see* vernal equinox  
 equant, **212, 216**. *see also* {focal point, empty}  
 equatio elegantissima, **187**  
 equation(s) of motion (EOM), **xxv, 5–7, 144, 147–149, 153, 160, 162, 174, 178–180, 232, 233, 236, 244, 247, 256–258, 263, 264, 266–270, 337–339, 341, 436, 437, 443, 444, 456, 478, 488, 491, 501, 506, 515–520, 529–531, 532, 546, 558, 571, 573, 607–609, 617, 618, 626, 639, 640, 659, 692, 706**. *see also* Euler's equations  
     linearized, **532, 546**  
     Newton's gravitational, **178, 180, 258, 232–233, 236, 506**  
     normalized, **148, 149, 437, 491**  
     reduced, **443, 491**  
     rocket, **5–7, 144**  
 equation of lateral motion, **185, 186, 195**  
 equation of radial motion, **185, 186, 187, 247–249, 252, 276**  
 equation of rocket motion, **7**  
 equations of rotational motion, **706, 707**.  
     *see also* {Euler's equations}  
 equilateral configuration, **500, 506–508, 520, 552**  
 equilateral libration points, **509, 513, 520, 523, 545–551, 617**  
 equilibrium glide, **476, 487, 488–489**. *see also* {lifting reentry}  
 equilibrium longitude, **xxxiv, 563, 612, 613, 614, 618**  
 equinoctial elements. *see* orbital elements, equinoctial  
 Euler, Leonhard, **204, 500**  
 Euler configuration, **501, 506**. *see* {collinear configuration}  
 Euler equation, **11**  
 Euler's equation(s), **707**  
 Euler rate equations, **710, 730**  
 Eulerian points, **500, 509**. *see* {collinear libration points}  
 exhaust velocity ( $v_{\text{ex}}$ ), **xxxiii, 2–4, 8, 12, 14**  
     effective ( $v_*$ ), **xxxiii, 4, 5, 12, 16, 18–20, 28, 30, 31, 39, 45, 62, 113, 115**  
 exit cross section, **68, 75, 89**. *see also* expansion ratio  
 exitance  
     radiant, **736, 740, 755, 757–759, 761**  
     spectral, **736, 740, 748**. *see also* Planck's law  
 exosphere, **123, 124**  
 expansion. *see also* nozzle; thrust coefficient

angle of, **98**  
 ideal/over-/under-, **84–85, 91, 99**  
 infinite-. *see* infinite-expansion coefficient series. *see* series expansion  
     supersonic, **80, 81**  
 expansion ratio, **xxxiv, 75–76, 77, 84, 90, 91, 97, 100**  
     optimal, **84**  
 external efficiency, **17, 18, 32**  
     relativistic, **32**  
 external torque, **706, 711, 719–721, 724, 725, 729**

## F

Farquhar transfer orbit, **527**  
 Fay–Riddell equation, **430**  
 fast variable, **575**  
 figure of merit, **8, 19, 20, 43, 86, 88, 89, 113**  
 final approach, **355, 359, 361, 366, 370–375, 379**. *see also* {proximity operations}  
 finite differences method, **772**  
 First Point of Aries, **xxxvi, 635, 664, 665, 666**.  
     *see also* {vernal point}  
 flat spin, **723, 724–726**. *see also* rotation, flat flight mechanics, **121, 148, 149**  
 flight path angle (FPA), **xxv, xxxiv, 42, 145, 146, 154, 155, 158, 159, 197–198, 295, 427, 431, 432, 435, 436, 443, 449, 455, 457, 465, 472–477, 490, 642, 672**  
     initial, **465**. *see also* {entry angle}  
 flight path angle rate, **155, 158, 159**  
     constant (CFPR), **158**  
 flow density, **xxxii, xxxiv, 74, 108, 109, 427**  
     charge. *see* charge flow density  
     heat. *see* {heat flux}  
     mass. *see* {mass flux}  
 flow theory (hypersonic), **130–144**. *see also* hypersonic flow  
 fluid loop, **781, 783**  
 flyaround. *see* trajectory, flyaround  
 flyby, **44, 222, 291, 405–422, 423, 424, 426, 517, 527, 684**  
     before, **407–409, 411, 415**  
     behind, **407–409, 411**  
     powered, **291, 413**  
 flyby delta- $v$ , **413, 414, 415, 418**  
 flyby from inside, **407–409**  
 flyby from outside, **407–409**  
 flyby maneuver, **44, 405–422, 423, 517**  
 flyby plane, **407, 412, 416, 418**  
 flyby potential, **421**  
 focal point, **193, 194, 210, 213, 215, 222, 248, 276, 301–304, 306, 320**

- empty (equant), **212**, 213, **216**, 276
- force
  - central, **170–173**, 183, 185, 186, 574
  - centrifugal, 148, 154, 155, 177, 178, **188**, 341, 347, 349, 371, 387, 388, **421**, 443, 446, 455, 456, 469, 474, 476, 477, **516**, 518, 519, 521, 528, 539, 560, 607, 727
  - conservative/non-conservative (dissipative), **171–173**, 186, 574, 588
  - coriolis, **182**, 516, 519, 539, 547, 549
  - drag. *see* drag force. *see also* drag
  - external, 2, 5, 6, 38, 39, 42, **144**, 173, **176**, 177, **179**, 339, 341, **555**, 662, 695, 706, 717, **719–721**, 725. *see also* perturbation acceleration/force
  - fictitious, 519, **662**
  - gravitational, xxx, 6, 127, 145, **169–174**, 272, 341, 386, 387, 446, 494, 521, 555, 556, 574, 633. *see also* gravitational potential
  - inertial, 6, **176–178**, 519, **663**
  - lift. *see* lift force
  - propellant, xxxi. *see* {thrust force}
  - thrust, xxxi. *see* {thrust force}
- forced translation, **372–374**, 379
- free fall, 177, **252–253**, 485
- free molecular flow, **130–133**, 137, 429, 446, 720, 721
- free-return trajectory, **527–528**. *see also* rapprochement orbits
- frozen orbit. *see* orbit, frozen
- fuel demand, **43–45**, 152, 280, 333. *see also* {propellant demand}; delta- $v$
- fundamental ellipse. *see* ellipse, fundamental
- G**
- gas constant
  - specific, xxxii, **123**
  - universal, xxxii, 14, **69**
- gauge function, 559
- Gaussian variational equations (GVEs), **558–559**, 624, 634, 635, 642, **656**
- Gebhart factor method, 779
- geoid, xiii, 148, **560–561**, 566, **568–569**, 574, 627
- geostationary orbit (GEO), xxv, xxviii, 201, 205, 206, 284, **296–298**, 317, 324, **329–333**, 335, 556, 557, 575, 582, 608, **615–621**, 622, 625–629, **630–631**, **637–639**, 659, 679, 680, 685, **690–692**
- geostationary transfer orbit (GTO), xxv, 296–298, **314**, 329–333. *see also* transfer, super-synchronous
- geometrical mathematical model (GMM), 772, 773, **774–780**, 782, 783, 785, 786, 789
- Gibbs method, **693**
- gliding reentry. *see* {lifting reentry}
- Global Positioning System (GPS), 556, 595, 606, 608, **611–615**, 686
- gravitation, xxviii, **165–174**, **263**, 421, 519, 521, **561–563**. *see also* geoid
- gravitational constant, xxxi, **166**, 169
  - Gaussian, 169
  - geocentric, 169
  - heliocentric, 169
- gravitational field, 166, **170–174**. *see also* sphere of influence; weak stability boundary transfers
- gravitational force. *see* force, gravitational
- gravitational force field, 170
- gravitational loss, **42–43**, 48, 63, 152–155, **163**
- gravitational parameter, xxxiv, **169**, 211, 562, 602
- gravitational perturbation. *see* perturbation, gravitational
- gravitational potential, xxxiii, **165–169**, 172–173, 257, 262, **263**, 266, 271, 515, 516, **561–563**, 571, 574. *see also* potential, effective
  - anisotropic. *see* geoid
  - axisymmetric, **264**
  - general, **262–266**
  - perturbational (residual), xxxii, **563**, 576, **577**
- gravity. *see* Earth's gravity
- gravity-assist maneuver. *see* {flyby maneuver}
- gravity gradient (GG), xxv, xxviii, 719, **727–729**, 731, 734
- gravity-gradient dynamics, **729–734**
- gravity-gradient stabilization, **726–729**
- gravity-gradient torque, 649, **727–729**
- gravity turn, **155–156**, 157–159, 162
- Greenwich Mean Sidereal Time (GMST), xxv, **357**, 585, 587, 608, 667, **671**. *see also* hour angle
- Greenwich Mean Time (GMT), xxv, **673**
- Gregorian calendar, 674
- growth factor, 49. *see also* {mass ratio}
  - total, 51. *see also* {payload ratio, total}
- GTO. *see* geostationary transfer orbit (GTO)
- GTO+. *see* super-synchronous transfer orbit (SSTO)
- guiding center, **629–631**, 691. *see also* coordinate system, RSW
- gyro
  - free, 711
  - symmetrical, **713–716**, 722, 723, 725, 726

