Appendix A
Commonly Used Symbols

α	coefficient of thermal expansion; right ascension
β	backfocal to focal length ratio
δ	deflection; declination
ϵ	thermal emissivity
θ	field angle; seeing angle
κ	thermal conductivity
λ	wavelength
ν	Poisson's ratio; frequency
ρ	material density
σ	stress; image size; Stefan-Boltzmann constant
τ	torque
τ_0	coherence time (atmosphere)
ϕ	wavefront polar angle
φ	latitude
ω	angular frequency
A	azimuth angle; area
b	backfocal distance
C_n^2	refraction index structure coefficient
C_p	specific heat
C_T^2	temperature structure coefficient
D	mirror diameter
E	modulus of elasticity
Fr	Froude number
f	focal length; frequency
g	acceleration of gravity
G	gravitational constant
HA	hour angle
h	thickness; height; altitude (angle)
I	intensity; moment of inertia
J	inertia
K	structural stiffness
k	proportionality constant; gain
m	optical magnification; mass
N	f-ratio; number of counts
n	number count
Q	amount of heat
r	running radius on a mirror
r_0	coherence length (atmosphere)
RA	right ascension
$\mathcal{R}$	Reynolds number
s	mirror separation (prim.–sec.)
S/N	signal-to-noise ratio
T	temperature
ΔT	temperature gradient
t	time
v	velocity
Z_n	Zernike polynomial of order n
z	mirror surface ordinate

Appendix B

Basic Data and Unit Conversions

Name	Symbol	Value
Physical constants		
Velocity of light	c	$2.998 \cdot 10^8$ m/s
Gravitational constant	G	$6.670 \cdot 10^{-11}$ N m^2/kg^2
Planck constant	h	$6.625 \cdot 10^{-34}$ J s
Boltzmann constant	k	$1.381 \cdot 10^{-23}$ J/K
Stefan-Boltzmann constant	σ	$5.670 \cdot 10^{-8}$ W/m^2 K^4
Standard gravitational acceleration	g	9.807 m/s^2
Astronomical constants		
Solar luminosity	$L_\odot$	$3.90 \cdot 10^{26}$ W
Solar mass	$M_\odot$	$1.989 \cdot 10^{30}$ kg
Earth mass	$M_\oplus$	$5.976 \cdot 10^{24}$ kg
Mean radius of the Earth		6371 km
Eccentricity of the Earth's orbit		0.0167
Astronomical unit	AU	$1.49 \cdot 10^{11}$ m
Mean distance from Earth to Moon		$3.84 \cdot 10^8$ m
Altitude of geosynchronous orbit		36 000 km
Distance to Sun/Earth L2		$1.5 \cdot 10^6$ km
Solar constant	G_S	1358 W/m^2

Unit Conversions

Time	
1 day	86 400 s
1 sidereal day	86 164.091 s
1 year	$3.1558 \cdot 10^7$ s
Angle	
$1''$	$4.848 \cdot 10^{-6}$ radian
1 radian	$206\ 264''$
1 steradian (sr)	$3.283 \cdot 10^3$ degrees^2
	$1.182 \cdot 10^7$ arcmin^2
	$4.255 \cdot 10^{10}$ arcsec^2
1 arcsec^2	$2.350 \cdot 10^{-11}$ sr
Length	
1 statute mile	1609 m
1 nautical mile	1852 m
1 parsec	3.26 light years $= 3.086 \cdot 10^{16}$ m
1 lightyear	$9.46 \cdot 10^{15}$ m
1 AU	$1.496 \cdot 10^{11}$ m
1 Angström (Å)	10^{-10} m
Energy	
1 BTU	1055 J
1 eV	$1.6 \cdot 10^{-19}$ J
1 cal	4.186 J
1 kcal (cal kg)	4186 J
Pressure	
1 bar	$1 \cdot 10^5$ Pa
1 torr	133 Pa
1 psi	$6.89 \cdot 10^{-3}$ Pa
Velocity	
1 mph	0.447 m/s
1 km/h	0.278 m/s
1 knot	0.514 m/s
Miscellaneous	
1 Jansky (Jy)	10^{-26} W/m^2 Hz

Appendix C
The Largest Telescopes

The largest ground-based, space and airborne optical telescopes are listed in Tables C1, C2 and C3. Particulars for the headings and contents are as follows:

Telescope: The common name of the telescope; refer to the Glossary for the full official name. The list is limited to astronomical telescopes and excludes reflecting telescopes used for military purposes.

Diameter: The diameter of the useful aperture of the primary mirror(s), converted to an equivalent diameter in meters if not circular; the list of ground-based telescopes is limited to those with primary mirrors 3.0 meters or larger in diameter.

Mirror material: The material of the primary mirror substrate. *Cer-Vit Sitall* (i.e., *Astro-Sitall*), and *Zerodur* are ultra-low-expansion glass-ceramics; *ULE* is an ultra-low-expansion fused silica, *Pyrex* and *E6* are borosilicate low-expansion glass products.

Mass: The mass shown for a space observatory is for its entire payload, including instruments and space support systems.

Date completed: Date of first operation of the telescope; for observatories still under construction in mid-2001, the expected completion or launch dates are shown in parentheses.

Table C.1. The largest ground-based telescopes

Telescope	Location	Diameter (m)	Primary type	Primary f-ratio	Primary material	Mount	Date completed
LBT[1]	Arizona	11.8	honeycomb	1.14	E6	alt-az	(2004)
Keck I	Hawaii	10.5	segmented	1.75	Zerodur	alt-az	1993
Keck II	Hawaii	10.5	segmented	1.75	Zerodur	alt-az	1998
GTC	Canaries	10.4	segmented	1.65	Zerodur	alt-az	(2004)
Hobby-Eberly[2]	Texas	9.5	segmented	1.8	Zerodur	fixed	1999
SALT	South Africa	9.5	segmented	1.8	Zerodur	transit	(2004)
Subaru	Hawaii	8.4	meniscus	1.8	ULE	alt-az	1999
Gemini North	Hawaii	8.3	meniscus	1.8	ULE	alt-az	2000
Gemini South	Chile	8.3	meniscus	1.8	ULE	alt-az	2000
VLT UT1	Chile	8.2	meniscus	1.75	Zerodur	alt-az	1998
VLT UT2	Chile	8.2	meniscus	1.75	Zerodur	alt-az	1999
VLT UT3	Chile	8.2	meniscus	1.75	Zerodur	alt-az	2000
VLT UT4	Chile	8.2	meniscus	1.75	Zerodur	alt-az	2001
TIM	Mexico	7.0	segmented	1.5	Zerodur	alt-az	(2004)
MMT conversion[3]	Arizona	6.5	honeycomb	1.25	E6	alt-az	1999
Magellan I	Chile	6.5	honeycomb	1.25	E6	alt-az	1999
Magellan II	Chile	6.5	honeycomb	1.25	E6	alt-az	(2001)
BTA	Caucasia	6.0	solid	4	Sitall	alt-az	1976
LZT	Canada	6.0	liquid	1.6	mercury	transit	(2001)

1. Two 8.4 m primary mirrors.
2. Fixed altitude mount; equivalent diameter.
3. Originally with six 1.8 m mirrors; 6 m mirror installed in 1999.

Table C.2. The largest ground-based telescopes (Continued)

Telescope	Location	Diameter (m)	Primary type	Primary f-ratio	Primary material	Mount	Date completed
Hale	California	5.1	honeycomb	3.3	Pyrex	equatorial	1949
WHT	Canaries	4.2	solid	2.5	Cer-Vit	alt-az	1987
SOAR	Chile	4.2	meniscus	1.75	ULE	alt-az	(2002)
Blanco	Chile	4.0	solid	2.8	Cer-Vit	equatorial	1976
LAMOST	China	4.0	segmented	5		meridian	(2004)
AAT	Australia	3.9	solid	3.3	Cer-Vit	equatorial	1975
VISTA	Chile	3.9	meniscus	2	Sitall	alt-az	(2005)
Mayall	Arizona	3.8	solid	2.8	fused quartz	equatorial	1973
UKIRT	Hawaii	3.8	meniscus	2.5	Cer-Vit	equatorial	1978
CFHT	Hawaii	3.6	solid	3.8	Cer-Vit	equatorial	1979
ESO 3.6	Chile	3.6	solid	3	fused silica	equatorial	1976
NTT	Chile	3.0	meniscus	2.2	Zerodur	equatorial	1989
MPI	Spain	3.5	solid	3.5	Zerodur	equatorial	1984
WIYN	Arizona	3.5	honeycomb	1.75	E6	alt-az	1994
TNG	Canaries	3.5	meniscus	2.2	Zerodur	alt-az	1997
ARC	New Mexico	3.5	honeycomb	1.75	E6	alt-az	1994
Shane	California	3.1	honeycomb	5	Pyrex	equatorial	1959
IRTF	Hawaii	3.0	solid	2.5	Cer-Vit	equatorial	1979

Table C.3. The major space, airborne and balloon borne telescopes

Telescope	Site	Diameter (m)	Spectral range (μm)	Primary mirror material	Mass (kg)	Launch date	Lifetime (yr)
Stratoscope I	balloon	0.3	–			1957	
OAO 2	LEO	0.2 to 0.4	–	–	2000	1968	4
OAO 3	LEO	0.80	–		2200	1972	9
KAO	airplane	0.9	40–100			1976	20
IUE	GEO elliptic	0.45	0.11–0.33	beryllium	700	1978	20
IRAS	900 km polar	0.57	8–120	beryllium	1080	1983	0.9
HST	LEO	2.4	0.2–2.5	fused silica	11 000	1990	~ 15
ISO	GEO elliptic	0.6	2.5–200	fused silica	2200	1995	1.5
SOFIA	airplane	2.5	0.3–1600	Zerodur	$\sim 2\,000$	(2002)	(> 20)
SIRTF	drift	0.85	3–180	beryllium		(2004)	(2.5)
FIRST	L2	3.5	60–670		~ 3300	(2007)	
NGST	L2	6.5	0.6–28	glass or	~ 3800	(2010)	(10)
			–	beryllium			

Appendix D
Sharpness

A common and important problem in astronomy is the following. Given an image $I_{ij} = B + AP_{ij} + N_{ij}$ that is the sum of a background B (perhaps including a dark current contribution), a point source with total detected counts A, distributed by a point spread function P_{ij} (so that $\sum P_{ij} = I$, by definition), and noise N_{ij} with zero mean and known variance σ_{ij}, what is the best way to estimate A and what is the signal-to-noise ratio of the results?

Clearly, the answer does depend on how A is estimated. The simplest and more commonly used estimator is to choose an aperture that includes most of the flux and not too much background noise. However, this is not the best that can be done. A more general approach is to choose a set of weights W_{ij} and sum the weighted contributions to an estimate of A. The special case of aperture photometry is obtained when all weights have the same value inside the aperture so that pixels outside make some contribution (after all, they contain some signal), whereas pixels inside but near the edge of the aperture are less important than more central pixels because they individually have poorer signal-to-noise ratio.

The image noise has zero mean $< N_{ij} >= 0$, is uncorrelated from pixel to pixel $< N_{ij}N_{kl} = \delta_{ik}\delta_{jl}\sigma_{ij}^2$, and has known variance $\sigma_{ij}^2 = B + AP_{ij} + R^2$ (the sum of Poisson noise and read noise, R). The estimator of A that we choose is the most general linear unbiased estimator (and this estimator when optimized achieves the Cramer-Rao bound, so is the best that can be done and no nonlinear estimator will give better signal-to-noise ratio).

$S = \sum(I_{ij}B)W_{ij}/\sum W_{ij}P_{ij}$ is unbiased because by construction $< S >= A$. The noise N on this signal is given by

$$N^2 \equiv (S - < S >)^2 = \frac{\sum W_{ij}^2 \sigma_{ij}^2}{(\sum W_{ij}P_{ij})^2}. \tag{D.1}$$

This result has been obtained by direct substitution and reduction using the assumed uncorrelated nature of the noise. To maximize the signal-to-noise ratio $< S > /N$, one must minimize $N^2/ < S >^2$ with respect to the weights W_{ij}. To find the solution, one differentiates with respect to W_{ij} and sets the result to zero. This procedure shows that in the general case, the optimal weights are proportional to

$$W_{ij} \propto \frac{P_{ij}}{\sigma_{ij}} = \frac{P_{ij}}{B + R^2 + AP_{ij}}. \tag{D.2}$$

Two limiting cases are typically encountered. If the photon noise in the source dominates ($AP_{ij} \gg B + R^2$) over most of the image, then the expression for W_{ij} becomes constant and the signal-to-noise ratio comes out in the square root of the number of expected counts. This result is reassuring, but not usually the case for faint object imaging.

In the background- or read-noise-limited case when $AP_{ij} \ll B + R^2$ over all the image, the weights are proportional to the corresponding value of the PSF, and we can normalize them so that $W_{ij} = P_{ij}$ without loss of generality. In this case, the signal-to-noise ratio is given by

$$(\frac{< S >}{N})^2 = \frac{A^2\Psi}{B + R^2}\,, \tag{D.3}$$

where

$$\Psi = \frac{\sum P_{ij}^2}{(\sum P_{ij})^2} \tag{D.4}$$

is the quantity that we call sharpness. Notice that Ψ is always less than 1, but positive. It becomes equal to one in the sharpest case when all of the flux is in one pixel (note that one cannot just increase the pixel size to get better signal-to-noise ratio, because the quantity B generally grows with pixel size). This cleanly separates the contributions from the total detected flux A from the contribution caused by the telescope design.

This quantity has many amazing properties, which make it easy to work with. When the pixels are critically sampling the PSF or better, the sharpness is independent of pixel phase, so it does not matter where exactly the star is relative to pixel boundaries. For such pixels, the sharpness scales inversely with the pixel area (so smaller pixels give smaller sharpness, but this is exactly canceled by the corresponding change in B for the background-limited case). Thus the signal-to-noise ratio is independent of pixel size, provided the pixels are sufficiently small and the read noise is not important. The summation can

then be turned to an integral, and the signal-to-noise ratio can be written in terms of the integral of the square of the PSF. By Parseval's theorem, this is the integral of the square of the MTF, and the MTF can be obtained by an autocorrelation of the aperture function. Thus, one can derive analytic expressions for the sharpness in a number of important cases (such as circular apertures or redundant and nonredundant arrays).

(*Contributed by Christopher Burrows*)

Appendix E

Derivation of the Equation of Motions

The Lagrange equations for a generalized system of n independent coordinates are

$$\frac{\partial}{\partial t}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} + \frac{\partial F}{\partial \dot{q}_i} = Q_i, \qquad i = 1, \cdots n\,, \tag{E.1}$$

where q_i are the generalized coordinates (degrees of freedom), such as the displacement of a mass or a rotation angle for a moment of inertia, $L = T - V$ is the Lagrangian, with T and V being the system's kinetic and potential energy, respectively, both expressed in terms of q_i, F is the the Rayleigh dissipation function, and Q_i is the externally applied force (normally applied to the ith mass). The Rayleigh dissipation function is present when the frictional forces are linear and proportional to the velocities and is given by

$$F = \frac{1}{2}\sum_{i-1}^{n} B_i \dot{q}_i^2\,, \tag{E.2}$$

where B_i is the ith viscous friction coefficient.

