Section C. 2
Requirements Flowdown

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Section C.2 Outline

- **Requirements flowdown (graphical relationships)**
- **Requirements (values and rationale)**
- **Discussion of some requirements in more detail (not possible to go over them all)**
  - stray light effects
  - telescope placement accuracy
- **Top level error budget**
  - random and systematic
  - random breakdown

    leads to pointing requirements

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TIDI Flowdown Overview - 1

- Start with the requirements on the system as driven by the measurements required to perform the science.
- Flow down through the system until a reasonable requirement can be given to the engineers:
  - adequate: keep the CCD temperature between -75 and -85^{o} C
  - not adequate: keep the CCD noise below 10 electrons/pixel/second. [does not differentiate between a variety of noise sources]
- Some requirements are based on heritage, good engineering practice, or an experienced engineer's judgment and not detailed analysis.

TIDI Flowdown - 2

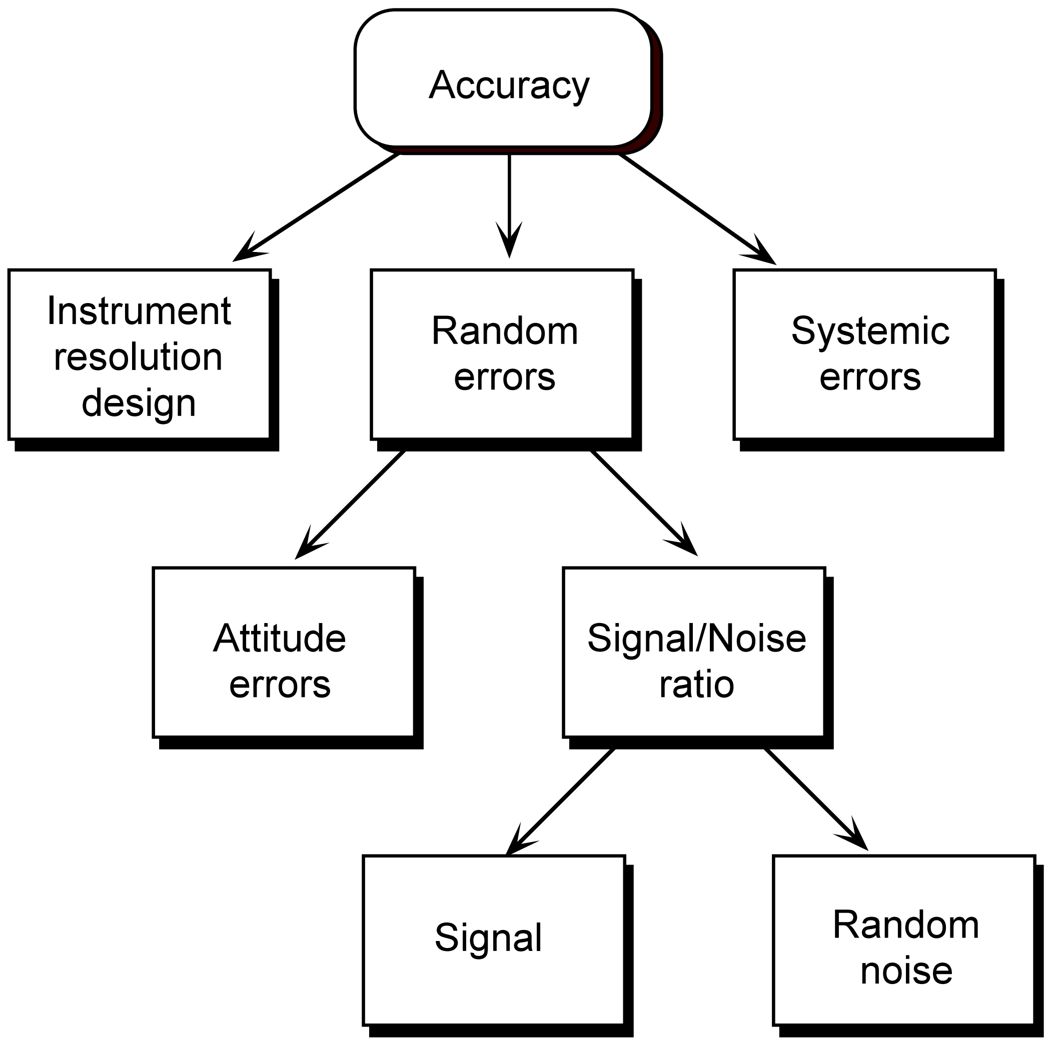
- **Some requirements are implicitly derived:**
  - Continuous operation implies that the instrument temperature must be controlled to such a degree that the filter drift does not cause the spectral line(s) to fall off the filter bandpass. This has significant implications for the thermal control system.