**H**

- halo orbit, **534–537**, 539–544  
 quasi-halo, 535
- harmonic coefficient, *xxxi*, **563**, 658  
 reduced, *xxxi*, **577**
- harmonics  
 odd, **589**, 591, 593  
 sectorial, **567**, 585, 615  
 spherical, **566**, **567**, 605  
 tesseral, **567**, 585, 593, 615  
 zonal, **567**, 583, 588, 589, 591, 593, 615
- Harris-Priester model, 126, 128
- H-bar, **362**
- h*-based transformation, **235–242**, 244, 252
- heat capacity, *xxx*, *xxxiv*, 70, 72, 737,  
 768–771, 783. *see also* {capacitance}  
 specific thermal, 70
- heat capacity ratio, *xxxiv*, 70, 72
- heat equation, 766, **768–770**, 772
- heat flow density, *xxxii*. *see* {heat flux}
- heat flow rate, *xxxii*, 428, 429, 768, 769
- heat flux, *xxxii*, 427–431, **451–454**, 459,  
 480–483, 487, 736, 737, 738, 760, 762,  
**768–770**, 772, 773, 777, 780, **782**, 783,  
 793, 794. *see also* heat load
- albedo, 782, 793, 794  
 conductive, 757, 759  
 convective, 428, 780  
 infrared (IR), 785  
 peak, **427**, 431, **451–453**, **459**, 476,  
**480–483**  
 planetary, 782  
 radiative, 736, **738**, 767, 769, 773. *see also*  
 radiant flux
- heat flux model, **429–431**, 452, 481
- heat load, 101, 378, **427–429**, 772, 788.  
*see also* heat flux  
 peak, **429**, **453**, 476, **480–483**. *see also*  
 peak heat flux
- heat pipe, 776, 784
- heliocentric reference frame. *see* reference  
 frame, heliocentric
- Herrick-Gibbs method, **693**
- heteroclinic orbit. *see* orbit, heteroclinic
- heterosphere, **123–127**, 129, 720
- Hill curve, 523. *see also* {zero velocity curve}
- Hill's equations, **341**, 342  
 solutions of, **343**
- HITEN mission, 423
- Hohmann transfer, 280, 292, **313–325**,  
 327–329, 334, 335, 347, 363–365, 368,  
 369, 380–382, **393–394**, 396, 405, 422
- Earth to planets, **393–396**  
 near-Hohmann, 325, **399–402**, 426
- Hohmann (transfer) orbit, 150, 151, **314–316**,  
 317, **320–322**, 323–325, 364, 389, 390,  
 392, 394, 396, 399, 405
- Hohmann transfer orbital elements, 150, **151**,  
**317**
- homing (phase), **355**, **361–364**
- homing transfer. *see* transfer, homing
- homoclinic orbit. *see* orbit, homoclinic
- homosphere, **123–125**, 431
- horizon  
 local, 142, 145, **197**  
 true outer, **680–682**
- hot case (satellite), 680, **788**, 789, **795**
- hour angle, **357**, 358, 562, 585, 587, 608, 667,  
 671
- Householder transformation, 690
- hyperbola, 34, 185, 192, **193**, 222, **223**, 234,  
**382**, **402**, 407, 528. *see also* orbit,  
 hyperbolic  
 approach/arrival, **402–403**, 389  
 departure, **390–393**  
 flyby, 407, **410–411**  
 radial, **250**. *see* trajectory, radial hyperbolic
- hyperbolic excess velocity. *see* velocity, excess
- hypersonic flow, **130–144**

**I**

- ideal cycle efficiency, 74. *see* {thermal  
 efficiency}
- ideal gas law, 14, **69**, **123**
- ideally adapted nozzle. *see* nozzle, ideally  
 adapted
- impact parameter, *xxxiii*, **222–223**, 260, 291,  
 403, 404, 410, **411–412**, 414
- impulse  
 mass-specific, 5, 20. *see also* exhaust  
 velocity, effective  
 maximum obtainable specific, **86**, 95  
 specific ( $I_{sp}$ ), *xxxi*, 5, **19**, 20, 43, 64, 87, 95,  
 105, 115. *see also* exhaust velocity,  
 effective  
 total, **19**, 20, 40
- inclination, *xxxi*, 127, 154, 162, **200–203**,  
**356–358**, 471, 472, 591, **595–596**, 622,  
 631  
 change of, 287–289, **292–294**, 296–298,  
 329–333, 421–422, **579–580**, **586**, 588,  
**634–638**, 659  
 critical, **579**, 597, 599
- inclination function, **608**, 614
- inclination vector, **201**, **634–636**, 638, 639
- inertia tensor, *xxxi*, **701–703**, 707
- infinite-expansion coefficient ( $C_\infty$ ), *xxx*, **76**,  
 91, 104

injection, 356  
 transfer, 318, 323  
 injection burn, 323, 324, 329–331, 391, 393, 394, 403, 424, 541  
 injection burn error analysis, 324, 401, 402  
 in-plane time. *see* launch time  
 integral efficiency. *see* {external efficiency}  
 integral(s) of motion, 194, 199, 493–494, 522  
 Jacobi's, 517  
 internal efficiency. *see* efficiency, internal  
 International Atomic Time (TAI), 674  
 International Celestial Reference Frame (ICFR), xxv, 664  
 International Space Station (ISS), ix, xxv, 141, 209, 279, 337, 338, 341–342, 345, 354, 355–377, 435, 592, 593, 649, 652–653, 654, 659  
 International Terrestrial Reference Frame (ITRF), xxv, 562, 667  
 interplanetary flight, 223, 279, 389–404, 422–426  
 invariant elements. *see* orbital elements, invariant  
 ion thruster. *see* engine, ion  
 irradiance, 735, 741, 791  
 solar, 621, 756, 761  
 isolating washers, 784

## J

Jacchia model, 126  
 Jacobi constant, 513, 517, 520, 524, 548, 550, 552  
 Jacobi's integral, 517–520, 522, 523  
 jet engine. *see* engine, jet  
 Julian centuries, 358, 675  
 Julian date, xxv, 358, 674–675  
 modified, xxvi, 675

## K

Kaula's resonant perturbation theory, 603, 605, 608  
 Kaula's rule of thumb, 610  
 keep-out sphere (KOS), 361, 368–372  
 Kepler (Johannes), 195, 211, 216, 217  
 Keplerian elements, 204, 207. *see also* orbital elements, Keplerian  
 Keplerian problem (and solutions), 195, 211, 217, 218, 219, 229, 573  
 Kepler's equation (and solutions), 213–214, 217–219, 222, 225–227, 230–246, 307  
 universal, 237  
 Kepler's first law, 210  
 Kepler's second law, 184–185

Kepler's third law, 211  
 Kepler transformation, 211–212, 221, 231, 232, 246  
 generalized. *see*  $\varepsilon$ -based transformation  
 kick-burn, xxx, xxxiii, 43, 280–289, 314–317, 325, 330, 381, 404, 526, 543, 620, 621, 645, 656–659. *see also* maneuver, impulsive  
 kinetic energy, 17, 18, 32, 43, 176, 199, 209, 315, 428, 443, 447, 451, 517. *see also* virial theorem  
 lateral, 188  
 radial, 189  
 specific, 186, 430  
 Kirchhoff's law, 749  
 Kronecker delta, xxxiii, 566, 702