Let us apply the Lagrange equations to the altitude axis of the lumped mass model shown in Fig. 7.1. The Lagrange coordinates are the rotation angles of the three lumped masses in the system: θ_m, θ_M, and θ_T for the motor, mount, and tube, respectively. The corresponding angular velocities and angular accelerations are denoted by $\dot{\theta}$ and $\ddot{\theta}$, respectively. The gearbox is a speed reducer of ratio $N : 1$, where N can be either positive or negative (negative when a clockwise motor rotation causes a counterclockwise load rotation). The motor torque, τ_m, is applied against the motor moment of

inertia, J_m, and reacts against the gear case and mount moment of inertia, J_M. The tube is assumed subjected to disturbance torque τ_d. A fourth coordinate θ_G, the rotation of the output shaft of the gearbox, is not an independent variable and can be defined by an equation that relates the relative output shaft rotation of the gearbox to the relative input shaft rotation:

$$\theta_m - \theta_M = N(\theta_G - \theta_M) \quad \text{or} \quad \theta_G = \frac{1}{N}\Big[\theta_m + (N-1)\theta_M\Big]. \tag{E.3}$$

The kinetic energy of the system is

$$T = \frac{1}{2}(J_m\dot{\theta}_m^2 + J_M\dot{\theta}_M^2 + J_T\dot{\theta}_T^2), \tag{E.4}$$

and the potential energy is

$$V = \frac{1}{2}\Big[K_M(\theta_M - \theta_G)^2 + K_T(\theta_T - \theta_M)^2\Big]. \tag{E.5}$$

Substituting θ_G from equation E.3 into equation E.5 gives

$$V = \frac{1}{2}\left[K_M\theta_M^2 + K_T\Big(\frac{\theta_m}{N} + \frac{N-1}{N}\theta_M - \theta_T\Big)\right]. \tag{E.6}$$

The Rayleigh dissipation function is given by

$$F = \frac{1}{2}\left[B_m(\dot{\theta}_m - \dot{\theta}_M)^2 + B_T(\dot{\theta}_T - \dot{\theta}_M)^2 + B_M\dot{\theta}_M^2\right]. \tag{E.7}$$

The terms of the Lagrange equation for the first independent coordinate, θ_m, can then be expressed as follows:

$$\frac{\partial}{\partial t}\Big(\frac{\partial L}{\partial \dot{\theta}_m}\Big) = J_m\ddot{\theta}_m, \tag{E.8}$$

$$\frac{\partial L}{\partial \theta_m} = -\frac{K_T}{N}\Big(\frac{\theta_m}{N} + \frac{N-1}{N}\theta_M - \theta_T\Big), \tag{E.9}$$

$$\frac{\partial F}{\partial \dot{\theta}_m} = B_m(\dot{\theta}_m - \dot{\theta}_M). \tag{E.10}$$

Since the forcing function for the coordinate θ_m is $Q_1 = \tau_m$, inserting the above terms into the Lagrange equation leads to the dynamic time domain equation of motion for the motor:

$$J_m\ddot{\theta}_m + B_m(\dot{\theta}_m - \dot{\theta}_M) + \frac{K_T}{N}\Big(\frac{\theta_m}{N} + \frac{N-1}{N}\theta_M - \theta_T\Big) = \tau_m. \tag{E.11}$$

Using a similar process, one can develop the remaining two equations of motion. For θ_T, we obtain

$$J_T\ddot{\theta}_T + B_L(\dot{\theta}_T - \dot{\theta}_M) - K_T\left(\frac{\theta_m}{N} + \frac{N-1}{N}\theta_M - \theta_T\right) = \tau_d, \tag{E.12}$$

and for θ_M,

$$J_M\ddot{\theta}_M + B_M\dot{\theta}_M + K_M\theta_M - B_m(\dot{\theta}_m - \dot{\theta}_M) - B_T(\dot{\theta}_T - \dot{\theta}_M) + K_T\frac{N-1}{N}\Big(\frac{\theta_m}{N} + \frac{N-1}{N}\theta_M - \theta_T\Big) = -\tau_m\,. \tag{E.13}$$

Equations E.11, E.12, and E.13 represent the simultaneous linear, time-domain dynamic equations of motion for the lumped mass system around the altitude axis. Note that the external forcing function τ_m is independent because its value varies with the electric current applied to the motor.

(*Contributed by Marvin (Tim) Cornwell*)

Appendix F
Glossary

This glossary covers terms and acronyms that may be encountered in the telescope building profession, whether or not they appear in this text. Definitions will be found under the most commonly used term of reference, acronym or full form, with the alternative forms cross referenced. Words used in definitions that are themselves defined in the Glossary are identified by q.v. (quod vide, i.e., "see this").

AAS American Astronomical Society. An organization of professional astronomers in the United States, Canada, and Mexico. The society has more than 6000 members and publishes the *Astronomical Journal* and the *Astrophysical Journal*.

AAT Anglo-Australian Telescope. A 4 m equatorial telescope at Siding Springs, Australia.

aberration In optics, the imperfections of an image due to wavefront errors (of geometric or chromatic origin).

aberration of starlight The apparent angular displacement of a celestial object caused by the finite velocity of light in combination with the motion of the observer.

absorption coefficient In optics, a measure of the attenuation of the intensity of light as it passes through a medium.

absorption line A narrow region of the spectrum within which the intensity of radiation is lower than in the adjoining regions; typically produced when radiation from a background source passes through cooler matter.

achromat A composite lens that does not produce noticeable chromatic aberration. It is generally composed of two lenses with different indices of refraction, their powers being selected so as to cancel out chromatic effects.

acoustic sounder A device for measuring atmospheric turbulence by the scattering of sound. Also called a "sodar."

acquisition (of a target) The action of placing a target in the aperture of a science instrument. This happens automatically when the absolute pointing accuracy is better than the field of the instrument. When such is not the case, as in the centering of a target in a spectrograph slit, special techniques such as blind offsetting (q.v.) or spiral search are required.

active optics The controlled deformation or displacement of optical elements to correct for slowly varying effects (<1 Hz), such as gravitational deflections and temperature drifts. See also **adaptive optics**.

A/D Analog to Digital. See **analog-to-digital converter**.

adaptive optics The controlled deformation or optical elements to correct for rapid fluctuations (> 1 Hz) in image quality. On the ground, this technique is used to correct for atmospheric turbulence. See also **active optics**.

adiabatic lapse rate The rate of change of temperature with altitude of a parcel of dry air which is raised or lowered in the atmosphere without exchanging heat with the surrounding air. The adiabatic lapse rate in the atmosphere is 9.8 °C/km. The actual lapse rate of temperature in the troposphere averages about 6 °C/km.

afocal Characteristic of an optical system that receives parallel rays of light from a distant source and outputs parallel rays of light at a different magnification.

afocal telescope A telescope with no final focus, both the object and image being at infinity.

air mass A measure of atmospheric extinction as a function of the path length traversed by starlight in the atmosphere before it reaches the telescope. The air mass is equal to 1 when pointing at the zenith and is about 3 for a 70° zenith angle.

Airy disk The central portion of the diffracted image of a point source formed by an optical system with a circular aperture. It contains 84% of the total energy in the case of a circular aperture with no obstruction by vanes or secondary mirror. The diameter of the disk (i.e., the diameter of the first dark ring) is $2.44\lambda/D$ measured on the sky, where λ is the wavelength and D is the diameter of the aperture. Named after George Airy, who was the first to derive the mathematical description of the PSF of a circular aperture.

albedo The fraction of incident sunlight that the surface of a celestial body (e.g., Earth, Moon, planet) reflects (identical to reflectance).

aliasing See **Nyquist theorem**.

ALOT Adaptive Large-Optics Technologies. A DoD-sponsored project that developed a lightweight, 4 m space telescope equipped with an advanced active optics system.

alt-az mount Altitude-azimuth mount. A mounting for a telescope, one axis of rotation being horizontal (altitude axis) and the other vertical (azimuth axis).

altitude The angular distance above the horizon to a celestial object, as measured along a vertical circle. Also called elevation.

altitude axis In an alt-az mount, the horizontal axis about which the tube of a telescope rotates.

aluminizing The process of coating a mirror surface with aluminum.

amorphous solid A state of solid material in which atoms are organized over short ranges but lack the recurring pattern found in crystals. Glass is an amorphous solid. The amorphous solid state is obtained by the rapid cooling of a viscous fluid (e.g., glass) or direct solidification of the vapor phase by vacuum deposition or other techniques (e.g., silicon).

analog signal A signal that continuously represent a variable.

analog-to-digital converter (ADC) An electronic device that converts analog signals to an equivalent digital form.

anastigmat An optical system that does not suffer from common optical defects such as coma, astigmatism, or spherical aberration.

Anglo-Australian Telescope See **AAT**.

Angström A unit of length used for light wavelengths or coating thicknesses, equal to 10^{-10} m.

angular size The angle over which an object appears to extend.

annealing A process of heating followed by cooling, used for softening metals or removing internal stresses. Also, slow cooling following melting in mirror blank fabrication.

ANSI American National Standards Institute. A professional organization in the United States responsible for accepting and designating the standards developed by other organizations as national standards.

antireflection coating A coating applied to a lens or optical window to minimize reflections and maximize transmission.

AO Announcement of Opportunity. A NASA announcement inviting a proposal. AOs tend to be for larger programs than NRAs (q.v.), but are not as specific as RFPs (q.v).

APART Arizona's Paraxial Analysis of Radiation Transfer. A program for analyzing stray light in optical systems, developed at the University of Arizona and commercialized by Breault Research Organization, Inc.

aperture The size of the first optical element in an optical system (e.g., the primary mirror of a telescope). The aperture diameter is the simplest measure of the light-gathering power of a telescope.

aperture stop A physical element, usually circular, that limits the light bundle an optical system will accept.

apex In orbital mechanics, one of two points on an elliptic orbit lying on the major axis.

aphelion The point at which a body (spacecraft, planet) in a heliocentric orbit is farthest from the Sun.

apogee The point at which a body in orbit around Earth reaches its farthest from the Earth.

ARC Astrophysical Research Consortium, which operates a 3.5 m telescope at the Apache Point Observatory, New Mexico.

areal density The mass per unit area (e.g., of a mirror).

Arecibo radio telescope A 305 m radio dish at the National Astronomy and Ionosphere Center in Arecibo, Puerto Rico. The dish is not movable and consists of a fixed metallic surface located in a natural valley. The receiver is supported at the focus by cables and moves to track sources being observed. The Arecibo telescope is the largest telescope of any kind in the world. It was completed in 1963 and is operated by Cornell University for the NSF.

array Short for "detector array." A two-dimensional matrix of individual electronic detectors, typically constructed on centimeter-sized wafers of silicon or other materials.

ASCII American Standard Code for Information Interchange. ASCII (pronounced "askee") is a standard developed by the American National Standards Institute (ANSI) to define how computers write and read characters. The ASCII set of 128 characters includes letters, numbers, punctuation, and control codes.

aspect ratio of mirror The ratio of thickness to diameter. A misleading characteristic of mirror flexibility. See **diameter to thickness ratio**.

aspheric An optical element (lens or mirror) that does not have a spherical surface (e.g., conic).

astatic lever A counterweighted lever used in mirror support systems.

astigmatism An optical aberration which causes off-axis rays to form an ellipse or a straight line at the focal plane instead of being brought to a point focus. An optical system designed to avoid such defects is known as an "anastigmat."

astrology The pseudoscience that treats the supposed influence of the configurations and positions of the Sun, Moon, and planets on human destiny.

astrometry The branch of astronomy concerned with the measurement of precise positions of celestial objects.

astronautics The study of celestial mechanics and engineering fields as applied to placement and control of manned or unmanned objects in space.

Astronomical Almanac A yearly publication of the U.S. Naval Observatory and the Royal Greenwich Observatory which provides the ephemerides of the Sun, Moon, and planets and other astronomical data.

astronomical unit (AU) The mean distance between the Earth and the Sun (about 149 million kilometers).

astronomy The branch of science that treats the physics and morphology of that part of the universe that lies beyond the Earth's atmosphere.

astrophysics The branch of astronomy concerned with the composition and physical properties of celestial objects.

athermal, athermalized Designed so as to ensure that system changes do not occur over a given temperature range.

atmospheric refraction The bending of light rays as they pass through atmospheric layers of varying density.

attenuation The reciprocal of gain. A dimensionless ratio defining the decrease in magnitude of a signal as it passes between two points or two frequencies. Large values of attenuation are expressed in decibels (dB).

attitude The orientation of a spacecraft with respect to a reference frame.

AU Astronomical Unit (q.v.).

AURA Association of Universities for Research in Astronomy. A consortium of universities and other nonprofit institutions that manages observatories in Arizona, Hawaii, and Chile, and the Space Telescope Science Institute (STScI).

autocollimation A technique used to test the alignment and image quality of an optical system. A source is placed at the focus of the system and the output (collimated) beam is reflected back to it by a flat mirror.

AXAF Advanced X-Ray Astronomy Facility, renamed the Chandra X-Ray Observatory (q.v.) after its launch in 1999.

azimuth The angular distance measured clockwise along the horizon from a specified reference point (usually North) to the intersection with the great circle passing through a body on the celestial sphere.

azimuth axis In an alt-az mount, the vertical axis about which the mount rotates.

back emf (back electromotive force) The voltage generated when a permanent magnet motor is rotated. This voltage is proportional to motor speed and is present whether or not the motor windings are energized.

back focal length In an optical system, the distance from the vertex of the last optical element to the focus.

background-limited observation An observation whose signal-to-noise ratio is limited by the background noise. The source of the background can be cosmological emission, zodiacal light, atmospheric emission, or thermal emission from the system itself, but not from the detector itself. When only natural background is considered (i.e., excluding thermal emission of the observatory), one refers to "sky limited" (on the ground) or "zodiacal light limited" (in space) observations.

backlash The relative movement of interlocked mechanical parts that occurs when motion is reversed (as in gears). The consequence is hysteresis in the control system.

baffle A structure in an optical system that obstructs or scatters stray light which would otherwise reach the detector.

bake out A cleaning process in which an item is heated, during or after manufacture, to outgas contaminates.

band gap The difference between the lowest energy level of the upper (conduction) band and of the lower (valence) band in an insulator or semiconductor, usually expressed in electron-volts.

bandpass In optics, the portion of the spectrum which is transmitted through an optical system. In control systems, the disturbance frequency range over which the system has control authority.

bang-bang A servo control process that uses a square-wave control. When control is needed, the controller commands the opposite extreme point. Typically used in thermal control, but also in crude mechanical systems.

baud rate The rate of a serial communication data transmission, expressed in bits per second (from Émile Baudot, an early telegraph innovator).

B.C.E. Before the Common Era. For dates, equivalent to B.C.

beam splitter An optical device for dividing an incoming beam into two separate beams, one being transmitted and the other reflected. See also **dichroic**.

beam walk The displacement of the footprint of a light beam on an optical element as a function of the change of direction in the field of view. There is no beam walk at a pupil.

bias frame The readout of a CCD detector of zero integration time with shutter closed. The number of electrons registered per pixel must be subtracted from a science exposure, since they were not created by photons from the source.

bimorph mirror A type of deformable mirror. See **DM**.

binary star Two stars in orbit about their common center of mass.

birefringent Said of an optical material whose index of refraction has a different value in different directions.

bit A binary digit. In digital computing, the smallest unit of information. A bit can either be "on" or "off," represented as a "1" or a "0." Data processed by a computer is organized into larger groups such as bytes (8 bits).

blackbody A hypothetical perfect radiator which absorbs and reemits all radiation incident upon it. A blackbody has an effective emissivity of 1.

Blanco telescope An NOAO 4 m telescope on Cerro Tololo, Chile. It is a near twin of the Mayall telescope on Kitt Peak.

blank The substrate used for a mirror after it is made into the correct size and thickness, but before the optical figure is ground.

blind offset A telescope pointing procedure used for faint targets which consists of (1) very accurately predetermining the position of the target with respect to a nearby reference star (e.g., by measurement of a previously taken long-exposure image of the field), (2) pointing the telescope to the reference star, (3) centering the telescope on that star, and (4) offsetting the telescope by the predetermined target/reference-star vector.

blind pointing Pointing a telescope in a specific direction solely by using its attitude sensors or encoders.

blind spot The region of the sky near zenith where targets cannot be tracked with an alt-az mount because the required azimuth drive velocity is too high.

BOE Basis of Estimate. The justifications for arriving at a particular cost estimate, which include the estimating methods, approach taken, and prices used.

boiling time See **coherence time**.

BOL Beginning of Life. Term used to refer to the beginning of operation of a facility (especially in space).