Science-Driven Requirements

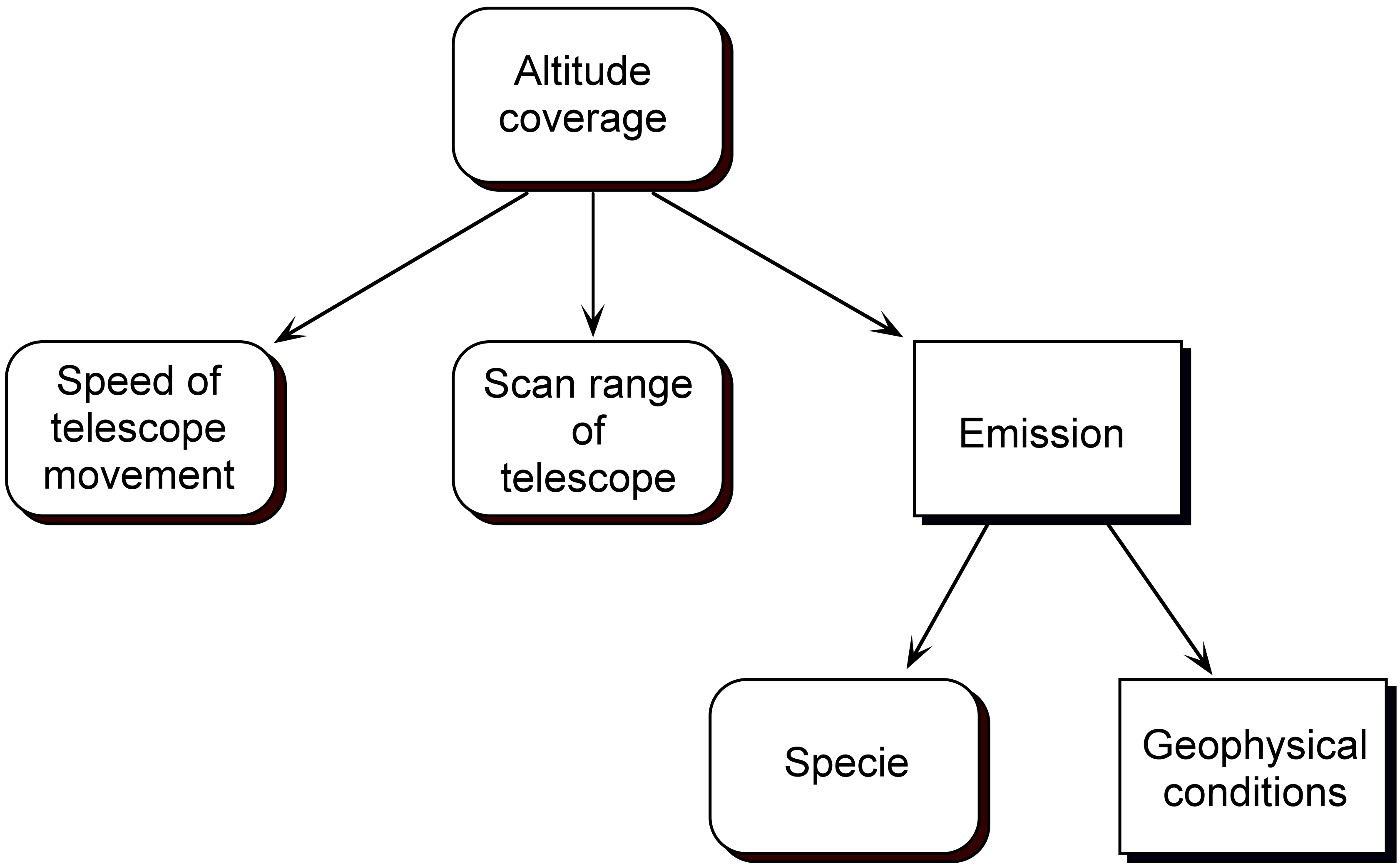
Requirement	Value
Accuracy (wind) [other products do not drive design]	**~3 m/s line of sight (uninverted)**
Altitude coverage	**60-300 km (primary 60-180 km)**
Vertical resolution	**2.0 km**
Tangent point altitude knowledge	**1 km**
Telescope field overlap	**~100 km**
Lifetime	**>2 years**
Local time coverage	24 hours/120 days (3°/day)
Latitude coverage	Pole-to-pole
Horizontal resolution	~500 x 500 km

BOLD - most directly drives TIDI design

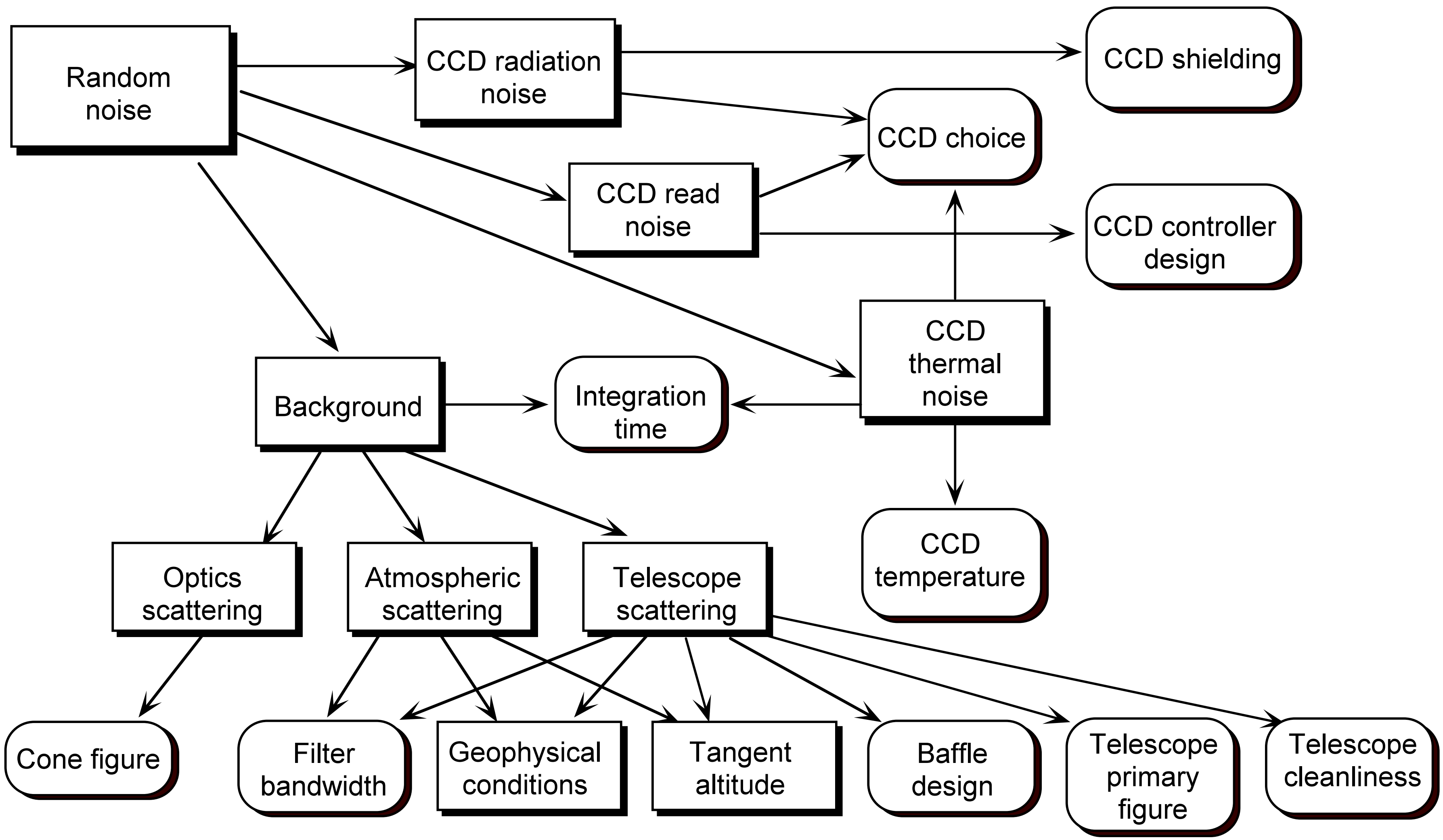
TIDI Flow-Down Requirements: Measurement Accuracy