## L

Lagrange (Joseph-Louis), 206, 388, 506, 508, 559  
 Lagrange configuration, 506. *see also* {equilateral configuration}; libration point  
 Lagrange constraints, 559. *see also* osculation constraints  
 Lagrange's planetary equations (LPE), xxv, 206, 570, 574, 583  
 Lagrange's quintic equation, 504, 505  
 Lagrangian multiplier method, 53  
 Lagrangian points, 509. *see* {equilateral libration points}  
 Lagrange region, 733, 734  
 Lambertian radiator. *see* radiator, Lambertian  
 Lambert's cosine law, 742, 748, 749  
 Lambert's equation, 305, 307, 309–310  
 universal formulation, 309–310  
 universal solution, 312  
 Lambert's problem, 300, 306–312, 382  
 Lambert's theorem, 308, 310  
 Lambert transfer, 280, 298–313, 321–322  
 minimum effort, 313  
 minimum energy, 303–305, 313, 320–321  
 Landau notation, xxxv  
 Laplace (Pierre-Simon), 165, 190  
 Laplace-Runge-Lenz vector (a.k.a. Laplace vector), 191  
 lateral motion, 184, 186, 195, 196  
 latitude  
 argument of, xxxii, 204, 208, 562, 635, 671, 688  
 geocentric, xxxiii, 163, 174, 562, 666, 671  
 launch site, 329, 330, 331, 356–358  
 launch, 356–359

- launch azimuth, 154, **356–359**  
 launch mass, 34, **37**, 45, 46, 65  
 launch phase, **355–359**  
 launch time, **357–359**  
 launch window, 356, **358–359**, 361, 375, 393, 395  
   planar, **358**, 360  
 Laval nozzle, **68**, **75**, 78, 82, **100**. *see also*  
   nozzle, bell; nozzle, conical  
 L/D control, 143–144, **479**, 485. *see also* angle  
   of attack (AOA)  
 L/D ratio. *see* lift-to-drag ratio  
 Legendre polynomials, xxxii, 531, 561, **562**,  
   **564**, 583  
   associated, xxxii, **562**, **564**  
 Leibniz (Gottfried Wilhelm), 185, 192  
 Leibniz's equation, **185**, 237  
 LEO, xxv, 610, **611**. *see* orbit, low Earth  
 L-function, 310  
 libration damper, 732  
 libration points, xxv, xxviii, **509**, **510**, 513,  
   **519**, 520, **521**, 527, 529, 552, 553  
   collinear, **500**, **509**, **510–512**, 530–544,  
   551, 552  
   dynamics about, **529–553**  
   equilateral, **509**, **513**, 523, 545–551  
   stability of, **520–522**  
 lift, xxviii, 6, **131**, 133, 134, **136**, 141, **142**,  
   **145**, 147, 148, 154, 443, 486, 659  
   horizontal, 141, **142**, 479  
   negative, 143, 471  
   vertical, 141, **142**  
 lift coefficient, xxx, **137**, 140  
   reduced, xxxiv, **137**  
 lift force, xxxi, 6, **141**, 142, 144, 145  
 lifting reentry. *see* reentry, lifting  
 lift vector, **141**, 467, 471, 659  
 lift-to-drag ratio (L/D), 133, **143–144**, 149,  
   **438**, 442, **443**, 447, 461, 464, **465**, 466,  
   467, 476, 477, **479**  
 line of apsides, **192**, 194, **210**, 223, 326, 392,  
   503, 626. *see also* {apse line}  
   progression of, 272, 575, **579–581**, 602  
 line of nodes, **200**, 205, 664–666  
 Lissajous orbit, **534**, 535, 541, 544  
 longitude  
   ecliptic, 666  
   equilibrium, xxxii, **563**, 608, 611,  
   612, 618  
   geographic, xxxii, **562**, 671  
   mean, **205**, 206  
   orbital, **205**, 778  
 longitude of periapsis, 205  
 longitude of the ascending node, 603, 609, 612,  
   614. *see also* right ascension of  
   ascending node  
 longitude of the Sun, 626  
 longitude station-keeping/control, 631. *see*  
   {East-West station-keeping}  
 loss factor, xxxiv. *see also* efficiency  
   discharge, **114**. *see also* correction factor,  
   discharge  
   exhaust, 112, **113**  
   ionization, **114**  
   nozzle-divergence, xxxiv, **8**, 112  
   VDF, **21**  
 low Earth orbit (LEO), 610, **611**  
 L sphere, **718**, 719  
 luminance, 738, 741. *see* {radiance}  
 lumped parameter method, 771  
 lunisolar perturbations. *see* perturbations,  
   lunisolar  
 LHLV. *see* reference frame, LVLH  
 Lyapunov orbit, **534**, 535
- M**  
 Mach number, xxxi, **79**  
 maneuver  
   atmospheric (reentry), 427, 436, 659  
   constant-pitch-rate, **157**, 162  
   correction, 366, 629–632  
   dogleg, 357, 393  
   elementary, **281–287**  
   escape (Oberth), 291. *see also* transfer,  
   escape; velocity escape  
   general, **289–291**  
   gravity turn, **155–156**  
   impulsive (thrust), xxxiii, **40–41**, 280, 285,  
   314. *see also* {kick-burn}  
   one-impulse, **280–298**  
   orbital, **279–336**  
   plane change, **281**, 286, **292–294**, 298, 357  
   pitch. *see* pitch maneuver  
   roll. *see* roll maneuver  
   tangent, **281**, **295–298**  
   tangent plane, **292–293**, 295, 298, 330  
 manifold, **522**  
   center, **523**, 533, **534–541**  
   hyperbolic (saddle), **523**, 533, **541**  
   invariant, 422, **522–523**, **532–544**, **546–551**  
   stable/unstable, **523**, **541**  
 manifold tube, **541**, **542**  
 many-body system, 405, 422, **493–498**.  
   *see also* {n-body system/problem};  
   flyby