Bol'shoi Teleskop Azimultal'nyi See **BTA**.

bonnette A combination of guiding head and field visualization, generally mounted at a telescope focus directly in front of the instrument (from the French for "eyepiece cup").

boresight In a telescope, the mechanical axis of the tube, which is near but not necessarily coincidental with the optical axis. See also **line of sight**.

borosilicate glass A low-expansion glass such as Pyrex (a Corning product).

boule From the French, "ball." In optics fabrication, an elementary volume of raw glass, typically about one meter in diameter. Large mirror blanks are sometimes made by cutting individual boules into hexagonal segments and fusing them.

boundary layer In atmospheric physics, the air layer near the ground where wind velocity increases from zero at the surface to its full value, which corresponds to external frictionless flow. The boundary layer extends to a height of roughly 1 km and is more properly referred to as the "planetary boundary layer." The layer nearest the ground, where thermal and friction effects are strongest and which is affected by surface roughness and small-scale topography, is called the "ground" or "surface layer." The layer above the planetary boundary layer, which can be affected by large-scale thermal effects and large scale topography, is called the "atmosphere boundary layer." For more details, see Chapter 12.

brassboard, breadboard An engineering hardware mock-up used to verify a design. A breadboard is cruder than a brassboard, the latter being implemented with specific components.

BRDF Bidirectional Reflectance Distribution Function. A function that characterizes light scatter off surfaces.

bright time See **dark time**.

BTA Bol'shoi Teleskop Azimultal'nyi. A 6 m aperture telescope of the Special Astrophysical Observatory on Mt. Pastukhova, Russia.

BTDF Bidirectional Transmission Distribution Function. A function that characterizes light scatter off transmissive optical elements (e.g., lenses and windows).

burn rate The monthly rate at which a contractor's funds are expended during the period of the contract.

bus The module containing the space support systems for a space observatory. See **SSM**.

byte A unit of information used in reference to computers and quantities of data. A byte consists of 8 bits (q.v.) and generally corresponds to a single character or number. See also **MB**.

$\boldsymbol{C_3}$ The C_3 coefficient is the square of the hyperbolic excess velocity, or velocity at infinity, and is used to describe a vehicle's orbital energy with respect to that required for escape. This is easier to understand by looking at the governing equation for a vehicle thrusting on an escape trajectory:

$$V_{\rm bo}^2 - 2\mu/R_{\rm bo} = V_\infty^2 = C_3$$

where $R_{\rm bo}$ is the distance from Earth center at burnout, $V_{\rm bo}$ is the burnout velocity, V_∞ is the velocity at infinity (hyperbolic excess velocity), and μ is the Earth's gravitational constant ($\mu = GM_{\rm Earth}$). From an energy perspective, the above equation is: kinetic energy at burnout + potential energy at burnout (always negative) = kinetic energy at infinity. For trajectories that do not escape Earth, such as a transfer trajectory to L2, the value of C_3 is negative.

C_n^2 Coefficient of the structure function which describes the statistical variation of the index of refraction in the atmosphere. Seeing is a function of the integral of C_n^2 along the optical path in the atmosphere.

CAD Computer-Aided Design. Computer techniques used in the design and drawing of mechanical systems.

CAIV Cost As an Independent Variable. A design in which project cost is allowed to vary when determining the optimal architecture.

calibration The determination of the relationship between values indicated by a sensor and the actual corresponding values. For an astronomical instrument, the procedures employed to remove the instrumental signature from the scientific data.

camera In astronomy, an instrument for recording telescopic images, consisting of the optics and a photosensitive detector.

Canada-France-Hawaii Telescope See **CFHT**.

Cassegrain An optical arrangement in a two-mirror reflecting telescope in which light is reflected by a convex secondary mirror to a focus near the primary mirror.

Cassegrain focus The final focus of a two-mirror "Cassegrain" optical system.

caustic zone In an optical system, the zone in which rays approaching focus intersect. When no aberrations are present, all rays intersect at the focus. In the presence of aberrations, however, they meet at different points. The larger the aberration, the greater the spread of these intersection points and the larger the caustic zone.

CCB Configuration Control Board. A board which approves or disapproves change requests for project implementation and procedures (but not changes to the scientific requirements). The project manager is normally the board chairman.

CCD Charge-Coupled Device. A solid state light detector that has replaced photographic emulsions as the primary recording medium for astronomical images in the visible. The recording portion of the chip is divided into discrete photosensitive elements (pixels).

CDR Critical Design Review. A design review to evaluate the complete design of a project.

C.E. Common Era. In dates, equivalent to A.D.

celestial equator A great circle of the celestial sphere 90° from the celestial poles.

celestial mechanics That branch of astronomy dealing with the motions and gravitational influences of solar system bodies.

celestial poles Points about which the celestial sphere appears to rotate; intersection of the celestial sphere with the Earth's polar axis.

celestial sphere An imaginary sphere of arbitrary radius upon which celestial bodies may be considered to be located, when seen from Earth.

central obscuration In an on-axis reflecting telescope, the part of the aperture that is blocked by the secondary mirror and baffle.

centroiding An image-processing technique for determining the "center of light" of a guide star.

Cerenkov radiation A luminous emission occuring when charged particles (e.g., cosmic rays) cross a material medium (such as an optical element) at a speed higher than the speed of light in that medium.

Cer-Vit Ceramic Vitrified. An ultralow-expansion glass ceramic produced by Owens Illinois in the 1970s; no longer in production (similar to Zerodur).

CFD Computational Fluid Dynamics. A numerical technique for analyzing the thermal and dynamic effects of the air surrounding bodies such as telescopes and enclosures.

CFHT Canada-France-Hawaii Telescope. A 3.6 m aperture telescope on Mauna Kea, Hawaii jointly operated by the National Research Councils in France and Canada and by the University of Hawaii.

CFRP Carbon-Fiber-Reinforced Plastic. A family of composite materials of carbon fibers in a polymer matrix that includes "graphite epoxy" (GrEp).

CGH Computer-Generated Hologram. A hologram used in the testing of aspheric optics.

Chandra X-Ray Observatory The Chandra X-Ray Observatory, formerly known as the Advanced X-Ray Astronomy Facility (AXAF), is a NASA observatory operating in the 0.1–10 keV band. Launched in 1999, it is named after the late Indian-American astrophysicist Subrahmanyan Chandrasekhar of the University of Chicago.

characterization A process for determining a sensor's output compared to a basic input. This is similar to a calibration but is less rigorous and not completely traceable.

chopping A technique for observing faint sources in the presence of a strong, varying sky background. It consists of rapidly alternating pointing between the source and an empty portion of the sky.

clean room A room or area where temperature, humidity, and concentration of airborne particulates is strictly controlled. Clean-room specifications are defined by various national and international standards (e.g., U.S. Federal Standard 209 and ISO EN 146611-1). Particulate concentration is generally defined as the number of suspended particles of a given size in a unit volume of air. In FED-STD-209, clean-room "class" is defined as the maximum number of particulates 0.5 μm or larger per cubic foot. A typical clean room for optics and electronics assembly, class 10 000, contains fewer than 10 000 particulates per cubic foot. See also **cleanliness level**.

cleanliness level An established maximum of allowable contaminants based on size, distribution, and quantity on a given surface area. Cleanliness levels are formally defined by standards, such as U.S. MIL-STD-1246, based on counts and sizes of particles deposited onto a unit area. See also **clean room**. Note that clean-room

class defines the maximum number of particulates per unit volume of air in a room, whereas *cleanliness level* categorizes the maximum number of particulates deposited on a given surface area (e.g., optical surface).

closed loop A broadly applied term relating to any system in which the output is measured and compared to the input, which is then adjusted to reach the desired output condition.

COBE COsmic Background Explorer. A NASA satellite that operated from 1989 to 1993 measuring the primordial background radiation.

CODE V An optical design ray-trace program developed and commercialized by Optical Research Associates.

cogging A condition in which a motor does not rotate smoothly, but steps or jerks from one position to another during revolution. Cogging is most pronounced at low motor speeds.

coherence length A parameter, represented by the symbol r_0, introduced by David Fried in 1966 to characterize atmospheric turbulence. In a beam affected by atmospheric turbulence, r_0 is the diameter of the area in the incoming wavefront where the rms of the phase fluctuation is 1 radian (i.e., within which the beam is essentially in phase).

coherence time In a light path affected by atmospheric turbulence, the time over which, at a given aperture point, the rms of the phase error difference is 1 radian. It is also referred to as the "Greenwood time delay." Its inverse is the Greenwood frequency. The coherence time is somewhat shorter than the average lifetime of an individual speckle (q.v.), also called "boiling time." At good observatory sites, the coherence time is on the order of 10 ms.

coherent light source A light source producing radiation in which all the emitted waves vibrate in phase (such as a laser).

cold stop In an infrared instrument, a stop, generally located at a pupil, which is cooled in order to minimize thermal radiation toward the detector.

collimated beam A beam of parallel rays.

collimation The process of aligning the optical system of a telescope to minimize aberrations at the focus.

collimator An optical element in an instrument producing a beam of parallel rays. Also, a system in optical shops used to simulate a point source at infinity in order to test telescope optics.

Columbus telescope See **LBT**.

coma An optical aberration in which the image of an off-axis point source is a comet-shaped (hence the name) blur.

commissioning The phase following construction (or launch) during which the capabilities of an observatory are demonstrated in its final operational configuration. During commissioning, both verification and validation tests are performed on the complete system to ensure that the observatory meets all its science requirements and is ready for operation.

conduction band The upper energy band in a semiconductor that is not completely filled with electrons. Electrons can conduct in a conduction band.

configuration management Technical and administrative action to monitor changes to project elements, obtain the necessary approvals, and disseminate the approved changes.

controller An electronic device in a feedback control system (hardware or software) that processes a signal to regulate a controlled variable.

corner cube See **retroreflector**.

coronagraph An optical system used to block the light of a star in order to permit the observation of the star's surroundings. Developed by Bernard Lyot in the 1930s for the observation of the Sun's corona, hence the name. Also used for the detection of faint sources very close to a bright star (e.g., low-mass companion, circumstellar disk, planets). It consists of a mask located in a focal plane to reduce the light of the star by occultation, followed by a stop in a pupil plane to block the light diffracted by the edge of the entrance aperture. This second stop is called a Lyot stop.

cosmic rays Charged particles of matter (not radiation), mostly electrons, protons, and helium nuclei, moving through the Galaxy at close to the speed of light. They are produced by stars, supernovae, etc.

cosmological window The spectral region around 3.5 μm where zodiacal light is minimal, potentially allowing the most sensitive observations of the cosmos beyond the solar system.

cosmology The study of the general nature of the universe in space and time.

COSPAR Committee on Space Research. A scientific committee of the United Nations established to encourage cooperative programs of rocket and satellite research. COSPAR is only concerned with scientific research and does not address technological problems.

cost plus fee A type of contract in which the contractor is reimbursed for all allowable costs and receives an additional percentage of those costs in fee.

coudé A French term meaning "bent," used to describe the series of flat mirrors on a ground-based telescope which fold the optical beam so as to keep the focus stationary as the telescope rotates. The term is also applied to the focus itself.

CPM Critical Path Method. A mathematical technique for analyzing and optimizing project schedules. Similar to PERT (q.v.).

critical path In project scheduling, the string of connected activities requiring the longest time for completion.

cryogenic Relating to low-temperature refrigeration and/or achieving, maintaining, and experimenting with low temperatures. Generally used for temperatures lower than 100 K (or at least lower than those achievable with thermoelectric coolers, which is about 200 K).

cryo-null-figuring (improperly called "cryofiguring") A figuring technique for mirrors operating at cryogenic temperatures wherein the mirror is figured at room temperature, tested at cryogenic temperature, then refigured at room temperature to correct (null out) the surface error determined during the test.

cryostat A vessel designed to keep its contents at a low (cryogenic) temperature. The external part is a dewar (q.v.) which eliminates conduction losses. To minimize losses via radiation, the cryogenic content is surrounded by reflective radiation shields at intermediate temperatures.

CSA Canadian Space Agency. An agency of the Federal Government of Canada.

CTE Coefficient of Thermal Expansion. The proportionality factor between the relative change of dimension of a material ($\Delta l/l$) and temperature.

CTIO Cerro-Tololo Inter-American Observatory. An NOAO observatory located on Cerro Pachón, Chile, which houses the Blanco 4 m telescope (q.v.).

curvature sensing A wavefront-error-sensing method invented by François Roddier, which consists of measuring the local curvatures of the wavefront and integrating them to determine the wavefront error.

CVD Chemical Vapor Deposition. A process in which solid substances are made by deposition over a substrate in a controlled atmosphere. The substrate can then be removed to leave a free-standing piece.

dark time The period in the lunar month when the Moon is less than a quarter full. "Bright time" is when the Moon is more than half-full; other nights are classified as "gray time."

DARPA Defense Advanced Research Project Agency. A U.S. DoD agency that promotes R&D in defense technologies.

DDD Displacement Damage Dose. Radiation-induced degradation of an electronic device due to displacement of nuclei from their lattice position in a material.

deadband The range through which an input signal, although introduced into a system, does not produce an observable response.

dead time The interval between the initiation of a change in the input and the start of the resulting observable response.

Decadal Survey A report by a committee of the U.S. National Academy of Sciences which recommends priorities to NASA and NSF for all federally funded projects in astrophysics. The committee meets every 10 years to make recommendations for the following decade (e.g., 2000–2010).

DEC See **declination**.

decibel (dB) A dimensionless number expressing a logarithmic measure of the ratio of two signal levels or two powers. By definition, the number of decibels related to two amounts of power P_1 and P_2 is

$$10 \log_{10} \left(\frac{P_1}{P_2} \right)$$

For example, 3 dB represent a power ratio of about 2, and 10 dB represent a power ratio of 10.

declination (also called δ or DEC) The angular distance on the celestial sphere measured along the hour circle passing through a celestial object. Measured from zero at the equator to $+90\,^\circ$ north and $-90\,^\circ$ south.

deformable mirror See **DM**.

deformation Also referred to as "strain." Dimensional change of a body produced by stress. The deformation is *elastic* if the deformation disappears when stress is removed. It is *permanent* if the deformation remains when stress is removed. The least stress that causes permanent deformation is called the *elastic limit.*

depth of focus The tolerance on the axial position of the detector relative to the best optical focus.

design review A formal, systematic examination of a design to evaluate its requirements and its capability to meet those requirements. See also **PDR** and **CDR**.

detector In optical astronomy, a device for recording images or spectra.

devitrification The process by which an amorphous substance (e.g., glass) converts to crystalline form (and, in the case of glass, loses its transparency).

dewar A double-walled vacuum vessel (thermos-bottlelike) for the storage of cryogenic materials or thermal isolation of cold-temperature equipment (e.g., detectors and cold stops in an infrared instrument). Named after its inventor, Joseph Dewar.

diameter-to-thickness ratio (also "aspect ratio") The diameter of a mirror divided by its thickness. Traditionally, a mirror is considered stiff for a 6:1 ratio and flexible for 15:1 ratio or greater. As shown by André Couder, this rule of thumb is completely wrong and should never be used to judge mirror stiffness. Stiffness is inversely proportional to D^4/t^2, not to D/t.

dichroic A thin-film interference coating that separates a light beam into two separate wavelength bands, (e.g., visible and infrared). See also **beam splitter**.

diffraction The deviation of light from rectilinear propagation when an incoming wavefront passes over the edge of an obstructing body (e.g., an opaque body in the beam itself, or the edge of an aperture). This phenomenon is a characteristic of the wave nature of light and also occurs with water and sound waves, as well as with atomic particles which show wavelike properties. When the various portions of the wavefront interfere at a point beyond the obstacle, the pattern formed is called a "diffraction pattern." The point spread function (q.v.) of an optical system is a particular diffraction pattern occurring at focus. Diffraction caused by obstructions in the aperture of a telescopes, such as a secondary mirror support vane, gives rise to "spikes" in stellar images.

diffraction grating An optical surface, transparent or reflecting, ruled with parallel grooves at precisely spaced distances. The active parts are not the grooves but the flat sections between them, which act like a large number of parallel slits. Light passing through (or reflecting from) these slits diffracts and interferes in a way which depends on wavelength, causing different wavelengths to be steered in different directions. The overall effect is similar to that of a prism, but the spectral dispersion, which is a function of groove spacing, can be much higher.

diffraction limit The finest detail that a perfect (aberration-free) optical system can discern in the absence of atmospheric turbulence. This limit, which is then only due to the wave nature of light (hence, to diffraction effects), is a function of the size and shape of the aperture and of the wavelength of light.

diffraction limited Term applied to a nearly perfect optical system in which aberrations (or seeing effects) are negligible; traditionally defined as having a Strehl ratio greater than or equal to 0.8 (Maréchal condition).

diluted aperture A telescope aperture which is not complete, but has a collecting area large enough and spatially distributed so as to fully sample the *uv* plane (q.v.). The aperture may be diluted because of missing segments in the primary segmented mirror of a single mount telescope, or because the system is an interferometric array composed of separate telescopes. The dilution factor is the ratio of the actual collecting area to the total area of the aperture. Dilution is typically 25% or higher. An incomplete aperture which does not fully sample the *uv* plane is referred to as a "sparse aperture." The dilution factor of a sparse aperture is typically 5% or less.