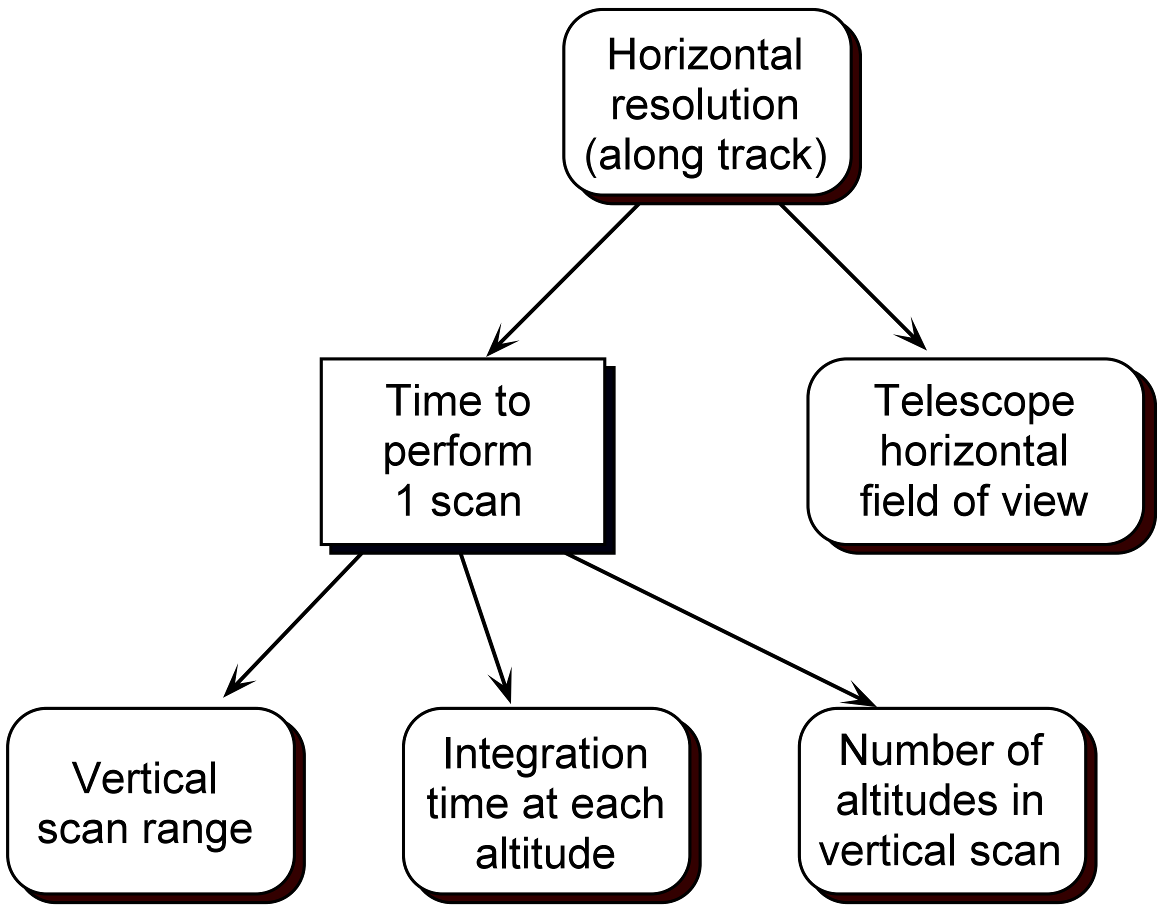
TIDI Flow-down Requirements: Altitude Coverage