- Mars mission/transfer, **56, 106, 316, 322, 389–404, 415, 423–425**
- mass, **xxxi**  
 anisotropic, **263, 560–569**. *see also* geoid  
 gravitational, **167, 168, 169, 178**  
 inertial, **176, 178**  
 payload (ratio). *see* payload mass/ratio  
 reduced, **xxxiv, 508, 514, 516**  
 structural (ratio), **xxiv, 15, 16, 17, 37, 47, 49, 59**
- mass conservation, **74, 108**. *see also*  
 conservation of mass
- mass flow density, **xxxiv, 74**.  
*see* {mass flux}
- mass-flow distribution function, **7**
- mass flow rate, **xxxi, 2, 4, 5, 10, 62, 74, 88, 89, 92, 110, 111**. *see also* continuity equation. *see also* mass flux
- mass flux, **xxxiv, 74, 75**
- mass ratio, **xxxiv, 15, 34, 49**. *see also* {growth factor}
- max  $q$  ( $q_{\max}$ ), **157**
- mean anomaly. *see* anomaly, mean
- mean motion, **xxxii, 195, 211, 502**. *see also*  
 {orbital frequency}  
 Sun's, **626**  
 variation of, **607**. *see* orbital elements, variation of
- mechanical efficiency, **17**. *see* {external efficiency}
- Mercury capsule, **429, 447**
- meshing (FEM, GMM), **771, 774–777, 783**
- mesosphere, **123**
- microgravity ( $\mu g$ ), **141, 341–342**
- Michielsen chart, **390**
- molar mass, **xxxix, 69, 87**
- molecular flow, **81**  
 free, **130–135, 137–141, 429, 446, 720, 721**. *see also* Newtonian flow theory
- moment of inertia, **70, 701–703, 719, 722, 733**  
 Earth's, **566**  
 polar, **495**
- momentum conservation. *see* conservation of (linear, angular) momentum
- Moon mission, **325, 390, 434**. *see also* Apollo
- motion. *see also* rotation  
 asymptotic, **229**  
 epicyclic. *see* epicyclic motion  
 integrals of, **493–494**  
 lateral. *see* lateral motion  
 mean. *see* mean motion  
 radial. *see* radial motion  
 stellar, **262–273**
- MSIS atmospheric model, **125, 126, 652, 654**
- multi-layer insulation (MLI), **736, 757–759, 776, 784, 787, 789**
- multipole (gravitational), **556, 564–569, 583, 605–606, 611, 615, 616**. *see also* harmonics; harmonic coefficient
- multipole approximation. *see* Legendre polynomials
- multipole coefficient, **xxx, xxxii, 562, 564–567, 610, 615**. *see also* Kaula's rule
- multipole pattern, **606**. *see also* nodal surface
- multisteping, **47**. *see* {staging. serial}
- multistaging, **47**. *see* {staging. serial}
- N**
- nadir, **680, 681, 708, 791**
- $n$ -body. *see also* many-body system  
 choreographies, **498–500**  
 system/problem, **493–498, 500**  
 virial theorem of, **vii, 496–497**
- Newton (Isaac), **165, 168, 192**
- Newtonian field equation, **166**. *see* {Poisson's equation}
- Newtonian flow theory, **133–135**
- Newton iteration. *see* Newton's method
- Newton's absolute space, **166**
- Newton's gravitational equation of motion. *see*  
 equation of motion, Newton's gravitational
- Newton's first law, **177**
- Newton's law of gravitation, **170**
- Newton's laws, **165, 174, 175–178**
- Newton's method, **217–220, 226, 340**
- Newton's second law, **4, 6, 176–177**
- Newton's third law, **4, 175**
- nodal surface, **567**
- nodal transfer (maneuver), **293, 330, 331**
- node equation, **769, 770, 780, 782, 793**
- node, thermal. *see* {thermal node}
- node vector, **202, 206, 687, 688**
- Noether's theorem, **174, 256**
- NORAD TLE. *see* TLE
- North-South drift, **638, 691**
- North-South station keeping.  
*see* station keeping
- NOZOMI mission, **423, 424**

- nozzle, **xxviii, 97–102**  
 aerospike, **100, 101**  
 annular. *see* nozzle, circular  
 Bell, **24, 81, 98–100**  
 circular, **100, 101**  
 conical, **7, 8, 8–9, 98, 100**  
 flow, **75–81**  
 ideally adapted, **12, 14, 23, 81–84, 85, 86, 88, 93–95**  
 Laval. *see* Laval nozzle  
 linear, **101**  
 plug, **100, 101**. *see* {nozzle, circular}  
 radial inflow/outflow, **100, 101**  
 Rao, **9, 24, 98**  
 SSME, **95**
- nozzle coefficient, **xxx, 93, 94**  
 nozzle design, **97–102**  
 nozzle divergence, **7–9, 83**  
 nozzle-divergence loss factor, **xxxiv, 8, 83**  
 nozzle efficiency, **xxx, 90, 93–95**  
 nozzle instabilities, **99, 100**  
 nutation, **665, 714–717, 723, 726**  
 nutation angle, **716, 719**  
 nutation angle rate, **723**  
 nutation cone, **715, 716**  
 nutation damper, **721, 722**  
 nutation frequency, **715**
- O**
- Oberth effect, **290–291, 323, 326, 413**  
 Oberth maneuver, **224, 291**  
 oblate body/geometry, **716, 717**  
 oblate rotation, **716, 717, 722, 723**  
 oblateness (perturbations), **561 578–582, 583, 585, 587, 588, 595, 602, 635, 636, 658, 695–697**. *see also* Earth's flattening
- one-node model, **768, 785**
- optimization problem  
 ascent, **150–155, 160–163**  
 combustion chamber, **95–97**  
 ideal nozzle, **81–84**  
 orbit transfer, **314–317**. *see also* Hohmann transfer; Lambert transfer, minimum-effort  
 thrust, **90–93**. *see also* optimization problem, ideal nozzle
- orbit, **165–273**  
 arrival, **402, 403**  
 bounded/unbounded, **199, 404, 520, 534, 541, 542**. *see also* Keplerian orbit  
 circular. *see* circular orbit  
 capture, **403, 404**  
 commensurate, **601**. *see* orbit, resonant  
 conic, **208, 193**. *see also* {orbit, Keplerian}; conic section  
 conjugate, **300, 301–303**  
 degenerate, **204–205, 247**. *see also* trajectory, radial  
 departure, **224, 389, 390–392**  
 determination of. *see* orbit determination  
 elliptic, **210–222, 233–234, 239, 305, 307, 340, 581, 643–647, 655**. *see also* ellipse  
 epicyclic. *see* epicyclic motion  
 frozen, **xxviii, 597–601**. *see also* orbit, magic  
 geostationary (GEO). *see* geostationary orbit (GEO)  
 geostationary-transfer orbit (GTO). *see* geostationary transfer orbit (GTO)  
 guiding, **264–265, 271**  
 halo. *see* halo orbit  
 heteroclinic, **543–545**  
 Hohmann transfer. *see* Hohmann (transfer) orbit  
 homoclinic, **543–545**  
 horseshoe, **549–551**  
 hyperbolic, **222–227, 234, 238, 307**. *see also* hyperbola  
 inner, **xxxvi, 314, 319**  
 Keplerian, **150, 192–194, 208–246, 389, 500, 502, 505, 556, 557, 561, 573, 607, 640**. *see also* {orbit, conic}; conic section  
 low Earth (LEO). *see* low Earth orbit  
 Lyapunov. *see* Lyapunov orbit  
 magic, **596**  
 osculating. *see* osculating orbit  
 outer, **xxxvi, 295, 314, 319**  
 parabolic/near-parabolic, **227–229, 239–240, 325–326**. *see also* parabola  
 parking, **390, 392, 393, 402, 527, 541**  
 phased. *see* phased orbit  
 polar, **201**  
 prograde, **163, 201, 393, 599**  
 quasi-halo. *see* quasi-halo orbit  
 radial. *see* trajectory, radial  
 rapprochement. *see* rapprochement orbits  
 rectilinear, **247**. *see* {trajectory, radial}  
 relative, **336–353**  
 repeat ground track, **596, 601, 604–605, 610**. *see also* orbit, resonant  
 resonant, **601–621**  
 retrograde, **201, 357, 596, 600, 641**. *see also* orbit. sun-synchronous  
 stellar, **262–273**  
 Sun-synchronous. *see* Sun-synchronous orbit