DIMM Differential Image Motion Monitor. An automatic device for measuring seeing, used in observatory site testing.

DIRBE Diffuse Infrared Background Experiment. A COBE (q.v.) onboard experiment.

dispersion The spreading of light as a function of wavelength as it passes through a transparent medium. The effect is due to the fact that the refractive index of transparent substances varies with wavelength. It is lower for long wavelengths (e.g., red) than for short ones (e.g., blue).

dither In a mechanical system, a useful oscillation of small magnitude introduced to overcome the effects of friction, hysteresis, or clogging. In astronomical observations, a small stepwise motion of the line of sight that is introduced during an observation to reduce (1) pixelization effects in digital detectors or (2) background fluctuations when working in the infrared.

DM Deformable mirror. A mirror whose figure can be deformed to compensate for wavefront errors. The two main types used in astronomy are (1) the piezostack mirror, composed of a thin glass plate supported by an array of piezostacks acting in piston fashion to deform the plate, and (2) the bimorph mirror, composed of a pair of piezoelectric wafers embedded with electrodes that act in shear to deform them (in a manner similar to the bimetallic effect).

DoD Department of Defense of the United States of America.

DOF Degrees of Freedom. For an element in a system, the number of ways that element can move.

dog and pony show Slang term for an informative briefing presentation, often for nonexperts, as opposed to a working-level session.

drift Undesired change in an input-output relationship over a period of time.

DRM Design Reference Mission. A representative set of mission activities used in simulations to validate the hardware and operational software of space missions prior to launch.

DRP Design Reference Program. A strawman scientific program used to determine the optimal set of observatory parameters (spatial resolution, sensitivity, wavelength range, lifetime, etc.) that globally satisfies a scientific goal at its most general level.

DSN Deep Space Network. An international network of large antennas that supports interplanetary spacecraft missions and, occasionally, radio astronomy observations.

The DSN currently consists of three deep-space communication facilities placed approximately 120° apart around the world: at Goldstone, California, near Madrid, Spain, and near Canberra, Australia. This placement permits constant communication with spacecraft as the Earth rotates. The DSN is managed and operated for NASA by the Jet Propulsion Laboratory.

duty cycle For a repetitive cycle, the ratio of on time to total cycle time. Duty cycle (%) = [On time/(On time + Off time)] × 100%.

dynamic range Ratio of the largest to the smallest signal level a circuit or detector can handle (expressed in dB for electronic systems).

E6 A low-expansion glass made by the Ohara Corporation in Japan.

échelle grating From the French "échelle," ladder. A grating with short steep groove facets facing toward the light. Thus, the angle of incidence for optimum efficiency (blaze angle) is high, greater than 45°.

échelle spectrograph A spectrograph which uses an échelle grating. Associated with the use of high orders, an échelle spectrograph allows high-resolution spectra to be obtained. Since it operates in several diffraction orders, it can cover a large spectral domain, provided that a cross-dispersing element is added to separate the overlapping orders and permit stacking onto a two-dimensional detector array.

ecliptic The mean plane of Earth's orbit around the Sun.

edge sensor A device for determining the position of the edge of a mirror segment relative to adjoining segments.

effective focal length The product of the aperture diameter by the focal ratio of the converging beam at the focal position in use. For a single mirror, the effective focal length is the same as the focal length of the mirror.

eigenfrequencies From the German, eigen, "proper," "own." Characteristic vibration frequencies of a system in the absence of externally applied excitations. The lowest frequency is called natural or fundamental frequency.

elastic limit See **deformation**.

electromagnetic compatibility (EMC) The ability of communication and electronic equipment to operate together without suffering or causing unacceptable degradation because of unwanted electromagnetic radiation. This is especially important in space systems and instrument detectors.

electromagnetic waves (or **radiation**) A combination of oscillating magnetic and electric fields spreading in wavelike fashion through space at a constant speed of about 300 000 km/s. They are characterized by their wavelengths and extend from gamma-rays (very short wavelengths, $\sim 10^{-8}$ m) up to radio waves (very long wavelengths, several hundreds of meters).

electro-optics The branch of optical science dealing with the effects of applied electrical voltage on the optical properties of materials.

elevation See **altitude**.

enclosure In an observatory, the structure/building surrounding and protecting a telescope. Also called a "dome" when approximately hemispherical in shape.

encoder A measuring device that converts mechanical motion into encoded electronic signals.

engineering model An advanced prototype used during the development phase to demonstrate the maturity of a design and prepare the final specifications and drawings. See also **prototype** and **flight model**.

EOL End of Life. Term used to refer to the expected end of operation of a facility (especially in space).

ephemeris A table of predicted positions of bodies in the solar system or of a spacecraft (plural: ephemerides).

epitaxy The growth of crystals on a crystalline substrate that mimic the orientation of that substrate (used in solid-state detectors).

epoch A particular instant of time used as reference in the determination or measurement of celestial object positions. A catalog for the equinox 2000, for example, lists positions valid for that date (or epoch). To obtain positions at some other epoch, the effects of proper motion, nutation, and stellar aberration must be included in calculations. A full description of an object's position must include both the epoch of the measurement and the equinox (q.v.) to which it is referred.

equatorial mounting A mounting for a telescope, one axis of which is parallel to the Earth's axis, so that a motion around this axis can compensate for the Earth's rotation.

equinox Either of the two points (vernal, autumnal) on the celestial sphere where the ecliptic (the apparent path of the Sun on the sky) intersects the celestial equator. Due to precession, this point moves over time, so positions of stars in catalogs are usually referred to a given "equinox." Currently, the standard equinox is that of Julian year 2000 and is denoted by the prefix J (i.e., J2000). The previous common standard was for J1950 and the differences in an object's position between equinoxes 1950 and 2000 may amount to several arcminutes. Care must be taken to distinguish the *equinox* value, which relates to the position of objects in a time-dependent coordinate system, from the *epoch* value, which refers to the position of a specific object at a given date expressed in that coordinate system. The latter will be different due to effects such as stellar aberration and proper motion.

error, random In a sensor, the amount of error remaining after calibration. See also **error, systematic**.

error, systematic In a sensor, a repeatable error that either remains constant or varies according to some law. This type of error can be eliminated by calibration. The residual error is referred to as "random."

ESA European Space Agency. An intergovernmental organization with a mission to provide and promote the exploitation of space science, research and technology, and space application for exclusively peaceful purposes. It has 15 European member states: Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Italy, Norway, the Netherlands, Portugal, Spain, Sweden, Switzerland, and the United Kingdom. Canada takes part in some projects under a cooperation agreement.

escape velocity The minimum velocity required to remove an object from a given point in a gravity field (e.g., the surface of the Earth) to infinity, without the imposition of a thrust at a later time.

ESO European Southern Observatory. A major observatory operated by Belgium, Denmark, France, Germany, The Netherlands, and Sweden, with sites at La Silla and Paranal in Chile.

étendue From the French, "expanse." In astronomical optics, the product of the solid angle under which a source is seen by the area of the primary mirror of the telescope. This quantity remains constant throughout the optics up to the detector, provided that all diaphragms on the light path are properly sized. The larger the étendue, the larger the field of view that can be accommodated. Commonly used as a figure of merit for the useful field of view of a spectroscopic device.

Fabry-Perot An interferometer, named for its two inventors (Charles Fabry and Alfred Perot), composed of two parallel, high-reflectivity plates separated by a gap. An incoming plane wavefront is multireflected inside, producing the equivalent of a narrow-band filter for wavelengths whose wavefronts are in phase. By slightly changing the gap, the corresponding peaks are shifted. This compact device can be placed in front of a camera for large-field imaging of emission lines.

factor of safety In structural analysis, the ratio of the load that causes failure to the service load.

failure analysis The systematic examination of an item or its diagram(s) to identify and analyze the probability, causes, and consequences of potential and real failures.

far infrared The part of the infrared spectrum from 30 μm to $\sim$ 500 μm. See also **infrared**.

fast Fourier transform A computer algorithm devised by James Cooley and John Tukey in 1967 for the numerical computation of the Fourier transform. This extremely efficient algorithm has revolutionized many fields and, in particular, optics, in that it allows the PSF of optical systems with wavefront errors and complex apertures to be readily determined.

fast optics An optical system with a small f-ratio (imported from the terminology of photography).

fatigue The weakening and eventual failure of a material due to repetitive stresses *within* its elastic range. It is caused by the gradual propagation of microcracks generated by internal defects. Fatigue should not be confused with the permanent deformation (and potential failure) that occurs when a material is stressed *beyond* its elastic limit.

fault tolerant Referring to an electronic design in which a single-event upset or the failure of a single piece of hardware does not significantly degrade the system's performance.

feedback A signal transferred from the output back to the input for use in a closed-loop system.

FEM Finite Element Model. A mathematical model of a structure made of two- or three-dimensional subdivisions called "finite elements." Used in the computer-based calculation of stresses and deflections under load. See also **NASTRAN**.

field derotator A device that compensates for field rotation at the focal plane of alt-az telescopes.

field of regard The maximum possible angular pointing ability of a telescope (as opposed to "field of view," which is the field accessible with a given pointing).

field of view The region of the sky visible to a telescope (or detector) at any one time. See also **field of regard**.

figure The exact shape of the surface of a mirror or other optical component.

figuring The process of grinding and polishing a mirror blank in order to give it a specific geometric shape.

filter An optical device which removes portions of the spectrum of an incident beam of light. Colored-glass filters work by selective absorption and transmission. Interference filters work by selective reflection and transmission within thin coating layers.

fine guiding sensor An instrument in the focal plane of a space telescope used for fine tracking by centroiding on guide stars in the telescope's field of view. A device used for coarse tracking which has its own optical system is called a star tracker (q.v.).

firm fixed price A type of contract in which the contractor receives for his efforts a fixed price, which is agreed upon in advance. See also **cost plus fee**.

FIRST Far Infrared and Submillimetre Telescope (renamed the Herschel Space Observatory). A 3 m ESA space observatory mission operating in the 85–900 μm range, with an anticipated launch in 2007.

flat field An image taken with a light source having a flat (uniform) energy distribution, (e.g., a uniformly illuminated screen). This is used to calibrate the response of individual pixels in a two-dimensional detector.

flight model A realization of a system using design, processes, and components in all ways identical to those of the final product and which undergoes testing in simulated space environment. The flight model may be used as a spare.

fluence In radiation effects, the total number of particles incident on a sample (i.e., integration of flux over irradiation time).

flux The rate at which energy crosses a unit area of a surface in a transverse direction.

focal ratio (f-ratio) The ratio of the effective focal length of an optical system to the diameter of the aperture.

fold-flat mirror A flat mirror used to change the direction of an optical beam (e.g., in a coudé configuration, or to reduce the overall dimensions of an instrument by folding the beam).

Foucault test Also called "knife-edge test." A test developed by Jean Bernard Foucault for the qualitative evaluation of figure errors in a mirror. It consists of using a straight edge (knife edge) to block parts of the rays converging near focus. Figure errors appear on the illuminated mirror as areas of variable intensity.

Fourier transform A mathematical operation which, when applied to a function $f(x)$ of the variable x, generates the function $F(u)$ with $u = 1/x$. For a time-dependent signal, u is a frequency, and thus $F(u)$ represents the distribution of

frequencies present in the signal. The transformation can be generalized to a two-dimensional function, $f(x, y)$. If x and y are space dimensions, $f(x, y)$ describes a surface and u and v are in units of spatial frequencies. The Fourier transform of F is f. An efficient digital implementation of the transform is the "fast-Fourier transform," or FFT (q.v.).

Fourier transform spectrometer (FTS) A Michelson interferometer with a movable mirror. By scanning the movable mirror over some distance, an interference pattern is produced that encodes the spectrum of the source (it is its Fourier transform). Fourier transform spectrometers offer a flexible choice of resolution and a multiplex advantage over grating spectrometers since they cover the total spectrum in a single data acquisition, but have a multiplex disadvantage for photon noise.

FOV Field of View (q.v.).

FPA Focal Plane Assembly. In an instrument, the assembly containing the detector and associated elements (window, cooling finger, connectors, etc.).

f-ratio See **focal ratio**.

frequency The number of cycles over a specified time period during which an event occurs; normally expressed in Hertz, or cycles per second.

frequency domain When the Fourier transform is applied to a time-dependent signal, $f(t)$, or to the distribution of a signal on a surface, $f(x, y)$, the resulting function, F, is transposed in frequency. Since the variables, t or x, y, are only defined on a given domain, the frequency variables are only defined over a limited range called the "frequency domain" of the signal. The two representations, F and f, carry the same information expressed in different ways.

frequency response The frequency-dependent characteristic that determines the phase and amplitude relationship between a system's sinusoidal input and output.

Fried parameter (r_0) Also called "Fried length" or "coherence length" (q.v.).

fringe The light and dark bands caused by interference of light waves.

FSM Fine Steering Mirror. A small mirror near the focus to correct for line-of-sight jitter and drift. Also called "Fast Steering Mirror" in some military applications, where the mirror is driven at up to kHz rate.

Full width at half-maximum (FWHM) The diameter of the image of a point source at half the peak intensity. Used as a measure of image quality.

FUSE Far-Ultraviolet Spectroscopic Explorer. A NASA satellite for high-resolution observations at far-UV wavelengths; launched in 1999.

fused quartz A type of glass made by melting quartz sand, cooling it rapidly to the annealing temperature, maintaining it there for hours, and then cooling it slowly to avoid devitrification. See also **fused silica**.

fused silica An amorphous silica glass made by flame hydrolysis. Fused silica and fused quartz are essentially the same material, but fused quartz has some short-range order — a residual of the original crystal structure. The impurities are also slightly different: fused quartz has metallic impurities that cause UV absorption and some fluorescence, whereas fused silica has hydroxyl ions (a by-product of flame hydrolysis) that cause infrared absorption. Physical properties (e.g., CTE) are virtually the same.

FWHM Full Width at Half-Maximum (q.v.).

gain For a linear control system or element, the ratio of the amplitude of a steady-state sinusoidal output relative to a causal input.

Galileo Galilei Italian physicist and astronomer who, in 1609, was the first to develop and use the telescope for astronomical purposes.

gamma-rays Photons with the highest energies, in excess of 10^5 eV, and highest frequencies, above 10^{20} Hz.

Gantt A scheduling chart developed by Henry Gantt in 1916, where project activities are plotted against a time line. These charts are used for planning, scheduling, and then recording progress.

Gaussian distribution The Gaussian (or "normal") distribution describes the behavior of a continuous random variable. The probability density is

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2} ,$$

where μ is the mean and σ is the standard deviation. In this distribution, 68.3% of the events fall in the range of $\mu \pm \sigma$, 95.4% fall within $\mu \pm 2\sigma$, and 99.7% fall within $\mu \pm 3\sigma$.

gegenschein A diffuse glowing area on the ecliptic in the direction opposite the Sun, caused by sunlight backscattering from zodiacal dust.