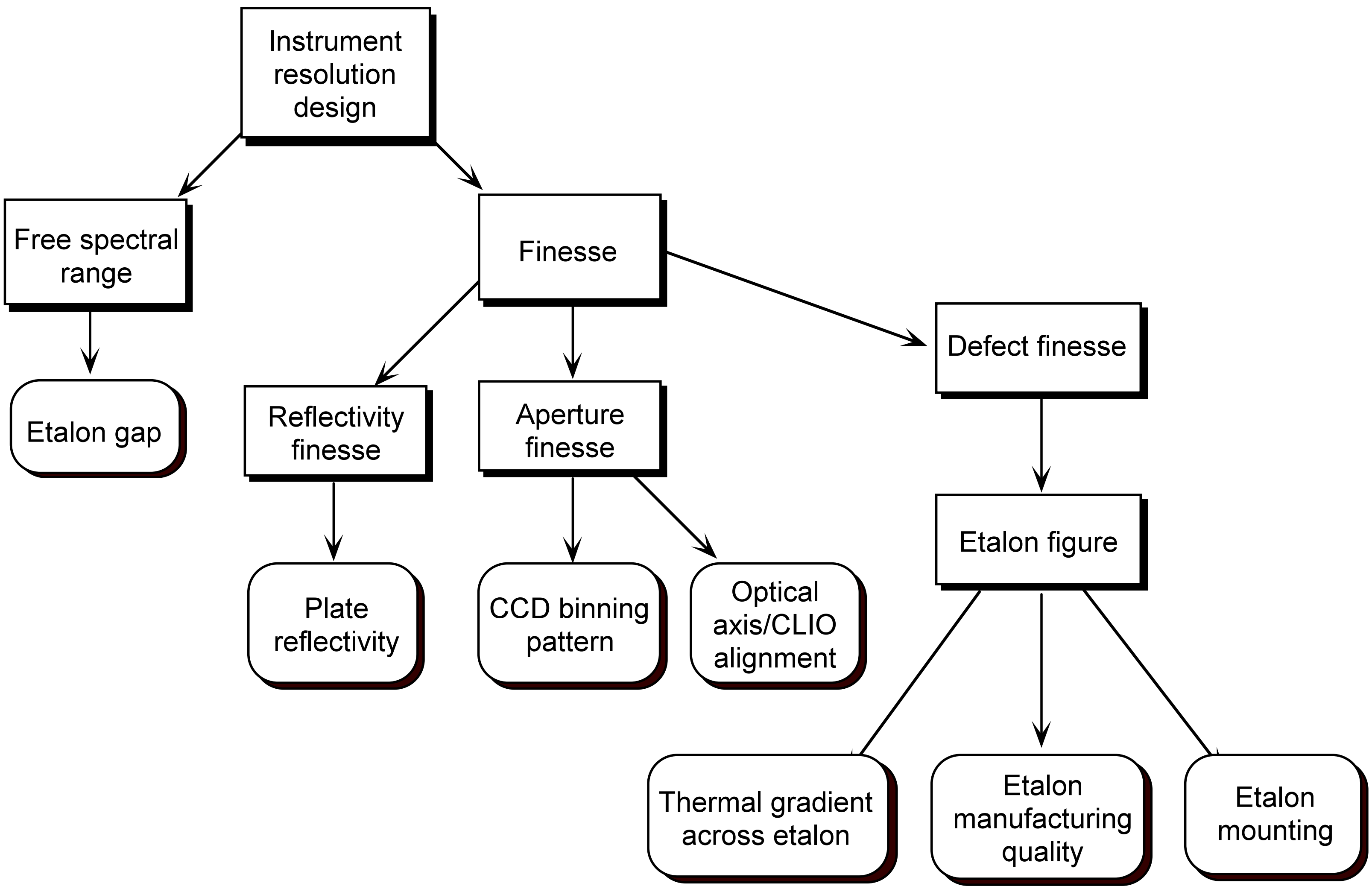
TIDI Flow-Down Requirements: Random Noise



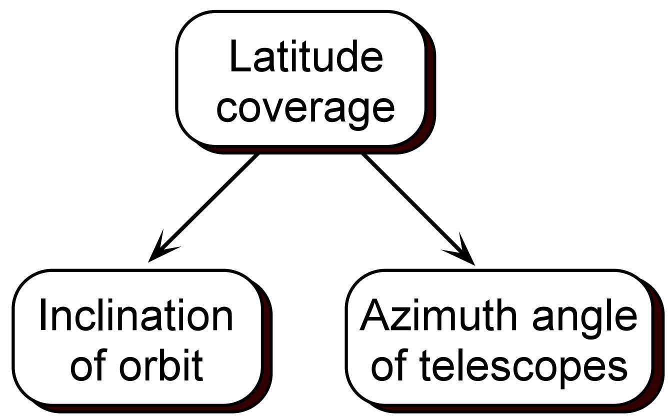
TIDI Flow-down Requirements: Horizontal Resolution