- tadpole, **549, 550**  
 transfer. *see* transfer orbit  
 transit/non-transit, **541–543**  
 orbit angle, *xxxiv*, **194, 204**. *see also*  
 {anomaly, true}; Keplerian problem  
 orbit circularization, **643–647**  
 orbit decay, **650–655**  
 orbit determination, *202, 207, 580, 682–697*  
 orbit equation, *190, 191, 212, 225, 228, 229,*  
*233, 234, 237–243, 249, 252, 274, 276,*  
*277, 581, 651, 688*  
 relativistic, *640*  
 orbit estimation, **692–693, 697**  
 orbit inclination, **200, 203**. *see* inclination  
 orbit lifetime, *331, 332, 651–655, 660*  
 orbit perturbations, **555–656**. *see* perturbation  
 (force)  
 orbit phasing, *304, 359–361, 381, 394–396*  
 orbit propagation, **218, 219–221, 582, 649,**  
*697*. *see also* state (vector) propagation  
 orbit(tal) radius, *xxxii, 323*. *see* orbit equation;  
 radial vector mean, *211, 797–799*  
 orbit tracking, *414, 682–686, 697*  
 orbit transition. *see* transfer  
 orbital angles. *see* anomaly; latitude, argument  
 of; longitude, mean/orbital; longitude of  
 periapsis  
 doglegged compound, **205, 206**  
 orbital boundary value problem. *see* boundary  
 value problem  
 orbital elements, *151, 199–208, 247, 556*  
 angular, **200–202, 203, 204, 286**  
 classical, **203–204**  
 conversion of, *207, 208, 418, 693*  
 determination of. *see* orbit, determination of  
 equinoctial, **205–206**  
 Hohmann transfer. *see* Hohmann transfer  
 orbital elements  
 invariant, **183, 191, 199, 200–206, 421–422**  
 Keplerian, **204**  
 Lambert transfer, *301–306, 311*  
 mean, **575**  
 metric, **203, 694**  
 osculating. *see* osculating elements  
 fast/slow variable. *see* fast/slow variable  
 two-line (TLE), **649, 654**  
 variation of, *282–283, 289, 418–422, 559,*  
*570, 575–576, 579, 586–588, 589–595,*  
*607, 643, 646, 648, 651, 654*. *see also*  
 Gaussian variational equations;  
 Lagrange’s planetary equations  
 orbital frequency, *viii, xxxii, 195, 265, 421,*  
*502, 503, 508, 709*. *see also* mean  
 motion  
 orbital longitude. *see* longitude, orbital  
 orbital maneuvering. *see* maneuver  
 orbital parameter, **192**. *see* {semi-latus rectum}  
 orbital parameters, **682, 683**  
 orbital period, *xxviii, xxxii, 209, 211, 396, 522*  
 angular, *268*  
 change of, *284, 579, 646*. *see also*  
 progression of epoch  
 orbital phase shift, **268, 269, 271**  
 orbital plane, **183, 200, 356, 357, 407, 633,**  
*667–668, 686–697*. *see also* orbital  
 element, angular/metric  
 change of, *579–581*. *see also* orbital  
 element, variation of; maneuver  
 orbit pole vector, *201*. *see* {inclination vector  
 (three-dimensional)}  
 orbit position, *194–196*  
 orbital precession, **579, 582, 641**. *see also*  
 precession, apsidal/orbital  
 orbital rendezvous, *279, 280, 344, 353–380*.  
*see also* rendezvous and docking (R&D)  
 interplanetary, **303–402**  
 orbital resonance. *see* orbit, resonance  
 orbital transfer. *see* transfer  
 orbital velocity, **196–198, 207, 208, 672, 797,**  
*799*. *see also* state vector  
 mean, *799*  
 variation of. *see* maneuver, orbital  
 orbital velocity vector, **196, 208, 672**  
 osculating elements, **557, 587, 588**  
 osculating orbit, **557–558, 573, 591, 607, 695**  
 osculation constraints, *559*. *see also* {Lagrange  
 constraints}  
**P**  
 parabola, **192, 193, 227, 325–326**. *see also*  
 conic section; orbit, parabolic  
 escape, **325–326**  
 radial, **252**. *see* trajectory, radial parabolic  
 parabolic orbit. *see* orbit, parabolic; parabola  
 parallel staging. *see* staging, parallel  
 parking orbit. *see* orbit, parking  
 partial rocket. *see* rocket, partial  
 patched conics method, **386–390, 423, 494, 528**  
 payload, *xxviii, 15–17*  
 true, **48, 49, 50**  
 payload mass, **15, 17, 18, 37, 47, 55, 63, 105,**  
*106, 115, 116, 118, 145*  
 payload ratio, *xxxiv, 15–17, 47, 49, 55, 57–60,*  
*115–117*  
 optimized, **53, 54, 60**  
 total, **51, 52, 54, 55, 57, 59**. *see also*  
 {growth factor, total}  
 uneven, **61**. *see also* rocket staging, uneven

- uniform, **59**. *see also* rocket staging, uniform
- periapsis, **xxviii**, **193**, **194**, **196**, **204**, **210**, **211**, **213**, **222**, **228**, **248**, **291**, **316**, **326**, **403**, **404**, **413**, **592**, **593**, **645**, **655**, **659**, **667**.  
*see also* perigee; eccentricity vector  
argument of. *see* argument of periapsis  
change of, **286**, **579**, **580**. *see also*  
progression of line of apsides
- pericenter, **210**. *see* {periapsis}
- perigee, **151**, **541**, **542**, **597**, **632**. *see also* periapsis
- period
  - draconitic, **602**
  - orbital. *see* orbital period
  - synodic, **396**
- perturbation (force), **555–656**
  - celestial, **632–639**
  - gravitational, **456**, **458**, **560–574**, **582–583**, **632–637**, **666**
  - higher-order, **582–595**, **602**
  - lunisolar, **596**, **613**, **631**, **632–639**, **695**
  - multipole, **556**, **564–569**, **582–585**, **595**, **598**. *see also* perturbations, gravitational
  - oblateness, **578–582**, **583**, **585**, **587**, **588**, **589**, **595**, **602**, **635**, **636**, **641**, **658**, **695**, **696**
  - relativistic, **639–641**
  - resonant, **601–611**
  - triaxiality. *see* {triaxiality}
- perturbation acceleration. *see* acceleration, perturbational
- phase angle. *see* angle, phase
- phased orbit, **604**. *see also* {orbit, repeat ground track}
- phase space, **202**, **522–523**, **607–608**, **610**, **613**, **614**
- phase window, **359**, **360**
- phasing. *see* orbit phasing
- phugoid mode, **472–476**
- phugoid period, **475**
- pitch angle. *see* angle, pitch
- pitch maneuver, **156–157**
  - rendezvous, **375**, **377**
- pitch oscillation, **730–731**, **733**
- pitch rate (constant) (CPR), **157**, **159–160**
- pitch-rate maneuver (constant), **156–160**
- Planck's law, **743**, **795**
- planetary capture, **403**, **655**. *see also*  
{aerocapture}; ballistic capture
- planetary constellation, **396**, **406**, **408**. *see also*  
period, synodic
- planetary entry, **427**. *see* {reentry}
- planetary parameters, **388**, **797**
- plume impingement, **378–380**
- pogo effect, **85**
- Poincaré (Henry), **494**
- Poincaré map, **538**
- Poinsot ellipsoid, **718**
- Poisson's equation, **166**, **167**, **273**
- polar flattening. *see* Earth's polar flattening
- polar moment of inertia, **495**
- polhode, **718**, **719**
- position vector, **xxxii**, **xxxiv**, **167**, **180**, **181**, **182**, **501**, **689**. *see also* {radial vector}  
normalized, **xxxiv**, **514**  
relative, **529**
- potential
  - centrifugal potential, **173**, **188**, **518**. *see*  
{potential, rotational}
  - effective, **xxxv**, **189–190**, **264**, **265**, **519–523**, **537**, **541**, **547**
  - electric, **xxxiii**, **107–109**
  - gravitational. *see* gravitational potential
  - pseudo, **189**, **519**. *see* {potential, effective}
  - rotational ( $U_\omega$ ), **188**, **189**, **517–519**
- potential energy (specific,  $\epsilon_{pot}$ ), **169–171**, **186**, **199**, **209**, **224**, **315**, **486**, **495–497**, **517**, **520**
- power
  - jet, **20–22**, **113**, **114**
  - rotational, **711**, **724**, **725**
  - specific, **xxxiii**, **116**
  - transmitted spacecraft, **19**
- power plant mass (electric), **116**
- precession, **636**, **641**, **665**, **717**, **725**, **726**
  - apsidal/orbital, **579**, **582**
- pressure
  - aerodynamic. *see* aerodynamic pressure
  - ambient, **9**
  - atmospheric, **122–123**
  - center of, **6**, **469**
  - dynamic, **136**, **157**, **162**, **427**, **447**, **483**, **490**. *see also* aerodynamic pressure
  - solar radiation, **555**, **621**, **707**
  - throat, **78**, **93**
- primary(ies), **xxxiii**, **508**, **514**, **517**, **522**, **529**, **551**
  - major, **508**, **514–515**, **543**, **544**
  - minor, **508**, **509**, **514**, **535**
- principal axes, **xxviii**, **566**, **702**, **703**, **705**, **707**, **709**, **713–715**, **718**
- principal moments of inertia, **xxxi**, **702**
- problem. *see* {...} problem
- progression of epoch, **579**
- progression of the line of apsides, **579**, **580**, **581**, **604**, **639**. *see also* {apsidal precession}
- prolate body, **716**, **717**, **732**
- prolate cycloid, **345–348**, **351–352**, **367**, **369**
- prolate rotation, **716**, **717**, **722**, **723**