Gemini observatory An international partnership that operates twin 8 m telescopes, one on Hawaii's Mauna Kea and the other on Chile's Cerro Pachon. The partners include the United States, the United Kingdom, Canada, Chile, Australia, Brazil, and Argentina. AURA manages Gemini under the auspices of an international board and the U.S. National Science Foundation.

GEO Geostationary Earth Orbit. See **geostationary orbit**.

geostationary orbit A geosynchronous orbit which is circular and has zero inclination. The geostationary orbit is at an altitude of 36 000 km. A geostationary satellite remains stationary over the same location on Earth.

geosynchronous orbit Any orbit about the Earth which has a period of rotation equal to that of the Earth, and in the same sense. This orbit can be circular or elliptic.

glass ceramic A material composed of a glassy matrix within which microscopic crystals have precipitated. Such a material is made by fusion and cooling to an amorphous solid, which is subsequently heated to develop the crystal phase. Nucleating agents are used to control the degree of crystallization.

glow discharge A method for cleaning optical surfaces prior to coating, which consists of bombarding that surface with ions.

GMT Greenwich Mean Time. Identical to universal time (q.v.).

GO Guest Observer. Guest observers are astronomers who use instruments on spacecraft to make scientific observations, but who are not part of the original team that planned and built the spacecraft and instruments. See **PI**.

Golay configuration A particular configuration of a diluted aperture system where the subapertures are located so as to provide near-uniform and nonredundant coverage of the *uv* plane (q.v.). Such configurations with, for example, 6, 9, or 12 subapertures are referred to as Golay 6, Golay 9, or Golay 12. Named after M.J.E. Golay, who studied such systems (see Ref. [17] in Chapter 1).

GPS Global Positioning System. A set of 24 U.S. Air Force satellites used for determining position and altitude on or near Earth with an accuracy of about 10 m or better. The system also provides time with nanosecond accuracy.

Gran Telescopio Canarias See **GTC**.

gravity gradient Refers to the gradient in the approximately spherical gravity field around a celestial body. Unless counteracted, the gravity gradient around the Earth forces spacecraft to align themselves with their principal inertia axis along the local vertical.

gray time See **dark time**.

Greenwood frequency The inverse of the coherence length (q.v.).

Gregorian A two-mirror telescope combination with a concave secondary mirror.

GrEp Graphite Epoxy. See **CFRP**.

grism Contraction of grating + prism. A dispersing device composed of a transmission grating ruled or glued onto the surface of a prism. The prism deviation compensates for the grating dispersion angle, such that the output beam remains aligned with the input beam.

GSFC Goddard Space Flight Center. A NASA center in Greenbelt, Maryland.

GTC Gran Telescopio Canarias. A 10.4 m aperture telescope being built at the Roque de los Muchachos Observatory, La Palma, Canary Islands.

guide star catalog See **Hubble Space Telescope guide star catalog**. See also **Hipparcos catalog** and **Tycho catalog**.

gyroscope A rapidly spinning wheel which responds to an impressed torque by changing its angular momentum in magnitude and direction; used to sense direction changes.

Hale Telescope A 5 m telescope of the Palomar Observatory, California, owned and operated by the California Institute of Technology. This optical telescope, designed in the 1930s and completed in 1949, incorporated a number of technological innovations including a lightweighted, low-thermal-expansion primary mirror, a Serrurier truss, a horseshoe mount, hydrostatic bearings, aluminum-coated mirror, and an automated dome tracking system. Scientifically extremely successful, the Hale telescope remained the world's largest for three decades. It is named in honor of George Ellery Hale, an American astronomer who was the main force behind its construction as well as that of the pacesetting 60 inch and 100-inch telescopes on Mt. Wilson.

Harlan Smith Telescope A 2.7 m telescope of the McDonald Observatory on Mt. Locke, Texas.

health and safety For a ground observatory or a space mission, refers to the monitoring and trending of critical engineering parameters to verify that all systems

are functioning properly, are within their environmental ranges, and that there is no predictable risk of failure or damage.

Hertz (Hz) The unit of frequency, defined as one cycle per second.

HET Hobby-Eberly Telescope (q.v.).

hexapod A particular mechanical system with six actuated legs used to position and orient a body in all of its six degrees of freedom. Also called a "Stewart platform" after D. Stewart who first developed it for flight simulators. The design is unpatented and in the public domain.

HgCdTe Chemical abbreviation for mercury cadmium telluride, used in infrared detectors.

HIP Hot Isostatic Pressing. A technique used in the consolidation of powdered materials, particularly beryllium.

Hipparcos An astrometry satellite of the European Space Agency which operated from 1989 to 1993. The pronunciation of the acronym, standing for HIgh-Precision PARallax COllecting Satellite, is close to Hipparchus, the name of an early Greek astronomer. This observatory permitted the measurement of the position of more than 1 million stars with an accuracy of $0.02''$ to better than $0.001''$. See also **Hipparcos catalog** and **Tycho catalog**.

Hipparcos catalog A star catalog based on data obtained by the Hipparcos satellite. It supplies the positions and photometry of about 118 000 stars with an accuracy of about 0.7 mas and 0.0015 magnitude, respectively. The limiting magnitude of the catalog is about 12.4 in V. See also **Tycho catalog**.

Hobby-Eberly Telescope A 10 m fixed-elevation telescope at the McDonald Observatory in Texas.

HOE HOlography Element. A holographic grating patch used for phasing segmented-mirror systems.

honeycomb mirror A mirror consisting of thin front and back sheets sandwiching a honeycomb structure.

Hooker Telescope A 2.5 m telescope at the Mt. Wilson Observatory, California. This pace-setting reflecting telescope, completed in 1917, was responsible for a number of advances in astronomy, including the discovery of the expansion of the universe.

hour angle Angular distance on the celestial sphere measured westward along the celestial equator from the meridian to the hour circle passing through a celestial object.

hour circle A great circle on the celestial sphere that passes through the celestial poles.

Hubble Space Telescope guide star catalog The all-sky catalog of guide stars up to magnitude 14.5 and with an accuracy of about 1 arcsecond, established for the operation of the Hubble Space Telescope.

HST Hubble Space Telescope. A 2.4 m optical space telescope developed by NASA and the European Space Agency and launched in 1990. Named after Edwin P. Hubble, the American astronomer who discovered the expansion of the universe.

Hubble Space Telescope See **HST**.

hunting An undesirable oscillation which continues for some time after an external stimulus has disappeared.

hydrostatic bearing A bearing system using oil under pressure to support heavy rotating or sliding loads with essentially no friction.

hysteresis An undesirable property of a mechanical or electrical system wherein output is dependent, not only on the value of the input, but also on the direction of the movement or current.

IAU The International Astronomical Union. The IAU is an organization founded in 1919 to promote and safeguard the science of astronomy through international cooperation. It has over 8300 individual members and 66 adhering countries.

ICD Interface Control Document. A document defining the interfaces between subsystems. A draft is typically presented at PDR and the final version at CDR. See also **IRD**.

IEEE (pronounced Eye-triple-E) Institute of Electrical and Electronic Engineers. A professional association of more than 350 000 individual members in 150 countries which organizes conferences, publishes technical documentation, and establishes standards in domains such as computer engineering, telecommunications, electric power, and aerospace and consumer electronics.

image For an optical system, a point-to-point mapping of a luminous object located in one region of space (the object space) to another region of space (the image space).

image quality A qualification of the image of a point source supplied by an optical system. Traditionally measured by the angular size of the image (e.g., FWHM of the core), the energy contained in a given diameter, or the Strehl ratio.

image space The region downstream of an optical system, where the image is formed.

incentive contract A contract of either a fixed-price or cost-reimbursement nature, with a special provision for adjustment of the fixed price or fee as a function of the performance of the contractor (schedule compliance, cost containment, technical performance, etc.).

incoherent Denotes the lack of a fixed-phase relation between two electromagnetic waves.

index of refraction For a given wavelength, the ratio of the velocity of light in a vacuum to the velocity of light in a refractive material. It is a measure of the ability of an optical material to refract light. The denser the material, the higher the index.

inertial reference frame A frame which is not accelerating. In classical mechanics, the Sun is considered nonaccelerating with respect to the fixed stars, establishing a true inertial frame.

infrared The wavelength region between the visible and the shortest radio waves (i.e., microwaves). Infrared is usually divided into three spectral regions: near, mid- and far infrared. The boundaries between these three regions are not fully agreed upon but are generally taken as 0.7–5μm, 5–25μm, and 25–500μm, respectively. The region between 500 μm and 1 mm, sometimes considered part of the infrared, is commonly referred to as "submillimetric."

infrared cirrus Patches of interstellar dust which emit in the infrared and resemble cirrus clouds in infrared sky surveys.

Infrared Telescope Facility See **IRTF**.

InSb Indium antimonide. A material used in infrared detectors.

intensity In optics, the light power per unit area transverse to the direction of propagation.

interface control document See **ICD**.

interface requirements document See **IRD**.

interference The constructive and destructive superposition of two wavefronts with different phases. In an optical testing interferometer, the two wavefronts are produced by the reference surface and the test sample surface.

interference filter An optical filter with multilayered coatings selected to remove specific wavelength bands by destructive interference.

interferometer In optical testing, an instrument that employs the interference of light waves to measure wavefront errors. In astronomy, two or more telescopes that combine their signals from the same source to create interferences which permit the determination of direction and size of the observed object and also limited imaging. The spatial resolution of an interferometer is that of a single telescope with a diameter equal to the largest separation of the individual telescopes.

IPSRU Inertial Pseudo-Stellar Reference Unit. A device that provides an inertially stable light beam which can be tracked by an optical system in a spacecraft to maintain stable pointing.

IRAD Internal Research And Development (also IR&D). Company-funded technical research and development activity that is not strictly required in the performance of a contract.

IRAS Infrared Astronomical Satellite. A joint project of NASA, the Netherlands, and the United Kingdom. Launched in 1983, IRAS carried out an infrared survey of the entire sky for 10 months, before its liquid helium coolant became exhausted.

IRD Interface Requirements Document. A document defining the interface requirements between subsystems. A draft is normally presented for approval at PDR.

IRTF Infrared Telescope Facility. A 3 m telescope on Mauna Kea, Hawaii, operated for NASA by the Institute for Astronomy, University of Hawaii.

Isaac Newton Telescope A 2.5 m telescope at the Roque de los Muchachos Observatory on La Palma, Canary Islands.

ISO Infrared Space Observatory. A cryogenically cooled 60 cm infrared space telescope operated by ESA from November 1995 to May 1998 at wavelengths from 2.5 to 240 μm.

isoplanatic patch The angular region in which the turbulence characteristics of the atmosphere remain nearly constant. Formally, the angular distance between two beams arriving at a given aperture point, over which the rms of the phase error difference is 1 radian.

isostatic press The consolidation of a powdered material by application of pressure at ambient (cold isostatic press) or high temperature (hot isostatic press).

isotropic Having the same properties in all dimensions.

IUE International Ultraviolet Explorer. A space telescope developed jointly by NASA, ESA, and the United Kingdom for observations at UV wavelengths. IUE, which operated in geosynchronous orbit from 1978 to 1996, was one of the longest-lived satellites ever.

James Webb Space Telescope See **NGST**.

Jet Propulsion Laboratory See **JPL**.

jitter Spurious, unpredictable movement of the line of sight.

JPL Jet Propulsion Laboratory. A semiautonomous NASA center managed by the California Institute of Technology in Pasadena, California. JPL was the center of U.S. rocket development in World War II. Today, it is the focus of NASA's exploration of the planets.

J-T Joule-Thompson effect or Joule-Thompson cooler. A J-T cooler is a cryogenic cooler that employs the expansion of a gas through an orifice to produce a cooling effect.

Julian date (JD) The interval of time in days and fraction of days since January 1, 4713 B.C.E., Greenwich noon. Contrary to common belief, the name "Julian" does not refer to Julius Caesar, the Roman emperor. The system was proposed in 1582 by the Italian mathematician Joseph Scaliger, who named it in honor of his father, Julius Caesar Scaliger. The year 4713 was selected somewhat arbitrarily, but thought to be early enough to include all historical events and all precisely recorded astronomical phenomena.

Julian year A period of exactly 365.25 days which serves as a basis for the Julian calendar.

Kanigen A coating process patented by Electro-Coatings of Iowa, Inc. using a nickel-phosphorous alloy to improve corrosion resistance, polishability, hardness and coat adhesion of metals such as aluminum and beryllium.

KAO Kuiper Airborne Observatory. An infrared observatory consisting of a 90 cm Cassegrain telescope mounted in a Lockheed C-141 airplane flying at an altitude of 12 000 m. The observatory was operated by NASA from 1974 to 1995, at the rate of about 70 nights per year.

Karhunen-Loeve transformation An orthogonal representation of a wavefront or an image, similar to the Zernike decomposition.

Keck telescopes A pair of 10 m telescopes on Mauna-Kea, Hawaii. The observatory is operated by the California Institute of Technology, the University of California, and NASA. The Keck I telescope began science observations in 1993, and Keck II in 1996.

kickoff meeting The initial meeting held to discuss the organization and plans for a new phase of a project.

kinematic mount A mounting system which does not constrain more than the six rigid-body degrees of freedom of the supported body. Such a mount avoids inducing stresses in the supported body.

knife edge In a telescope, a thin member used to support the secondary mirror (also called a "vane," q.v.). Also, the blade used in a Foucault test (q.v.).

knife-edge test See **Foucault test**.

KPNO Kitt Peak National Observatory, part of the National Optical Astronomy Observatory (NOAO). KPNO operates the 4 m Mayall and 3.5 m WIYN telescopes on Kitt Peak, Arizona.

Lagrangian points Points in the space around a system of two large bodies (e.g., Sun-Earth, Earth-Moon) where a small third body will remain in a fixed position relative to the other two. Named after Joseph Louis Lagrange, who first studied these points and who showed that five exist for each such system. Two are stable (L4 and L5), the other three are metastable. In the Sun-Earth system, the two points which are relatively close to Earth are the L1 and L2. Both are on the Earth-Sun line, the L1 point at 236 Earth radii sunward of Earth and the L2 point at a similar distance on the night side.

laminar flow Flow without vortices or turbulence.

LAMOST Large sky Area Multi-Object fiber Spectroscopic Telescope. A 4 m Schmidt telescope being built at the Beijing Astronomical Observatory in Xinglong, China.

LAMP Large Active Mirror Program. A DoD-sponsored program from the late 1980s for the development of a 4-meter, actively controlled, segmented mirror for use in a space-based laser weapon.

lap A tool in the form of a disk charged with abrasive used in polishing mirrors.

lapping The operation of grinding, figuring, or polishing a mirror using a revolving circular lap supplied with an abrasive powder suspended in water.

Large Binocular Telescope See **LBT**.

Large Deployable Reflector (LDR) A NASA concept from the 1980s for a 30-meter aperture telescope dedicated to far-infrared and submillimeter observations from space.

Large Zenithal Telescope See **LZT**.

laser An acronym of Light Amplification by Stimulated Emission of Radiation. A device that produces highly amplified and coherent visible or infrared radiation.

laser star An artificial star created by a laser beam for use in the correction of atmospheric seeing.

LBT Large Binocular Telescope (formerly Columbus Project). A set of two 8 m telescopes sharing the same alt-azimuthal mount. The LBT is being built on Mt. Graham in Arizona by the Mt. Graham International Observatory, the main partners of which are the University of Arizona, Italy and the Research Corporation.

learning curve The reduction in cost per unit as more such units are produced.

LEO Low Earth Orbit. An Earth-centered orbit at an altitude of between 300 and 500 nautical miles (i.e., within the first Van Allen belt).

level of effort Effort of a general or supportive nature with no firm commitment to produce definite products or results. Often used to refer to a constant number of personnel assigned to a given program for a specified period of time.