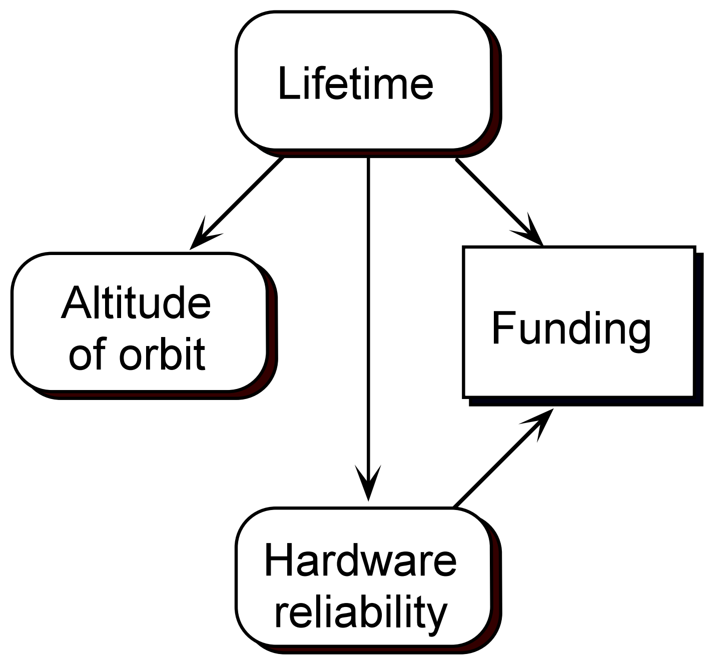
TIDI Flow-Down Requirements: Instrument Resolution



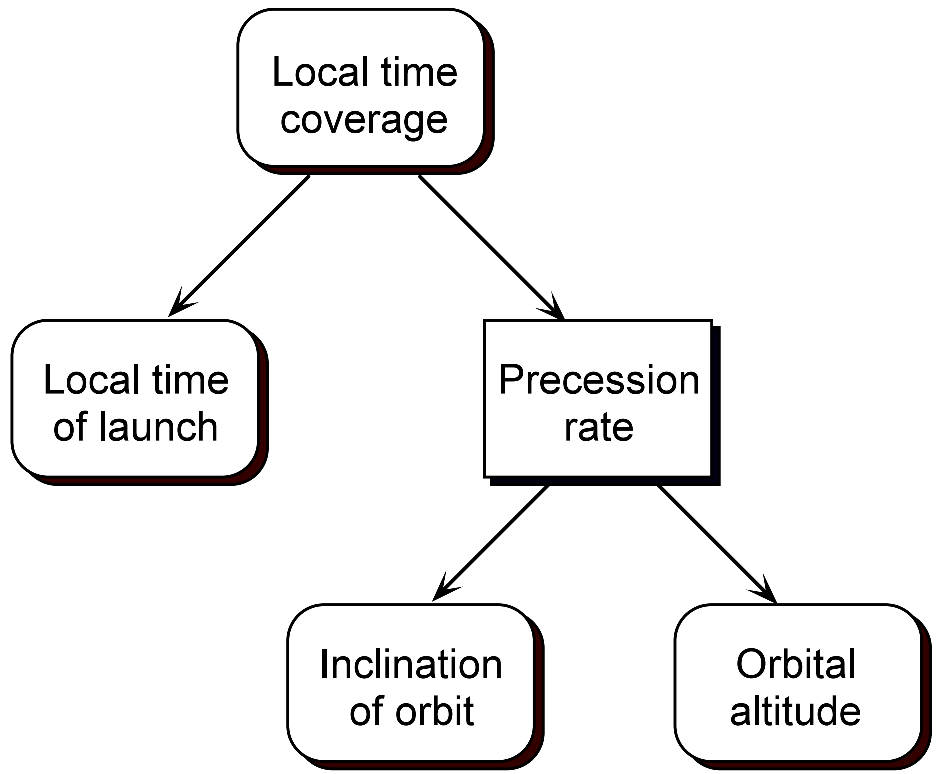
TIDI Flow-down Requirements: Latitude Coverage