- propagation. *see* orbital propagation  
 propellant/fuel demand, **44–46**, **115**. *see also*  
   delta- $v$  budget  
 propellant force, **xxx**. *see* {thrust}  
 propellant gas, **11**, **67**, **68–72**  
 propellant mass, **2**, **4**, **9**, **28**, **37**, **40**, **41**, **45**, **89**,  
   **115**, **116**  
   molar, **14**  
 proper acceleration. *see* acceleration, proper  
 proper reference frame, **25**, **26**, **28**  
 proper speed, **xxxiv**, **26–28**, **32–34**  
 proper time, **xxxiv**, **25**, **27**, **33**, **34**  
 propulsion. *see also* engine  
   electric, **105–119**, **333**  
   electrothermal, **20**  
   ion, **5**, **335**. *see* propulsion, electric  
   photon, **28**, **30**  
   thermal, **67–104**  
 propulsion demand ( $\Delta v$ ), **16–18**, **44**, **45–47**, **51**,  
   **117**, **118**, **162**, **290**, **291**, **293**, **294**, **314**,  
   **318**, **319**, **321**, **327**, **328**, **334**, **358**, **364**,  
   **367**, **368**, **380**, **381**, **404**, **405**, **413**, **418**,  
   **433**, **434**, **435**, **621**, **631**, **638**, **639**.  
   *see also* {delta- $v$  budget}  
 proximity operations, **370**, **374**, **378**. *see also*  
   {final approach}
- Q**  
 quasi-halo orbit, **535**
- R**  
 R3BP. *see* restricted three-body problem  
 RAAN. *see* right ascension of ascending node  
 radial motion, **184**, **185–186**, **188–190**,  
   **247–256**, **276**. *see also* trajectory, radial  
   equation of, **247**  
 radial trajectory. *see* trajectory, radial  
 radial vector, **xxxii**, **146**, **167**, **208**, **671**.  
   *see also* {position vector}; state vector  
 radiance, **736**, **741**  
   spectral, **736**, **738**, **739**, **745**, **749**  
 radiant energy. *see* energy, radiant  
 radiant flux ( $\Phi$ ), **736**, **738**, **739**, **746**, **752**, **753**,  
   **755**, **756**, **757**, **760**, **777**, **778**  
 radiant intensity, **736**, **741**, **742**  
 radiative coupling, **780–782**  
 radiator, **738**, **760**, **765**, **788**  
   black-body, **743–745**, **748**, **749**, **751**, **756**,  
     **763**, **791**, **795**  
   diffuse, **741–743**, **745**, **749**, **752**  
   gray-body, **751**  
   Lambertian, **742**, **752**, **775**, **778**  
   point, **755–756**  
   real, **741**, **745**, **747–749**  
 radioisotope heater units (RHU), **736**, **782**  
 radioisotope thermoelectric generator (RTG),  
   **xxvi**, **116**, **736**, **782**  
 radius  
   aiming. *see* {impact parameter}  
   orbit. *see* orbit(al) radius  
 range rate, **202**, **683**, **689**  
 ranging, **202**, **683**  
    $\Delta$ DOR, **684**, **685**  
   2/4-way TAR, **684**  
   laser, **685**, **686**  
   two-way, **683**  
 rapidity, **32**, **33**  
 rapprochement orbits, **526–527**  
 ray tracing (Monte Carlo), **754**, **778–780**  
 R-bar, **362**, **367–377**  
 R-bar approach, **362**, **369**, **373**, **374**  
 reciprocity relation, **753**, **776**, **792**, **793**  
 rectilinear orbit, **247**. *see* {trajectory, radial}  
 reentry, **427–492**. *see also* {entry}  
   Apollo, **471–472**  
   ballistic, **428**, **447–451**, **453**, **454**, **459**, **476**, **481**  
   “double dip”, **470**, **471–472**  
   interplanetary, **434**, **469–472**  
   LEO (from), **434–436**, **448**, **464**, **465**  
   lifting, **454**, **463**, **473**, **476–483**, **484**.  
     *see also* Space Shuttle  
   near-ballistic, **459–463**  
   reflection, **461**, **466–468**, **469**, **470**  
   reentry interface. *see* {entry interface}  
   skip, **466**, **469–472**  
   Space Shuttle, **483–491**  
 reentry equations of motion, **436–437**  
 reentry phases, **436**, **446**  
   Space Shuttle, **484**, **483–440**  
 reentry profile. *see* entry profile  
 reentry trajectory. *see* entry trajectory  
 reference frame (coordinate system), **661–675**.  
   *see also* reference system  
 equinoctial (EQW), **xxv**, **xxvii**, **205**, **206**, **668**  
 geocentric equatorial (IJK), **xxv**, **xxvi**,  
   **xxviii**, **200**, **205**, **207**, **208**, **602**, **625**,  
   **666**, **667**, **669–672**  
 geocentric perifocal (PQW), **xxvi**, **xxviii**,  
   **557**, **667**, **669–672**  
 heliocentric ecliptical (XYZ), **664**, **665**  
 inertial, **xxviii**, **2**, **3**, **19**, **180**, **204**, **263**, **336**,  
   **347**, **348**, **359**, **501**, **517–519**, **662–664**,  
   **704**, **706**, **711**  
 International Celestial (ICRF), **xxv**, **664**  
 International Terrestrial (ITRF), **xxv**, **562**,  
   **667**  
 local vertical local horizontal reference  
   system (LVLH), **xxv**, **xxviii**, **362**, **708**

- topocentric satellite (NTW, RSW), xxvi, xxviii, xxix, **668, 669–672**
- reference system. *see also* reference frame
  - barycentric, **661**. *see also* reference system, synodic
  - body, xxvii, **704, 705, 707, 709, 710, 718, 720, 729**
  - co-rotating, **422, 425, 504, 506, 514, 516, 668, 703**. *see also* reference system, synodic; reference system, body
  - heliocentric, **661**
  - planetocentric, 406, 409, 410, 415, 416
  - polar, 186, 257
  - proper, 25, 26, 28
  - rotating, **519, 662**
  - sidereal, 419, 518. *see* {reference frame, inertial}; *see also* reference frame, heliocentric ecliptical
  - synodic (system), 420, 506, **514, 515, 518, 529, 533, 539, 543, 549, 550**. *see also* reference system, co-rotating
  - topocentric, **661, 700, 704**
- reflection, xxix
  - diffuse/specular (molecular), **132–133, 137–140**
  - pressure, 97
  - radiation, **754, 757, 765, 779, 782**. *see also* ray tracing
  - reentry. *see* reentry, reflection
- regression of nodes, **579, 581, 596, 597, 604, 635**
- regularization, **214–215, 231, 236, 240, 252**. *see also*  $e$ -based transformation,  $h$ -based transformation; universal variable formulation
- relativistic rocket. *see* rocket, relativistic
- relativistic rocket equation. *see* rocket equation, relativistic
- rendezvous and docking (R&D), xxvi, **353–379**. *see also* orbital rendezvous
  - capture and berthing, 354
  - coelliptic, 364–366
  - docking, 354
  - Shuttle-ISS, **375–380**
  - stable orbit (SOR), 366
- rendezvous history, **364–366**
- repeat ground track orbit. *see* orbit, repeat ground track
- resonant orbit. *see* orbit, resonant
- restricted three-body system (R3BP). *see* three-body problem
- Reynolds number, xxxii, **125, 135**
- right ascension of ascending node (RAAN), xxvi, xxxv, **200, 203, 636, 676**
- change of, **287, 288, 293, 294, 296–298, 636, 695**
- adjustment maneuver, 638, 639
- rocket
  - annihilation, 34
  - partial, **48–50, 53, 55–57, 64**
  - relativistic, **24–34**
- rocket efficiency, **17–19, 47**
  - external. *see* efficiency, external
  - internal. *see* efficiency, internal
  - total, **17**
- rocket equation, **19, 39, 40, 153**
  - relativistic, **29**
  - serial-stage, **51**
  - single-stage, **39**
    - parallel-staging, **63**
- rocket flight (general issues), 37–46
- rocket fundamentals, 1–35
- rocket performance parameters, **15–24, 58, 86**. *see also* payload ratio; impulse, specific
  - Saturn V, 56
- rocket principles, 1–7
- rocket stage number. *see* stage number (rocket)
- rocket staging, 47–64
  - engine, 48, 64
  - number of stages, **55–57**
  - parallel, 62–64
  - serial, 47–62
  - single-stage. *see* rocket [...]
  - tank, 48, 64
  - uneven, 61–62
  - uniform, 58–59
- roll (S/C), 154, 162, 447, **708, 709, 730**
- roll maneuver, 154, 162, 447, 485
- roll reversals, 485. *see also* {bank reversals}
- roll–yaw oscillation, **731–734**
- rotation, 699–734
  - Earth's, 144, 145, 158, 163, 314, 463, 595, 601, 606, **611, 615, 673, 726**
  - equations of rotational motion, **706–708**. *see* {Euler's equations}
  - flat (flat spin), 717, **721–717**
  - oblate. *see* oblate rotation
  - prolate. *see* prolate rotation
  - sense of, **537, 538, 544**
- rotational power, **711, 724, 725**
- rotational stability, **712–714, 718–726**
- rotation damping, 720–724
- rotation rate. *see* angular velocity; angular frequency; orbital frequency
- rotation-to-translation equivalence, 710
- Runge–Kutta algorithm, 573