LGS Laser Guide Star. See **laser star**.

LHe Liquid Helium. Its boiling point at 1 atmospheric pressure is 3.2 K.

libration Oscillation of a body in space about a point of equilibrium (e.g., around a Lagrange point).

Lick Observatory A University of California observatory located on Mt. Hamilton, California.

life cycle The total life span of a system, commencing with concept formulation and extending through operation and eventual retirement of the system.

life cycle cost (LCC) The total cost of a system over its complete life cycle. LCC includes the cost of development, acquisition, operation, maintenance, and, when applicable, disposal.

light bucket A slang term for a large-aperture telescope operating in a mode where geometrical aberrations and phase errors have not been minimized.

line of sight (LOS) The direction on the sky corresponding to the center of the field of the telescope. When there is no image-compensation system, this usually coincides with the optical axis. The LOS is not necessarily the same as the boresight, which is the mechanical axis of the telescope.

LN2 Liquid Nitrogen. Its boiling point at 1 atmospheric pressure is 77.4 K

LN2 temperatures Temperatures associated with the use of liquid nitrogen, generally between 72 and 82 K.

load path The region in a structure with the highest concentration of stress.

long-lead part A part, component, or subassembly with a long delivery time compared to the program's overall schedule.

LOS Line Of Sight (q.v.).

Lyot stop A stop limiting the beam at the exit pupil in such a way as to prevent the detector from seeing any surface preceding the stop other than the optics itself. Used in coronagraphs (q.v) and as a cold stop (q.v.) in infrared instruments. Named after Bernard Lyot, who first used it.

LZT Large Zenith Telescope. A 6 m telescope with a fixed vertical optical axis using a liquid mercury mirror. The telescope is being built by the University of British Columbia in Vancouver, Canada.

Magellan I and II Two 6.5 m telescopes of the Las Campanas Observatory, on Cerro Manqui, Chile. The Magellan Project is a collaboration among the Universities of Arizona and Michigan, Harvard, and MIT. The first of the two telescopes has been in operation since 2000, and the second one since 2002.

magnetic storm A large-scale disturbance of the Earth's magnetosphere, often initiated by the arrival of a plasma cloud originating in the Sun. Such storms can cause severe disturbances to spacecraft.

magnetic torquer An attitude-control or momentum-dumping device on spacecraft, in which an electromagnetic coil interacts with the Earth's magnetic field to provide torque.

magnetosphere The region surrounding Earth or another planet where the magnetic field of that planet tends to exclude the solar wind.

magnification The magnifying power of an optical system can be described in two ways: linear and angular. Linear magnification is the ratio of the size of the object to the size of the image. Angular magnification is the ratio of the angular size of the object as seen through the instrument to the angular size of the object as seen without it. In astronomical telescopes, the object is at infinity for all practical purposes, and only angular magnification is applicable.

magnitude A logarithmic unit of brightness used for stars and other celestial objects. The fainter the star, the greater the magnitude.

Maksutov-Cassegrain telescope See **Schmidt-Cassegrain telescope**.

Maréchal condition A condition proposed by André Maréchal for the practical definition of diffraction-limited optical systems, namely a Strehl ratio greater than or equal to 0.8.

mas milliarcsecond.

master schedule The master schedule for a project, showing key milestones and critical tasks over the full duration of design and implementation phases.

Max Planck Institute See **MPI**.

Mayall telescope A 3.8 m telescope at the Kitt Peak National Observatory, Arizona.

MB Abbreviation for megabyte, a data unit equal to approximately 1 million bytes (1 048 576 bytes exactly). Not to be confused with Mb, the abbreviation for megabit.

meniscus mirror A mirror which is solid (not lightweighted), very thin (e.g., in the 10–20 cm range for 8 m in diameter), and typically has a back face parallel to the front face. For ground telescopes, meniscus mirrors require a large number of active supports to maintain their shapes.

meridian A great circle passing through the celestial poles and through the local zenith.

meteorite A meteoroid that survives passage through the atmosphere and strikes the ground.

meteoroid A small rocky or metallic bodies in interplanetary space. Meteroids have velocities of several tens of kilometers per second. When they enter the Earths atmosphere, the friction of their passage produces a brief luminescent trail called a meteor (popularly called a shooting star). The great majority of meteorites are fragments of asteroids, ranging in size from millimeters up to about 15 cm (very exceptionally). Larger bodies (> 10 m) are called asteroids. See also **micrometeoroid**, **meteorite**, and **orbital debris**.

microdensitometer A device for measuring the optical density of minute areas on a photographic plate (e.g., star images).

micrometeoroid A meteoroid with a diameter of less than 0.1 mm. These are too small to cause a luminous effect when entering the Earths upper atmosphere.

microthermal fluctuations Temperature fluctuations in the atmosphere, at the origin of "seeing."

microwaves The part of the electromagnetic spectrum between the infrared and short-wave radio wavelengths, i.e., approximately 1 mm to 30 cm in wavelength. See also **infrared**.

mid-infrared The region of the infrared spectrum between 5 and $\sim$ 30 μm. See also **infrared**.

MIDEX Medium-class Explorer. A medium-sized (cost <$140M) NASA mission.

Mie scattering The scattering of light caused by particles with dimensions on the order of the wavelength of light.

mil specs Short for U.S. military specifications. Detailed specifications defining materials, processes, and test procedures for military contracts.

milestone A significant event in a project, used as a monitoring tool for assessing progress.

mirror blank See **blank**.

mirror cell The mechanical and structural assembly supporting a mirror.

mirror substrate See **blank**.

MLE Maximum Likely Earthquake. The maximum earthquake level adopted for the design of an observatory. At this level, major damage is acceptable, but not to the point where it would be uneconomical to repair rather than completely rebuild the facility. See also **OBE**.

MLI MultiLayer Insulation. A radiation-insulating blanket used in spacecraft thermal control.

MMT Multiple-Mirror Telescope. Originally composed of six 1.8 m Cassegrain telescopes working together on the same mount. The MMT was installed on Mt. Hopkins, Arizona in 1978. It was converted in 1999 to a conventional telescope with a 6.5 m primary mirror.

modulus of elasticity See **Young modulus**.

moment of inertia of an area (I) In structural analysis, the second moment of a beam's cross-section area. If dA is an elemental area and y is its distance from a given axis (e.g., neutral axis, q.v.), the moment of inertia is equal to

$$I = \int y^2 \, dA \, .$$

momentum dumping A procedure employed on spacecraft for discarding excess momentum acquired through the continuous action of external torques such as those due to a gravity gradient or solar pressure.

Monte Carlo analysis An analysis of a system's behavior by evaluating its response to a large number of randomly selected discrete samples of input parameters. This technique is employed in cases where exploring the complete domain of possibilities would be too time-consuming. Some stray light analysis programs use this technique.

MPI The Max Planck Institute (Germany). Also the name of a 3.5 m telescope belonging to the German-Spanish Astronomical Center and located on Calar Alto, Spain.

MSFC Marshall Space Flight Center. A NASA center in Huntsville, Alabama.

MTBF Mean Time Between Failures. A measure of technical reliability. The total functional life of a population of an item divided by the total number of failures within the population. The definition holds for time, cycles, or other measures of life units.

MTF Modulation Transfer Function. A measure of the quality of an optical system, based on Fourier analysis.

Multiple Mirror Telescope See **MMT**.

multiplex advantage In an instrument, the advantage in integration time obtained by simultaneously measuring a signal over a range of spectral (or spatial) frequencies compared to scanning single channels. A Fourier transform spectrometer is an example of an instrument possessing a multiplex advantage because all spectral frequencies are detected at once.

multiplexer (mux or MUX) A switching device that sequentially connects multiple inputs or outputs in order to process several signal channels with a single A/D or D/A converter.

MUX See **multiplexer**.

NAR NonAdvocate Review. An evaluation of a project by reviewers who are not part of the project or the users' community.

NAS National Academy of Sciences. A private, nonprofit society of scientists in the United States. Advises the federal government on scientific and technical matters. See also **NRC**.

NASA National Aeronautics and Space Administration. The civil space agency of the United States, founded in 1958.

Nasmyth A Cassegrain focus folded along the altitude axis of an alt-az telescope.

NASTRAN Short for NASA STRuctural ANalysis. A finite element structural analysis program originally developed by NASA in 1965.

natural frequency The lowest vibration frequency of a system in the absence of externally applied excitation. Also called "fundamental frequency." See also **eigenfrequencies**.

NEA Noise Equivalent Angle. The angle on the sky corresponding to the rms random error of an attitude or guiding sensor.

near infrared The portion of the electromagnetic spectrum immediately beyond the visible, extending in wavelength from 0.8 to 5 μm. See also **infrared**.

near-net-shape processing The direct shaping of a mirror blank by casting, forging, or powder consolidation of discrete parts or components in a manner requiring little, if any, subsequent removal of material to comply with final part dimensions and tolerances.

NEMA National Electrical Manufacturer's Association. A U.S. organization which sets standards for motors and other industrial electrical equipment.

neutral axis In structural analysis, the line of zero fiber stress in a given section of a beam subjected to bending.

neutral density filter A filter which reduces the intensity of light equally over the entire bandpass. The reduction is usually expressed as the logarithm of the attenuation. An "ND2" will reduce intensity by a factor of 100.

New Technology Telescope See **NTT**.

Newtonian A telescope configuration with only one powered mirror (primary). The return beam is folded by a flat mirror to locate the focus outside the tube. The Newtonian configuration is popular for amateur telescopes, but rarely used for large ones.

NGST Next Generation Space Telescope. A joint NASA-ESA-CSA project for a successor to the Hubble Space Telescope operating in the 0.5–20 μm range, with an anticipated launch in 2010. Renamed the James Webb Space Telescope, after James E. Webb, NASA's second administrator.

NOAO National Optical Astronomy Observatory. An organization which operates telescopes at Kitt Peak, Arizona and Cerro Tololo, Chile. NOAO is managed by AURA for the NSF.

node The point at which the orbit of a celestial body or spacecraft intersects some particular plane, such as an equatorial plane. If the body passes the plane from south to north, the node is called an ascending node, and from north to south, it is called a descending node.

noise Any unwanted or contaminating signal competing with the desired signal. Also used to describe the random variation in the desired signal.

NRA NASA Research Announcement. A NASA request for a science or technology proposal. NRAs generally involve basic scientific research with end products that are expected to be published in the scientific literature. These are smaller programs than AOs (q.v.) or RFPs (q.v.).

NRC National Research Council. The principal operating agency of the National Academy of Sciences of the United States.

NSF National Science Foundation. An agency of the United States which promotes scientific progress by awarding competitive grants to institutions for research and education.

NTT New Technology Telescope. A 3.5 m telescope at the European Southern Observatory in La Silla, Chile, which was the very first to have an active primary mirror.

numerical aperture (N.A.) For a telescope with the object at infinity, the numerical aperture is 1/(2×focal ratio).

nutation A small periodic motion of the Earth's axis ("nodding") due to the Moon, which is superimposed on precession (q.v.).

Nyquist frequency A sampling frequency twice that of the minimum required resolution. See **Nyquist theorem**.

Nyquist theorem The law that is the basis for sampling continuous information. It states that the frequency of data sampling should be at least twice the maximum frequency at which the information might vary. This condition should be observed in order to preserve patterns in the information or data, without introducing artificial, lower-frequency patterns, a phenomenon called "aliasing" (see Section 4.5.3).

OAO Orbiting Astronomical Observatory. A set of three NASA space observatories in low Earth orbit. OAO-1 failed to deploy. OAO-2, launched in 1968, made observations in the far ultraviolet with 11 telescopes in the 20–40 cm range. OAO-3, launched in 1972 and renamed "Copernicus," made observations in the UV with an 80 cm telescope and also carried out an X-ray experiment.

OBE Operational Base Earthquake. The highest earthquake level that does not affect functionality of the observatory. See also **MLE**.

object space In an optical system, the region upstream of the optical train.

occultation The obscuration of one celestial body by another, as when the Moon passes in front of a star, or when the target observed by an Earth-orbiting telescope is blocked by the Earth.

off axis Refers to a source which is not part of the field of view. Also refers to an architecture for optical systems that positions the elements away from the axis. Off-axis systems benefit from having no central obscuration, thus avoiding parasitic spikes in the image of bright sources. They can also be well baffled.

Offner relay A 1-to-1 optical relay with limited aberrations.

off-ramp technology Standard technology that can be used in place of new technology under development, should the latter not be successful.

off the shelf Said of any equipment regularly produced by a manufacturer or stocked by a supplier.

OPD Optical Path Distance (q.v.).

open loop A system in which there is no feedback. Motion is expected to faithfully follow the input command. Stepping motor systems are an example of open-loop control.

optical astronomy The study of astronomical objects using electromagnetic radiation from the ultraviolet to the far infrared (0.01–500 μm). Sometimes restricted to the visible and the immediately neighboring spectral regions (0.3–1 μm). See also **optical telescopes**.

optical depth A measure of the integrated opacity in a transparent material or in the atmosphere. In a homogeneous material, the absorption along a light path varies as $e^{-\tau}$, where τ is the optical depth. The optical depth is equal to 1 when the intensity is decreased by a factor of e.

optical path distance (OPD) In an optical system, the distance traveled by light passing between two points along the optical path.

optical telescope A telescope working in the optical spectral domain, defined not just as the visible region but also including the adjoining spectral regions where the laws of geometric optics (reflection, refraction) apply *and* diffraction effects are neither negligible nor dominant. This domain extends from the far ultraviolet (100 nm) to about 500 μm wavelengths. In the X-ray domain, optical systems are driven only by geometric effects (diffraction is negligible), whereas in the radio domain, diffraction is dominant (antenna beam theory applies). Telescopes in these two surrounding domains require designs markedly different from those in the optical domain.

optical window The part of the spectrum around the visible wavelengths where Earth's atmospheric absorption is minimum. The optical window extends from about 320 to 760 nm.

optics The science of the generation and propagation of light. Also, the physical system that captures light and transmits it to a detector.

orbital debris Discarded man-made material in near-Earth orbit that can be as large as spent rocket motors and as small as the dust particles ejected from nozzles of maneuvering thrusters. The larger objects (>10 cm) are tracked (more than 7000 of them). The average impact speed of debris on a spacecraft is 10 km/s, only half that of meteoroids, but the population of debris in near-Earth orbits is much higher than that of meteoroids, making debris the greater hazard for low-Earth-orbit spacecraft.

orbital perturbation Deviation from the regular orbit due to a disturbing force.

OSA Optical Society of America. A professional organization founded in 1916 to promote the optical sciences, pure and applied. The society has about 14 000 members from over 70 countries and publishes the *Applied Optics* journal.

OSS Office of Space Science, at NASA Headquarters. Also known as Code S.

OTA Optical Telescope Assembly. Generally refers to the telescope proper in a space observatory.

PAMELA Phased Array Mirror Extendible Large Aperture. A concept for large segmented mirrors in space composed of small ($\sim$ 10 cm) "intelligent" segments. The segments would be mass produced and come equipped with edge sensors, actuators, and their share of the distributed control system. The concept was prototyped at MSFC in the 1990s.

parallax The apparent change in the position of an object when observed from different locations, as when a star is observed from two opposite points of Earth's orbit around the Sun. The annual parallax of a star is the angle subtended at that star by the semimajor axis of the Earth's orbit.

parsec The distance at which the heliocentric parallax would be $1''$, which is 3.26 light years.

payload In aerospace astronomy, the scientific equipment with its associated space-support systems and adapter carried by an aircraft, a balloon or a launch vehicle.

payload adapter In a launch vehicle, the hardware that provides (1) the structural interface between the payload and the launch vehicle and (2) a system for separating the payload from the launch vehicle.

PDR Preliminary Design Review (q.v.).

peak up During target acquisition, a method of refining pointing by small maneuvers so as to pinpoint the direction that will maximize the target signal in an instrument aperture.