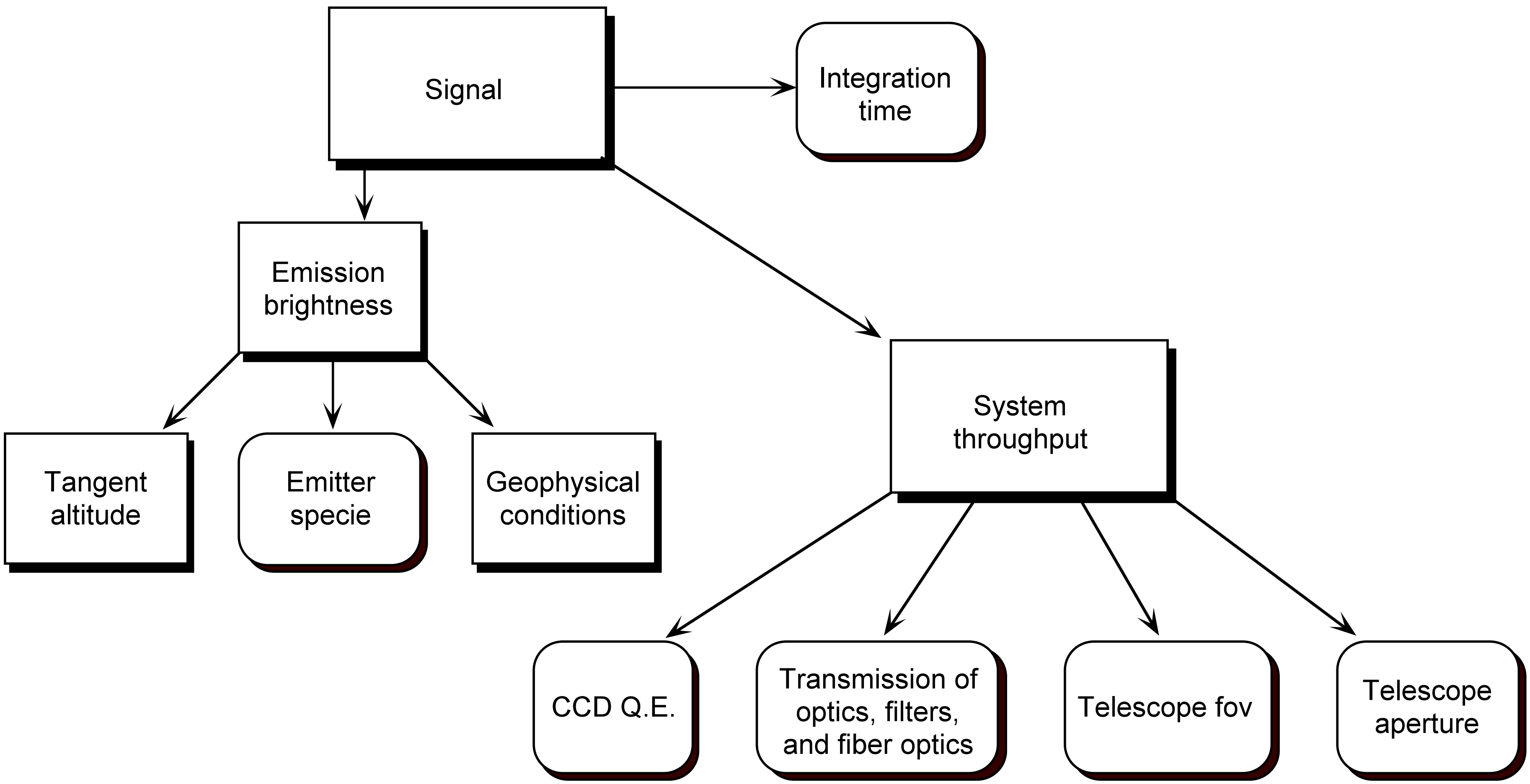
TIDI Flow-down Requirements: Lifetime



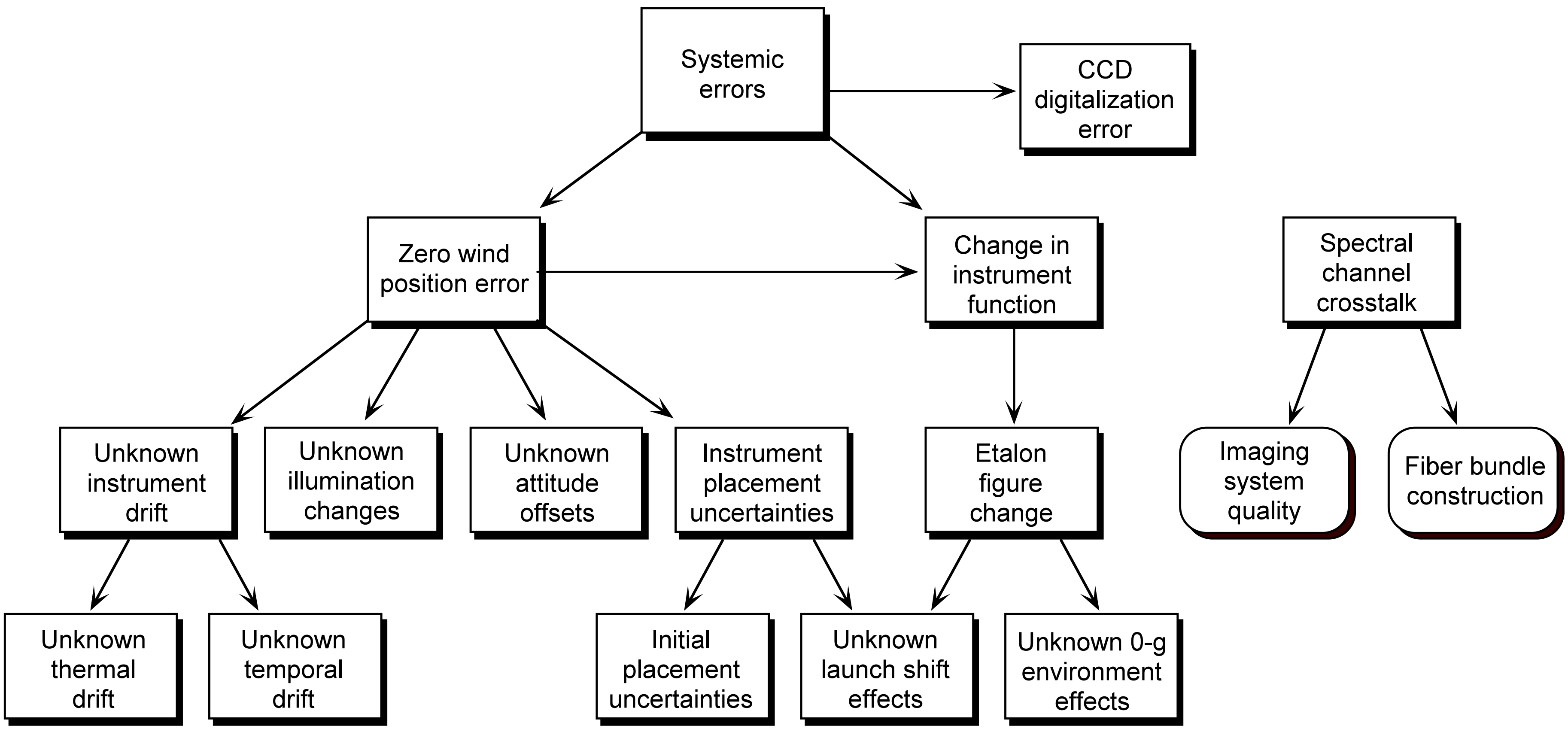
TIDI Flow-down Requirements: Local Time Coverage