Runge–Lenz vector (Laplace–Runge–Lenz vector), **191**

## S

satellite orbit paradox, **209, 210**

scale height, **xxx1, 124, 127, 129, 431, 445, 447**

sectorial harmonics. *see* harmonics, sectorial

secular variation, **xxix, 575, 576, 579, 582, 583, 585, 587, 588, 589, 593, 634–636, 638**

semi-latus rectum, **xxxii, 190, 191, 192, 193, 227, 301–304, 306, 308, 310, 311, 326. *see also* {orbital parameter}; orbital elements**

semi-major axis, **xxx, 187, 192, 193, 198, 203, 206, 207, 281, 317, 574, 603. *see also* orbital elements**

change of, **285, 287, 623–625**

semi-minor axis, **210**

sensitivity analysis

departure orbit, **391–393**

Hohmann transfer, **323–325, 399–402**

thermal modeling, **789, 790**

thrust, **91, 92**

serial staging. *see* staging, serial

series expansion, **220, 221, 237, 238, 275, 559, 562**

shock attenuation, **85**

shock waves, **85, 101**

Shuttle. *see* Space Shuttle

sidereal day, **673**

sidereal reference frame. *see* reference frame, inertial

Simplified General Perturbation Model (SGP), **453, 482, 649**

slow variable, **575, 588**

solar constant, **756, 791**

solar radiation effects, **621–632**

solar day, **673**

Soyuz capsule, **145, 355, 360, 361, 363, 366, 373, 435, 464. *see also* capsule (space)**

space

Newton's absolute, **166**

outer, **127, 128**

Space Shuttle, **ix, 6, 63, 65, 85, 134, 142–144, 431, 438, 472, 473, 479, 480, 659**

cross-range capability, **142, 479, 485, 486, 487, 151, 154, 155, 157, 158, 162**

main engine (SSME), **xxxvi, 35, 65, 86, 88, 95, 99**

R&D, **353–355, 358–361, 364, 366, 367, 373, 375–380**

reentry, **427–429, 435, 476, 477, 483–491**

terminal area energy management (TAEM), **xxvi, 484, 490, 491**

specific [...]. *see* [...], specific spectral intensity/luminance, **738. *see* {radiance, spectral}**

speed. *see* {velocity}

proper. *see* proper speed

speed of sound, **xxx, 34, 73, 79, 81. *see also* {sound velocity}**

sphere of influence (SOI), **xxvi, xxix, 386–388, 389, 390, 392, 402, 409, 411, 422, 424 Moon's, 389**

spherical harmonics. *see* harmonics, spherical stability, **259–262, 265, 266, 267, 366, 369, 494–498, 767. *see also* manifold, stable**

at libration points, **520–522, 523, 525, 534–537, 541, 546–551**

dynamic, **548–551, 607, 609, 610, 613, 614**

gravity-gradient, **727–734**

rotational. *see* rotational stability

weak stability boundary transfer, **422–424**

staging. *see* rocket staging

stagnation point, **429–431, 451, 453, 454, 481–483, 487**

Stanton number, **xxxii, 428–430**

state control, **438, 525, 526. *see also* attitude dynamics /kinematics; station-keeping terminal, 160–162**

state propagation. *see* orbit propagation; state (vector) propagation

state vector, **183, 202, 214, 239–246, 289, 370–372, 670–672**

conversion to/from orbital elements, **207, 208**

determination, **692–693, 697. *see also* orbit determination**

propagation, **242–246, 649, 697. *see also* orbit propagation**

stationary point, **506**

station keeping, **xxix, 112, 330, 361, 367, 379, 522, 543, 620, 621, 631–632, 638, 639. *see also* waiting point (S)**

East-West, **608, 620, 621, 626, 631, 639, 691**

North-South, **638, 639**

station-keeping point (S), **361, 366, 367. *see also* {waiting point}**

*see also* {waiting point}

steady-state mode, **787**

steering, **38, 154, 163, 374, 485. *see also* angle, steering; steering law; angle, bank; L/D control; gravity turn**

losses, **153, 154, 155, 163**

steering law

angle-rate, **159, 160, 162**

linear/bilinear tangent, **161, 162**

Stefan-Boltzmann constant, **xxxiv, 736, 745**

- Stefan-Boltzmann law, **745**  
 stratosphere, **123, 124**  
 Stumpff functions, **245**  
 St. Venant–Wanzel equation, **73**  
 Sundman’s inequality, **497, 551**  
 Sundman’s theorem, **498**  
 Sundman transformation, **244**  
 Sun-synchronous orbit (SSO), **xxvi, 595–596, 600–601, 604, 605**. *see also* orbit, polar frozen, **600–601**  
 phased, **604, 605**  
 super-synchronous transfer orbit (SSTO). *see* transfer, super-synchronous  
 surface reflectivity (radiation), **xxxiv, 621, 721**. *see also* reflection, radiation  
 surface reflection (molecular). *see* reflection, diffuse/specular (molecular)  
 Sutton-Graves value, **430**  
 swing-by, **405**. *see* {flyby}  
 synodic period. *see* period, synodic  
 synodic (reference) system. *see* reference system, synodic  
 system dynamics, **522–525**
- T**
- tandem staging, **47, 48**. *see* {rocket staging, serial}  
 temperature (gas), **71**. *see also* thermal efficiency  
 effective, **755, 756, 762**  
 temperature enclosure, **784**  
 temperature gradient, **766**  
 spatial, **767, 776, 777, 784–785**  
 temporal, **767, 768, 784–787**. *see also* temperature stability  
 temperature reference point (TRP), **736, 784, 790**  
 temperature stability, **766, 767**  
 Temps Atomique International (TAI), **674**  
 terminal area energy management (TAEM). *see* Space Shuttle, TAEM  
 tesseral harmonics. *see* harmonics, tesseral  
 thermal balance, **737, 759–764**  
 thermal control  
 hardware, **783, 784**  
 reentry phase (Space Shuttle), **487–488**  
 system (TCS), **736, 766, 767, 773, 788, 789**  
 thermal design, **765, 768, 778, 779, 784–790**  
 thermal efficiency, **xxxiv, 14, 72, 77**  
 thermal engine. *see* engine, thermal  
 thermal mathematical model (TMM), **736, 772–774, 776, 780–783**  
 thermal modeling, **766–795**  
 thermal node, **768–771, 773–778, 780–787**  
 thermal radiation physics, **735–765**  
 thermodynamic efficiency, **72**. *see* {thermal efficiency}  
 thermodynamic (state) variables (extensive/intensive), **69, 72, 78, 79**  
 thermosphere, **123, 124**  
 three-body problem (3BP), **297, 334, 419, 493–551**. *see also* weak stability boundary transfer  
 circular restricted (CR3BP), **xxv, xxxv, 419, 513–528**  
 restricted (R3BP), **xxvi, xxxv, 501, 505, 508–513**  
 thrust/thrust force, **3–14**  
 angle. *see* angle, thrust  
 brief, **41**. *see* maneuver, impulsive  
 ejection ( $F_e$ ), **xxx1, 8, 111**  
 errors, **281–289**. *see also* sensitivity analysis  
 ideal engine. *see* thrust optimization  
 ion engine, **110–112**  
 momentum ( $F_{ex}$ ), **xxx1, 3–4, 8, 11, 12–13, 23, 34, 93, 111**  
 oscillations, **85, 96, 97**. *see also* pogo effect  
 optimization, **81–85**  
 pressure ( $F_p$ ), **xxx1, 9–10, 14**  
 relativistic, **29**  
 thermal engine, **88–95**  
 total ( $F_*$ ), **xxx1, 4, 12, 83, 88–93, 110–112**  
 thrust acceleration ( $a_*$ ), **158, 160, 162**  
 thrust chamber, **9–14, 68, 95–97**. *see also* combustion chamber  
 thrust coefficient ( $C_T$ ), **xxx, 89–91, 93, 94**  
 thrust correction factor, **23**  
 thrust phase (ascent), **150, 151, 154, 162, 163**  
 thrust sensitivity analysis. *see* sensitivity analysis, thrust  
 thrust-to-power ratio, **xxvi, xxix, 23–24, 110, 114, 115**  
 thrust variations. *see* sensitivity analysis, thrust  
 thruster. *see* engine  
 time. *see also* epoch; period  
 dimensionless, **xxxiv, 204, 516**. *see also* mean anomaly  
 Greenwich Mean Sidereal (GMST). *see* Greenwich Mean Sidereal Time (GMST)  
 Greenwich Mean (GMT). *see* Greenwich Mean Time (GMT)  
 International Atomic (TAI). *see* International Atomic Time (TAI)  
 proper. *see* proper time