Peltier effect A thermoelectric effect wherein electric current applied to a solid/solid or a solid/liquid junction creates heating in one side and cooling in the other. Used for cooling detectors at moderately low temperature (e.g., CCD).

penumbra The portion of a planet's shadow within which part of the disk of the Sun is still visible. See also **umbra**.

perigee The point at which a body in orbit around the Earth most closely approaches the Earth.

period In orbital mechanics, the time required to complete one orbital revolution.

PERT Program Evaluation Review Technique. A project-scheduling technique similar to CPM (q.v.).

perturbation In astrodynamics, a deviation in the position and velocity of a body from its regular trajectory due to the presence of a disturbing force.

Petzval curvature The paraboloidal optical curving of an image at the focal plane caused by astigmatism.

photon A "particle of light." Although light propagates as an electromagnetic wave, it can be created or absorbed only in discrete amounts of energy known as photons. The energy of a photon is inversely proportional to wavelength ($h\nu$): smallest for radio waves, increasingly larger for microwaves, infrared radiation, visible light, and ultraviolet light. It is largest for X-rays and gamma rays.

PI Principal Investigator. A researcher who is officially designated head of a group of scientists and technical staff submitting a proposal to carry out a project (e.g., to perform an observation or build a piece of scientific equipment). The PI is responsible for leading the effort and is usually given exclusive rights to the use of the data or equipment for a specified period following acquisition of the data or completion of the equipment.

PID Proportional Integral Derivative (q.v.).

piezoelectric An effect in a solid in which application of pressure induces a voltage, or vice versa.

piezostack mirror A type of deformable mirror. See **DM**.

pitch axis A space vehicle's axis of rotation normal to the plane of the orbit. See also **yaw axis** and **roll axis**.

pixel Contraction of "picture element." The smallest optically reactive element of an array detector used for imaging.

pixel matching The matching of pixel size to the spatial resolution of the optics.

plasma A highly ionized volume of atoms capable of supporting a current.

plate scale The angle on the sky subtended by a given unit length at the focal plane: plate scale = (angular size)/(image size). Typically expressed in arcseconds per micron or millimeter.

PNAR Preliminary NonAdvocate Review. See **NAR**.

p/n junction An interface formed by two semiconductor materials, the one containing a charge carrier which is an electron donor (n-type semiconductor) and the other containing a charge carrier which is an electron acceptor (p-type semiconductor).

pointing The direction in the sky to which a telescope is pointed. Also, the act of orienting a telescope toward a particular direction in the sky. See also **tracking**.

point spread function (PSF) The variation of intensity with distance from the center of an image of a point source created by an optical system. The PSF describes the optical system's effect on the image of a light source. An image is the convolution of the true brightness distribution on the sky with the PSF of the telescope (or instrument).

Poisson distribution The distribution describing the random fluctuation in a signal with a constant average (e.g., the arrival rate of photons from a source). The probability $p(n,t)$ of n photons falling on a given area of a detector in a time t is given by

$$p(n,t) = (Nt)^n \frac{\mathrm{e}^{-Nt}}{n},$$

where N is the average flux (photons per unit time). This distribution has the property that the rms fluctuation in the average flux N (i.e., photon noise) is simply $\sqrt{N}$. This fundamental property is used in the calculation of the signal-to-noise ratio of an observation. The Poisson distribution approaches the Gaussian distribution when N is large, but differs significantly for a small N (i.e., weak source).

Poisson noise The random fluctuation in a signal has a Poisson distribution (q.v.) and is referred to as Poisson noise. Also called "shot noise" or "photon noise."

Poisson's ratio When a piece of material is stretched, the ratio of the lateral contraction per unit breadth to the longitudinal extension per unit length.

polar axis In an equatorial telescope, the axis parallel to the Earth's rotation axis.

polarized light A light beam in which all of the electromagnetic waves are aligned.

polar orbit A low Earth orbit with an inclination near 90°. See also **Sun-synchronous orbit**.

polishing Strictly speaking, making a mirror surface smooth enough to be specular. Loosely speaking, the successive actions of grinding, figuring, and polishing a mirror by lapping.

powered mirror A jargon term for a mirror that has curvature (i.e., is not flat).

precession For the Earth, the apparent slow movement of celestial poles due to the attraction of the Sun on the Earth's equatorial bulge. For a gyroscope, the periodic swinging of the axis of rotation accompanying a torque.

precipitable water The depth of a column of water equivalent to all precipitable water in a column of the atmosphere of the same diameter.

preliminary design review (PDR) A formal examination of the design, including functional flows, requirements, flowdowns, and concepts. The design effort is usually about one-fourth to one-third complete at this point.

primary mirror The first and usually the largest mirror in a reflective optical system. It provides the light gathering and frequently sets the aperture size.

prime focus The focus of the primary mirror of a reflecting telescope.

prime meridian The meridian passing through Greenwich, U.K. adopted as the origin for longitudes on Earth (see **transit telescope**).

principal investigator See **PI**.

project life cycle See **life cycle**.

propellant The gas ejected from a rocket. Ejection may result directly from combustion or be produced by electronic expulsion.

proper motion The change in the apparent position of a star as a function of time as seen from the Sun. Expressed in angular change per year.

proportional control A control mode which generates an output correction in proportion to the system's error (i.e., the system variable's deviation from set-point).

proportional integral derivative (PID) Also referred to as a three-mode controller, combining proportional, integral, and derivative control actions.

prototype A close hardware replica of the final system. Usually at full scale and fully functional.

PSF Point Spread Function (q.v.).

pupil Any image of the entrance aperture (generally the primary mirror). The exit pupil is the last image of the entrance pupil.

Pyrex A glass with a low coefficient of thermal expansion developed by Corning Glass Works.

QE Quantum Efficiency (q.v.).

Quality Assurance The planned, systematic actions necessary to provide adequate confidence that a product will satisfy its intended performance and use.

Quantum efficiency In a detector, the ratio of detected photoelectrons to incoming photons.

radiation A broad term covering emission and propagation of both particles and true electromagnetic waves.

Rayleigh criterion A rule for determining the angular resolution of an optical system. Resolution is defined as the separation between two point sources of equal intensity when the peak of a diffraction pattern of one of the sources falls on the first dark minimum of the diffraction pattern of the other. It is equal to $1.22\lambda/D$, where λ is the wavelength and D is the aperture diameter.

Rayleigh scattering The scattering of light by particles which are small compared to the wavelength of light. See also **Mie scattering**.

Rayleigh star An artificial source created in the lower atmosphere by Rayleigh scattering of a laser beam.

reaction wheel A spinning flywheel used for controlling the attitude of space telescopes by momentum exchange.

redshift The increase in the wavelength of a spectral line from an astronomical body as compared to its value when measured in a laboratory on Earth. Redshifting of stellar spectra is usually interpreted as being due to the Doppler effect (motion away from the observer). The wavelength shift is traditionally expressed as $z = \Delta\lambda/\lambda$. At very large distances, the redshift is interpreted in many cosmologies as being due to the expansion of the universe.

reflectance The ratio of reflected to incident light. See also **albedo**

reflecting telescope A telescope whose main optics are composed of mirrors.

refracting telescope A telescope whose main optics are composed of lenses.

refractive index See **index of refraction**.

requirements The description of a system's function, constraints, and required performance. See also **specifications**.

resolution The ability to distinguish detail in an image, usually expressed in terms of the angular size of the smallest features that can be distinguished. See also **Rayleigh criterion**.

resonance A comparatively large oscillation in a system excited by a periodic input of small amplitude having a frequency close to one of the system's natural frequencies.

response time The time elapsing between the moment a command for change in a system is issued and the moment that change is obtained. When the response of the system has an exponential form, meaning that the time as defined above would be infinite, the response time is, by convention, the time required to reach $1 - 1/\mathrm{e}$ (63%) of the commanded value (also called "time constant").

retroreflector An optical device that returns a beam of light in a direction parallel to it, regardless of the orientation of the device. Usually made up of three mutually orthogonal reflective surfaces, forming a concave corner (corner cube retroreflector).

Reynolds number A nondimensional parameter used in assessing whether a flow is laminar or turbulent. It is equal to $V/\nu d$, where V and ν are the fluid's velocity and viscosity, respectively, and d is a characteristic length (e.g., diameter of a pipe).

RFP Request for Proposals. A solicitation of proposals for services, a specific product, or a work package.

right ascension A coordinate for measuring the east-west position of a celestial body; the angle measured eastward along the celestial equator from the vernal equinox to the hour circle passing through a body.

rms Root mean square. The square root of the arithmetic mean of the squares of a set of numbers: $\sqrt{\frac{1}{n}\sum x_i^2}$, where x_i is a series of n values. See also **standard deviation**.

roll axis A space vehicle's axis of rotation along the tangent to the orbit and in the direction of motion. Forms a right-handed coordinate system with the pitch and yaw axes (q.v.).

ROM Rough Order of Magnitude. Term denoting a coarse estimate or best guess for a value (especially cost).

roughness A measure of the smoothness of a surface, usually expressed as the rms of the surface variation.

rpm Revolutions per minute.

rps Revolutions per second.

rss Root sum of squares. The square root of the sum of the squares of a set of numbers (note the difference with **rms**). Used to combine errors of uncorrelated contributing factors (e.g., in an error budget). Must not be employed when the errors are partially correlated (in which case the errors may have to be added arithmetically).

RWA Reaction Wheel Assembly. See **reaction wheel**.

SAA South Atlantic Anomaly. A dip in the lower Van Allen belt created by a reduced magnetic field above Brazil. Passage through the SAA significantly perturbs the operation of electronics and detectors of low-Earth-orbit space telescopes.

SALT South African Large Telescope. A 9.5 m telescope planned at the South Africa Astronomical Observatory in Sutherland, South Africa.

S-band The microwave band near 10 cm wavelength used for satellite communication.

scale height The vertical distance in an atmosphere at which the density drops by the factor e ($\rho/\rho_0 = \mathrm{e}^{-h/h_0}$, where h is the altitude, ρ is the density, and h_0 is the scale height). For the Earth's atmosphere, the scale height is about 7 km.

scattering The process by which light is deflected by reflection and diffraction or absorbed and reemitted at a different wavelength.

Schmidt-Cassegrain telescope A telescope system composed of a spherical primary mirror with a corrector plate to correct for its spherical aberration (as in a Schmidt telescope) combined with a Cassegrain secondary mirror mounted on the corrector plate. The primary-mirror/corrector-plate is not a pure Schmidt arrangement, however, since the corrector plate is not mounted at the center of curvature, but in front of the primary mirror focus. The Schmidt-Cassegrain telescope combination is popular among amateur astronomers because of its compact design and large aperture and because the optics are completely enclosed.

A variation of the Schmidt-Cassegrain arrangement is the Maksutov-Cassegrain system in which the corrector plate is replaced by a thick meniscus correcting lens with a strong curvature.

Schmidt telescope A telescope optical combination with a very wide field invented by Bernhard Schmidt in 1930. A Schmidt telescope is composed of a spherical mirror whose spherical aberration is corrected by an aspheric corrector plate located at the mirror's center of curvature. Such a system produces excellent images over a field of several degrees, but the focal plane is curved. Schmidt telescopes are generally used for sky surveys.

Scientific Advisory Committee (SAC) A committee of scientists external to a project whose role is to advise the project office and funding agencies on the scientific goals and priorities of the project. Although the SAC is most active during the definition phase, it also makes recommendations during the construction and

commissioning phases concerning the scientific impact of proposed technical changes or workarounds. The project scientist is normally the chairman of the committee. Such a committee is referred to as the "Science Working Group" (SWG) when it acts in a pro-active manner (e.g., early in the project for the definition of the observatory's requirements).

secondary mirror The first powered mirror after the primary mirror of a telescope.

SEE Single-Event Effect (q.v.).

seeing Disturbance in a telescope image due to atmospheric turbulence. Ordinarily expressed as the angular size in arcseconds of a point source (star) seen through the atmosphere, assuming perfect optics.

segmented mirror A mirror composed of individual, close-packed mirror elements.

sensor A device that detects a variable, usually receiving the information in one form (e.g., displacement) and converting it into another (e.g., volts).

Serrurier truss A particular telescope tube structure that maintains optical collimation by parallelogram action. Named after its inventor, Marc Serrurier, who developed this design for the Hale telescope.

settling time The time required for a parameter to stop oscillating or ringing and reach its final value. When the amplitude decay is exponential, settling time is by convention defined as the time required to reach 1/e (37%) of the initial amplitude.

SEU Single-Event Upset (q.v).

Shack-Hartmann A type of wavefront-error sensor.

Shane telescope A 3 m telescope at the University of California's Lick Observatory, on Mt. Hamilton, California.

sharpness In telescope optics, a figure of merit for the detection of point sources in background-limited mode introduced by Christopher Burrows. It is the second moment of the pixelized image. See Section 4.4 and Appendix D.

shroud The upper part of a rocket that contains the payload. Also called "fairing."

SI (1) Science Instrument. (2) Système International d'Unités (q.v.).

sidereal time The measure of time defined by the apparent diurnal motion of the stars, hence a measure of the rotation of the Earth with respect to the stars rather than to the Sun.

signal A variable that carries information about another variable that it represents.

signal-to-noise ratio The ratio of signal amplitude to the rms amplitude of the background fluctuation. A measure of the detectability of a signal.

single-event effect (SEE) An electronic dysfunction caused by the lone strike of a charged particle. The effect on the part can be temporary or permanent. An example of a temporary effect is a single-event upset (SEU). A permanent effect is a single-event burnout (SEB), a condition that can cause device destruction in a power transistor due to high-current.

single-event upset (SEU) A radiation-induced, nondestructive error in a microelectronic circuit caused when a charge particle loses energy by ionizing the medium

through which it passes, leaving behind a wake of electron-hole pairs. A reset or rewriting of the device results in normal device behavior.

sintering A thermal process in which powdered material is consolidated by heating without melting.

SIRTF Space Infrared Telescope Facility. A NASA 85 cm cryogenic telescope for infrared (3–180 μm) observations. Scheduled for launch in 2003.

skunk works A separate program operation established to operate outside the normal process, either to expedite the program or because of high-security classification.

slew The action of repointing a telescope.

Sloane Digital Sky Survey (SDSS) A survey program using a 2.5 m telescope at the Apache Point Observatory on Sacramento Peak, New Mexico.

slow optics An optical system with a large f-ratio (imported from the terminology of photography).

SNR Also S/N. Signal-to-noise ratio (q.v.).

SOAR telescope SOuthern Astrophysical Research telescope. A 4.2 m telescope under construction on Cerro Pachón, Chile. The SOAR project is being developed through a partnership between NOAO, Brazil, Michigan State University and the University of North Carolina.

sodar SOund Detection And Ranging. See **acoustic sounder**.

sodium laser star An artificial source created in the upper atmosphere by a laser beam scattering off the sodium layer at 80 km altitude.

SOFIA Stratospheric Observatory For Infrared Astronomy. An observatory operated by NASA and DLR (German Aerospace Center) using a 2.5 m telescope carried by a Boeing 747 airplane flying at an elevation of 13 000 m. The observatory is to go into operation in 2005.

solar constant The flux of solar radiation at the Earth's distance, but outside of the atmosphere. It is equal to 1358 $\mathrm{W/m^2}$.

solar flare A strong, temporary emission of hard X-rays and charged particles originating primarily in sunspots. Can perturb the operation of high-orbit space observatories.

solar pressure The pressure created on a surface by sunlight photons. This is the dominant external disturbance for high-orbit space observatories.

solar wind A fairly continuous stream of low-energy charged particles (mostly protons of 100 keV or less) from the Sun. Not a major source of disturbance for space observatories except during solar flares (q.v.). Not to be confused with solar pressure (q.v.).

sole source Refers to a procurement contract that is entered into after soliciting and negotiating with only one potential source.

South African Large Telescope. See **SALT**.

SOW Statement Of Work. Also "scope of work." A detailed description of the efforts and tasks required of a contractor. Usually coupled with a requirements document.

space debris See **orbital debris**.