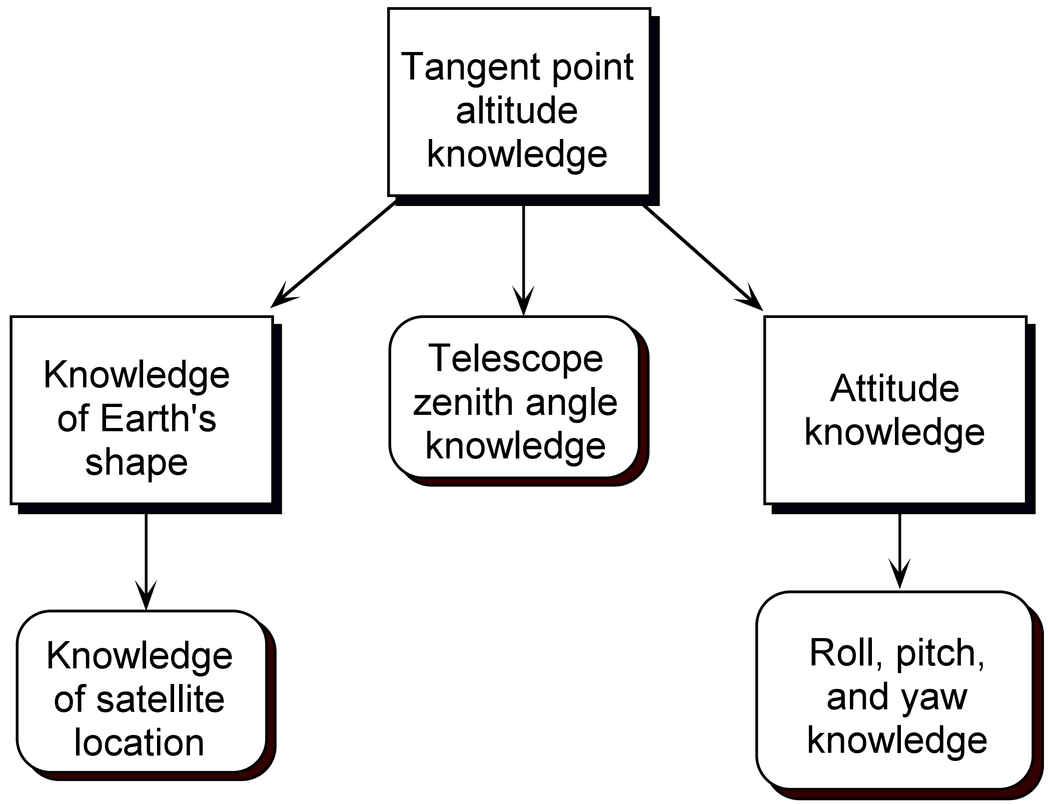
TIDI Flow-Down Requirements: Signal



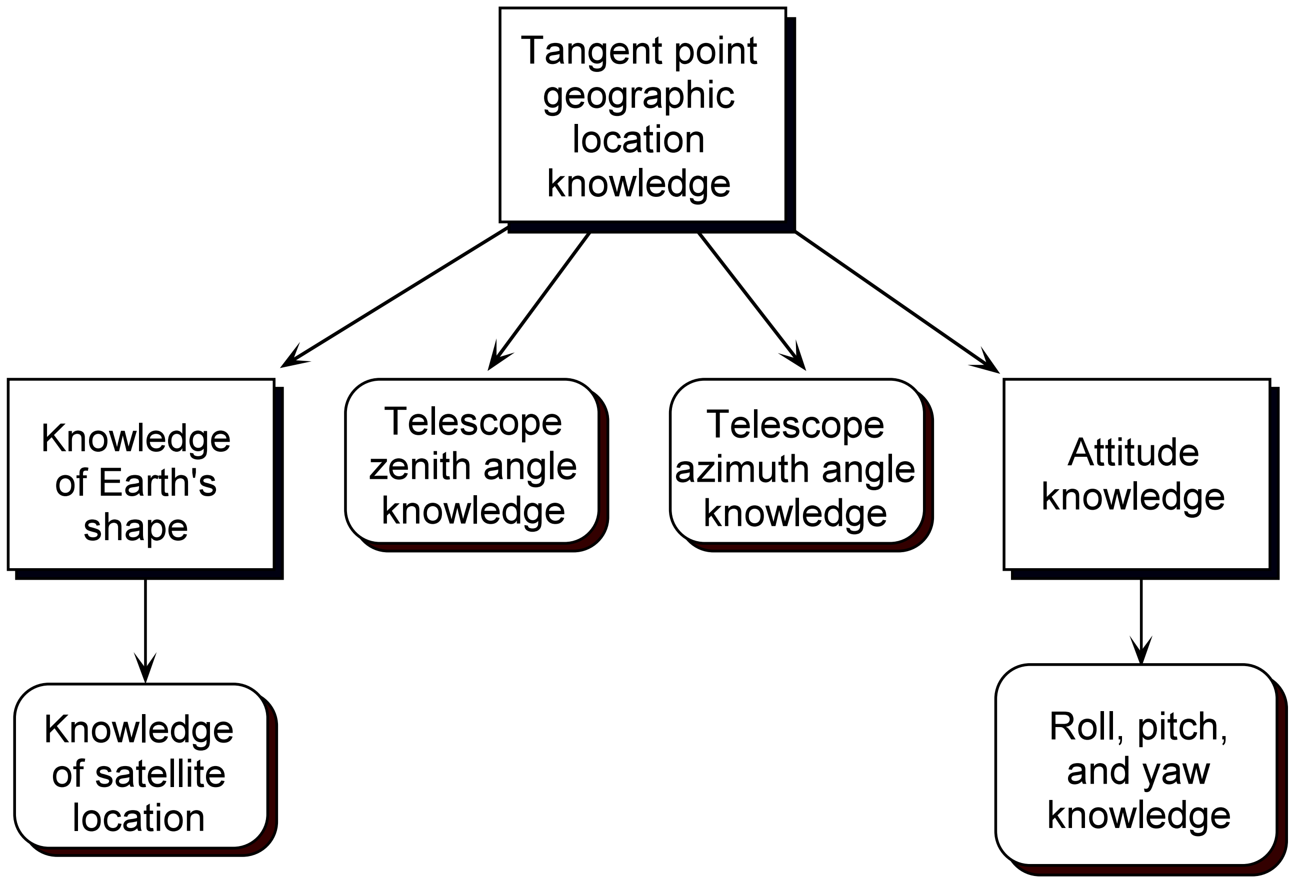
TIDI Flow-Down Requirements: Systemic Errors