- UT (Universal Time). *see* UT (Universal Time)
- UTC (Universal Time Coordinated). *see* UTC (Universal Time Coordinated)
- time reference frames, **672–675**
- Tisserand relation, **421–422**
- Titius–Bode law, **797**
- torque equilibrium attitude (TEA), **649**
- tracking. *see* orbit tracking
- Tracking and Data Relay Satellites (TDRS), **xxvi, 685**
- trajectory. *see also* three-body problem; invariant manifolds
- arrival/approach, **402, 403**
- ascent, **147, 150–163**
- chaotic, **525**
- departure, **391–393**
- entry, **147, 427, 434, 437, 438, 443, 444, 446, 458, 461, 464, 466, 471, 472, 478–479, 491. see also** entry profiles
- flyaround, **345–353, 368, 369, 373, 376**
- flyby, **407, 408, 410. see also** flyby
- free-return. *see* free-return trajectory
- orbital. *see* orbit
- radial, **247–255**
- transfer. *see* transfer orbit
- transfer, **150–152, 279–298. see also** transfer orbit; maneuvers; orbital maneuvering; manifold, hyperbolic (saddle)
- bi-elliptic, **327–329, 333–334, 381, 422. see also** three-impulse transfer; super-synchronous (SSTO)
- bi-parabolic, **327–329. see also** transfer, three-impulse
- continuous thrust, **321, 333, 334–336. see also** super-synchronous (SSTO)
- deorbit, **432–436**
- Earth-Moon, **423. see also** Farquhar transfer orbit
- escape (parabolic), **325–326**
- Farquhar. *see* Farquhar transfer orbit
- Hohmann. *see* Hohmann transfer; Hohmann transfer orbit
- homing (maneuver), **361, 363, 364**
- interplanetary. *see* interplanetary flight
- Lambert. *see* Lambert transfer
- minimum effort, **313**
- minimum energy (Lambert). *see* Lambert transfer, minimum energy
- n-impulse, **334**
- nodal, **293, 331**
- one-impulse. *see* maneuver, one-impulse
- super-synchronous (SSTO), **294, 329–333**
- tangential thrust, **334, 336. see** transfer; continuous thrust
- three-impulse, **280, 334. see** transfer, bi-elliptic; transfer bi-parabolic; super-synchronous (SSTO); Farquhar transfer orbit
- two-impulse, **280, 284, 285, 334, 527. see** Lambert transfer, Hohmann transfer
- weak stability boundary. *see* weak stability boundary transfer
- transfer boost. *see* apogee boost; maneuver, impulsive; kick-burn
- transfer orbit. *see* transfer; Hohmann transfer orbit; Lambert transfer
- transfer time, **304–305, 308, 317, 321, 333, 335, 381, 394, 423. see also** Lambert's problem
- transition time, **396–402**
- triaxiality, **615–621, 631, 632**
- troposphere, **123, 124**
- true anomaly. *see* anomaly, true
- Tsiolkovsky rocket equation, **39. see** {rocket equation}
- two-body problem (2BP), **165, 178, 179, 260, 315, 334, 522, 555**
- general, **178–181**
- two-body system, **178, 179, 202, 274, 405–407, 421, 493, 497**
- two-line elements (TLE), **137, 453, 482, 648, 649, 654, 682**
- U**
- UT (Universal Time), **xxvi, 673. see** {Greenwich Mean Time (GMT)}
- UTC (United Time Coordinated), **194, 674**
- universal anomaly. *see* anomaly, universal
- universal variable formulation, **244–246**
- unstable motion, **523, 541–544, 620–621, 629–634. see also** manifolds, stable/unstable
- unstable points, **520–521, 607, 617, 659**
- unstable system, **494–495**
- V**
- Vandenkerckhove function, **76**
- V-bar, **362, 367–377**
- vector. *see* [...] vector
- vector representations, **670–672**
- velocity
- angular. *see* angular velocity
- characteristic. *see* characteristic velocity
- cosmic. *see* cosmic velocity
- critical, **463, 480, 481**

- departure, 224, **390–391**  
 drift, 72, 73, 609. *see also* flow velocity  
 ejection ( $v_e$ ), xxxiii, 8, 14, 34, 67, 77, 81, **84, 89, 108**, 110, 111, 115, 117, 118  
 entry, **406**, 407, 411, 414, **431–434**, 436, 442, 447, **459**, 463, 466, 469, 470, 486  
 escape, 44, 224, **227**, 228, 325, 405  
 excess (hyperbolic), **223**, 224, 390, 391, 394, 398, 399, 401, 405, 497. *see also* velocity, exit; characteristic energy  
 exhaust. *see* exhaust velocity  
 exit, 407, 408, 413, **469, 470**  
 flow (gas), 21, 22, **73–75, 77, 78–82**  
 hypersonic ( $\gamma$  speed), 130, 134, 137, 143, 429, 430, 438  
 orbital. *see* orbital velocity  
 root-mean-square (molecular), **71**  
 sound. *see* sound velocity. *see also* {speed of sound}  
 supersonic, 13, 80, 82  
 velocity correction factor. *see* correction factor, velocity  
 velocity distribution function (VDF), xxvi, xxix, 8, 21. *see also* loss factor, VDF  
 velocity error, 391, 401. *see also* sensitivity analysis  
 vernal point, xxxvi, 200, **664, 665, 666**. *see also* {First Point of Aries}  
 view factor, 735, **752–755**, 775, 776, 778, 779, **781, 792**  
 virial theorem, **199**, 274, **496–497**  
 vis-viva equation, 186, **187**, 257. *see also* conservation of energy  
**W**  
 waiting point (S), 364, **366–372**. *see also* station keeping  
 waiting time, **396**, 424, 425  
 weak stability boundary transfer, **422–424**  
 wetted area, 132, 133, 138. *see also* {effective surface area}  
 Wien's displacement law, **744, 795**  
 winged body, 143, 155, 427, 438, 442, 476, 479. *see also* Space Shuttle  
**Y**  
 yaw, **708, 709**, 731, 733–734  
**Z**  
 zero-velocity curve, **523–525**. *see also* {Hill curve}  
 zonal harmonics. *see* harmonics, zonal