Sparrow criterion A rule for determining angular resolution of an optical system. It is defined as λ/D, where λ is the wavelength and D is the aperture diameter.

sparse aperture An observing interferometer where the number and distribution of individual apertures is not adequate to fully sample the *uv* plane (q.v) in a single exposure. The dilution factor of a sparse aperture is typically 5% or less. See also **diluted aperture**.

specifications A precise, detailed description of a system's functionality and constraints. Specifications are more precise and elaborate than "requirements" (q.v.) and typically put conditions on material, manufacturing, and testing procedures.

specific heat The amount of energy absorbed by a material that is required to raise its temperature by one unit (expressed in joules per kilogram and degree C).

specific impulse In a rocket motor, the total thrust attainable by a propellant divided by its burning rate. See also **thrust**.

speckle The broken-up pattern caused by atmospheric turbulence in a short-exposure image of a point source. Individual speckles are created by the regions of coherence (r_0) in the incoming beam and have an angular size of $\sim \lambda/D$ (where D is the diameter of the telescope aperture), whereas the size of the full image is $\sim \lambda/r_0$. The speckle pattern in repeated short-time exposures can be exploited to obtain diffraction-limited stellar images.

spectrometer/spectrograph An instrument used to record the spectrum of a celestial object.

specular Having the qualities of a mirror, that is, where a narrow incident beam of light is reflected in one direction only as opposed to being scattered (diffused). Specular reflection occurs when the irregularities of the reflecting surface are small compared to the wavelength of light. In practical optics parlance, "reflection" is synonymous with "specular reflection." See **speculum**.

speculum "Mirror" in Latin (from "speculor," to observe, to watch). Also, the name of a copper-tin alloy used by Isaac Newton and others to make early telescope mirrors.

spider The structure made of thin members (vanes) that holds the secondary mirror at the center of a two-mirror on-axis telescope.

SPIE Society of Photoelectric Instrumentation Engineers; now The International Society for Optical Engineering. A U.S.-based international professional society that organizes yearly technical meetings on optical engineering, including telescopes and instruments. The society has about 15 000 members worldwide and publishes the *Optical Engineering* journal.

SSM Space Support Module. The module of a space observatory that houses support systems such as communications, attitude control, and propulsion. Also referred to as "the bus."

stand-alone system A system requiring little or no assistance from interfacing systems to perform its functions.

standard deviation A measure of the average dispersion of a data distribution (usually denoted as σ). The standard deviation is the rms of the deviations from the mean: $\sigma = \sqrt{\frac{1}{n}\sum(x_i - \mu)^2}$, where x_i is a series of n values with a mean of μ.

standards Established or accepted rules, measures, or criteria against which comparisons are made.

star tracker An attitude determination device for spacecraft in which the locations of stars within the tracker's field of view are measured and compared with the coordinates from a star catalog. After supplying attitude determination, star trackers can also be used to correct gyroscope drift. Star trackers have their own optical systems. Guiding systems that use the main optics of a space telescope are called "fine guiding sensors" (q.v.).

station keeping Orbital maneuvers to maintain a spacecraft in a given orbit.

steady state A characteristic of a condition, such as value, rate, period, or amplitude, exhibiting only negligible change over an arbitrary, extended period of time.

Stewart platform See **hexapod**.

stick-slip Noncontinuous motion due to friction effects at low speed, characterized by successive starts and stops.

strain See **deformation**.

strain energy The mechanical energy stored in a stressed material.

Stratoscope A 30 cm telescope carried by a balloon up to an altitude of 25 km in 1957. This first quasi "space telescope" was used for observation of the Sun in the visible.

Stratospheric Observatory For Infrared Astronomy See **SOFIA**.

stray light Unwanted light from an off-axis source. Light that leaks into a system from outside the field of view.

Strehl ratio A measure of the quality of an optical instrument, equal to the ratio of the amplitude of the point spread function to that of an equivalent, ideal instrument.

STScI Space Telescope Science Institute. An institute that carries out the scientific mission of the Hubble Space Telescope from Baltimore, Maryland. AURA manages STScI under contract with NASA.

Subaru An 8.2 meter optical-infrared telescope on Mauna Kea, Hawaii, operated by the National Astronomical Observatory of Japan.

submillimetric Refers to the portion of the electromagnetic spectrum immediately below microwaves. See also **infrared**.

sunshade A "forebaffle" or shield extending forward from the front end of a telescope to block radiation from the Sun.

sunshield A surface used to block sunlight.

Sun-synchronous orbit A near-polar orbit around the Earth which precesses at the rate of 1 day per year in the eastward direction, thus keeping its plane at a fixed angle with respect to the Sun.

Système International d'Unités International system of units established in 1960 by the General Conference of Weights and Measures, to which most industrialized countries adhere, including the United States. A coherent system (derived from the metric system) with seven base units: meter (m), kilogram (kg), second (s), ampere (A), kelvin (K), mole (mol), and candela (cd). Unit definitions and usage can be found on the National Institute of Standards and Technology's website. Unit abbreviations are capitalized only when derived from proper names (e.g., "V" for volt, "A" for ampere, but "m" for meter). Spelled-out units are not capitalized (e.g., "ampere," "kelvin", "hertz"). Prefixes of 1000 or lower are lowercase (e.g., "kg," not Kg).

systems engineering An engineering technique for large, complex systems that controls the total life-cycle process and results in the definition, development, implementation, and operation of a system that is reliable, cost-effective, and responsive to users' needs. The discipline was formalized in the 1950s and 1960s by NASA and the aerospace and defense industries.

TDRSS Tracking and Data Relay Satellite System. A set of three NASA communications satellites in geostationary orbit used to communicate with the Space Shuttle, HST, and other low-Earth-orbit satellites. The spacecraft constellation is distributed to provide global coverage. TDRSS is operated by the Goddard Space Flight Center.

TEC ThermoElectric Cooler (q.v.).

telemetry Radio signals from a spacecraft used to encode and transmit data to a ground station.

Telescopio Infrarrojo Mexicano See **TIM**.

Telescopio Nazionale Galileo See **TNG**.

terminator The boundary between the illuminated and dark areas of the apparent disk of a planet or planetary satellite.

tertiary mirror The third powered mirror in an optical train.

testbed A system consisting of software simulators or actual hardware used to develop and validate a new technology.

thermal conductivity The ability of a material to transmit heat. Expressed in units of energy per unit area transverse to the direction of energy flow per unit thickness in the direction of flow per unit time per unit of temperature difference across the unit thickness.

thermal diffusivity Thermal conductivity divided by the product of density and specific heat.

thermal inertia The reluctance of a body to change its temperature.

thermoelectric cooler A solid state cooler that cools one side by employing the Peltier effect (q.v.). These devices, although highly reliable, typically have an efficiency of 1% or less.

thrust The propelling force of a rocket engine. It is equal to the propellant mass flow rate multiplied by the propellant exhaust velocity. The impulse is the time-integrated thrust, whereas the specific impulse is the total thrust attainable by a propellant divided by its burning rate.

TID Total Ionizing Dose. A long-term degradation of electronics due to cumulative radiation damage.

TIM Telescopio Infrarrojo Mexicano. A 7 m telescope being built at San Pedro Martir, in Baja California, Mexico.

time constant The amount of time a system requires during a transitory behavior to rise to $1 - 1/e$ (approximately 63%) of its peak final value.

TNG Telescopio Nazionale Galileo. A 3.5 m Italian telescope located at the Roque de los Muchachos observatory on the island of La Palma, Canary Islands.

tolerance A measure of the acceptable range in the dimensions of a part or in the characteristics of an assembly or function.

torr A unit of pressure equal to 1 mm of mercury. An atmosphere is equal to 760 torrs. Named after Evangelista Torricelli.

trackingThe action of rotating a telescope so as to follow a target, compensating for Earth's rotation on the ground or drift in a space telescope, or to correct for the proper motion of a target, if a planet. See also **pointing** and **guiding**.

trade study An analysis conducted to compare a technique, architecture, or component to others of its class over all pertinent attributes.

trajectory The dynamical path followed by an object under the influence of gravity or other forces.

transducer A device that receives information in one form and converts it into another. See also **sensor**.

transfer function A mathematical, graphical, or tabular statement of the influence which a system or element has on a signal or action when compared at the input and output terminals.

transient The behavior of a variable during the transition between two steady states.

transit The passage of a celestial body across the local meridian due to the Earth's rotation.

transit telescope A telescope mounted on a fixed east-west axis, which allows it to swing only along the local meridian. Generally used for timing the passages of stars across the meridian. Transit instruments were once the basis of all practical timekeeping. The location of the Airy transit instrument at the Greenwich observatory in the United Kingdom constitutes the zero for all longitudes on the Earth.

TRL Technology Readiness Level. A measure of progress in the development of a new technology. NASA has produced a formal TRL description which is widely accepted.

troposphere The lowest part of the Earths atmosphere where most weather occurs. Its height varies from about 8 km at the poles to about 18 km at the equator. Above it lies the stratosphere, and then the ionosphere and the exosphere.

twilight The time between full night and sunrise or between sunset and full night. Civil twilight is when the Sun is less than 12° below the horizon. Astronomical twilight is when the Sun is between 12° and 18° below the horizon.

Tycho catalog A star catalog based on data obtained by the Hipparcos satellite. The catalog supplies the positions and photometry of about 1 million stars with an accuracy of about 25 mas and 0.07 magnitude, respectively. The limiting magnitude of the catalog is about 11.5 in V. See also **Hipparcos catalog**.

UBV system A photometric system which consist of measuring stellar flux through three color filters: the ultraviolet, U, centered on 360 nm, the blue, B, centered on 420 nm, and the "visible", V, in the green-yellow centered on 540 nm.

UKIRT United Kingdom Infrared Telescope. A 3.8 m telescope on Mauna Kea, Hawaii, owned by the United Kingdom Particle Physics and Astronomy Research Council.

ULE UltraLow Expansion. A type of glass produced by Corning which is 92.5% SiO_2 and 7.5% TiO_2 and has an expansion coefficient of $0 \pm 30 \times 10^{-9}/°C$ over the 5 to 35 °C interval.

ultraviolet (UV) Photons of wavelengths shorter than those of visible light, in the range of 100–400 nm.

umbra The central, completely dark part of a planet's shadow. See also **penumbra**.

United Kingdom Infrared Telescope See **UKIRT**.

universal time (UT) The local mean time of the prime meridian (see **transit telescope**). Identical with Greenwich mean time.

UT Universal time (q.v.).

UV Ultraviolet (q.v.).

***uv* plane** In an observing interferometer, the mathematical plane used to represent the baselines of each pair of subapertures, projected perpendicular to the line of sight. The *uv* plane is so named after the commonly used coordinates u and v. It is also referred to as the "Fourier plane." A single pair of subapertures only provides information on the spatial frequency content of the source corresponding to the angular resolution of that subaperture pair. Satisfactory imaging of an extended source requires measurements with a sufficient number of such pairs, a condition referred to as good *uv*-plane coverage. With a limited number of subapertures, coverage of the *uv* plane can be significantly improved by repeating measurements after either moving the subapertures or rotating them about a common axis. On the ground, the Earth's rotation provides this subaperture rotation "gratis."

valence band The energy band in a semiconductor that is filled with electrons at 0 K. Electrons cannot conduct in the valence band.

validation The process by which it is proved that a system accomplishes its purpose. Validation can only occur at the system level, whereas verification (q.v.) is accomplished at the subsystem level.

value engineering An engineering function which examines proposed designs, methods, and processes with the object of identifying lower-cost techniques or processes to produce an item more economically, yet still consistent with the requirements for performance, reliability, quality, and maintainability.

Van Allen belts Zones of intense radiation surrounding Earth in broad bands parallel to the geomagnetic equator, caused by charged particles trapped in Earth's

magnetic field. There are two main zones: the outer belt centered at approximately 12 000 km altitude, made up chiefly of electrons, and the inner belt, centered at approximately 4000 km altitude, made up chiefly of protons.

vane In a two-mirror telescope, one of the thin members holding the secondary mirror at the center of the tube. Also called a "knife edge." See also **spider**. In an optical baffle, one of the concentric rings used to reduce stray light.

verification The process by which it is proved that a subsystem complies with its requirements and intended purpose. Verification can be accomplished by inspection, analysis, or test (in ascending order of confidence). Differs from validation (q.v.), which is done at the system level.

vernal equinox The ascending node of the ecliptic on the celestial equator. Also, the time at which the apparent longitude of the Sun is 0° (around March 21).

vertex The point on an axisymmetric surface at the intersection of its axis of symmetry.

vignetting Gradual fading near the edge of the field of an optical system due to partial obstruction by intermediate optical components.

VIS or V Visible (q.v.).

viscosity The property of a fluid measured by its resistance to deformation under the influence of shear.

visible The portion of the electromagnetic spectrum detectable by the human eye. It extends from about 0.35 to 0.7 μm. The transmission of visible filters ("V") are formally defined as part of the UBV photometric system (q.v.).

VLT Very Large Telescope. A set of four 8 m telescopes operated by the European Southern Observatory and located on Cerro Paranal, Chile. The individual telescopes are referred to as Unit Telescopes (UT) 1 to 4, or by their South American Indian names, Antu, Kueyen, Melipal, and Yepun, respectively.

VLTI An interferometric telescope array composed of the four VLTs (q.v.) and four auxiliary 2 m telescopes.

wave Short for "wavelength" when referring to wavefront errors. For example, "half a wave" is a $\lambda/2$ wavefront error where λ is assumed to be a specific optical test wavelength.

wavefront An imaginary surface of constant phase in a propagating electromagnetic wave. For a source at infinity, the wavefront is a plane. Near the focus of a perfect optical system, the wavefront becomes a portion of a sphere centered at the focus.

wavefront error Departure from an ideal wavefront surface (plane or spherical). This departure can be due to geometric differences in the optical path length or to chromatic effects in refractive systems.

wavelength The distance between two successive recurring features in a periodic sequence, such as the crests or troughs in a wave. For electromagnetic waves, wavelength (λ) is equal to c/ν, where c is the velocity of light and ν is the frequency.

wave number The number of complete wave cycles of electromagnetic radiation that exist in one unit of length. It is simply the reciprocal of the wavelength, expressed, for example, in reciprocal meters (m^{-1}). In a vacuum, the wave number w

(in reciprocal meters) is related to the frequency ν (in hertz) according to $w = \nu/c$, where c is the speed of light (in m/s).

WBS Work Breakdown Structure. A technique used to decompose a project into elements that can be readily priced and managed.

well A term used to describe the holding capacity of a unit cell (pixel) in a focal plane array.

WHT William Herschel Telescope. A U.K. 4.2 m telescope at the Roque de los Muchachos Observatory on the island of La Palma, Canary Islands.

William Herschel Telescope See **WHT**.

WIYN A 3.5 m telescope located on Kitt Peak, Arizona, and operated by the Wisconsin, Indiana, and Yale universities and NOAO (hence the name).

work package An element of a project that can be the subject of a separate contract.

X rays Photons of energies greater than those of ultraviolet rays and smaller than those of gamma rays, with frequencies from 10^{17} to 10^{20} Hz.

yaw axis A space-vehicle axis of rotation in the plane of the orbit normal to the orbit. See also **pitch axis** and **roll axis**.

yield point The point at which strain increases without significant increase in stress.

Young modulus The ratio of the change in stress applied to a body to the change in strain. When the relation is linear, the modulus is the slope of the stress-strain relation. Also called the modulus of elasticity.

Zemax A ray-tracing program for optical design, by Focus Software, Inc.

zenith distance The angular distance on the celestial sphere measured along the great circle from the local zenith to a body on the celestial sphere. Zenith distance is 90° minus altitude.

Zernike polynomials Orthogonal polynomials used in the description of wavefront errors.

Zerodur An ultralow-expansion glass ceramic manufactured by Schott, Germany.

zodiacal emission A faint glow caused by sunlight being reflected and scattered off interplanetary dust near the plane of the ecliptic.

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