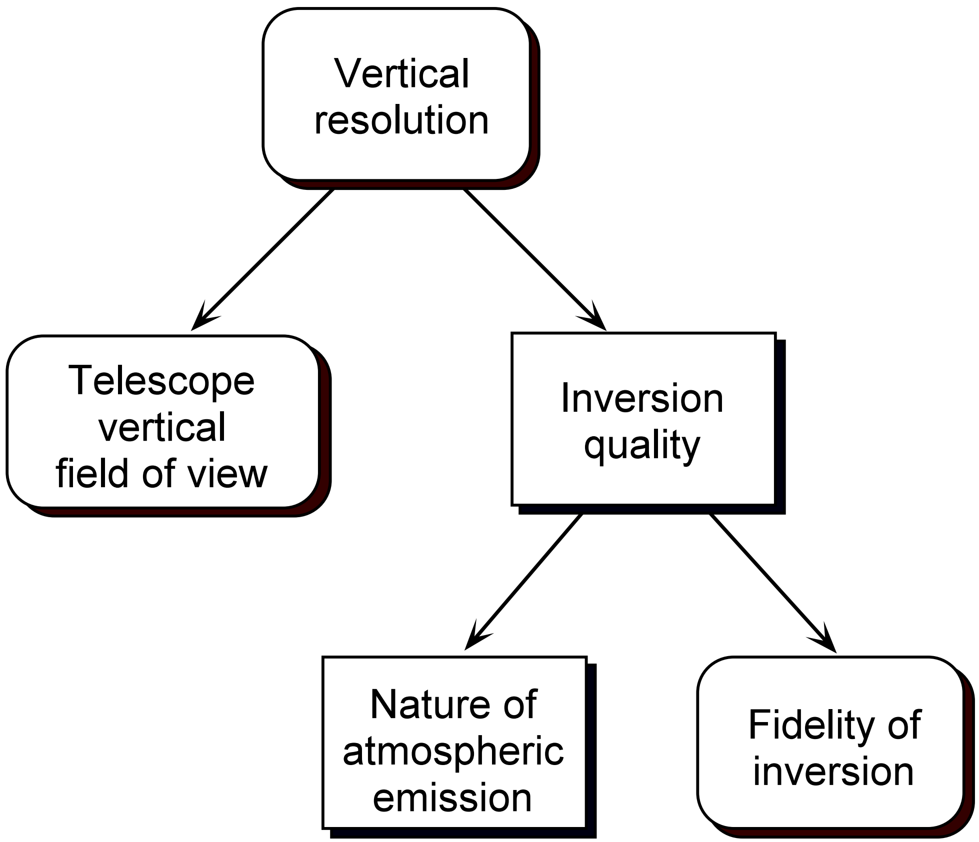
TIDI Flow-down Requirements: Tangent Point Altitude Knowledge



TIDI Flow-down Requirements: Tangent Point Geographic Location



TIDI Flow-down Requirements: Vertical Resolution



Etalon Requirements

Parameter	Value	Rationale
Plate material	Spectrosil-B	Good optical properties in visible. Used with HRDI etalons.
Post material	zerodur	Provides low thermal expansion. Always used for fixed-gap etalons.
Plate diameter	10.5 cm	Large enough for coated area and posts.
Coating diameter	7.5 cm	Required to match etendue of telescopes.
Plate thickness	2.65 cm	Want large value to minimize gradient effects, want small values to minimize mass and size. Aspect ratio from HRDI used.
Gap	2.2 cm	Optimized to provide best wind error for O_2 atmospheric band lines.
Reflectivity	0.80	Optimized to provide best wind error.

CCD Requirements - 1

Parameter	Value	Rationale
Pixel size	15 microns	At least 2 pixels are required for each spectral channel in the outermost field. Small pixel size minimizes the required focal length and hence size of the imaging optics. 15 microns is a standard size.
Area of interest	600 x 100 pixels	600 pixels are required in order to image 5 orders with at least 2 pixels per channel. 100 pixels are wider than the image and provides some margin for placement of the CLIO on the CCD.
Quantum efficiency (minimum) (%)	50@400 nm 55@500 nm 63@600 nm 63@700 nm 55@800 nm 35@900 nm	These values are state of the art for CCDs for use in the visible. Values correspond to -80□C.

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CCD Requirements - 2

Parameter	Value	Rationale
Operating temperature	-80±5^{o}C	There are 3 considerations for CCD temperature: 1. dark current - decreases with CCD temperature 2. radiation effects - less significant at cold temperatures 3. quantum efficiency - decreases by ~0.2%/^{o}C
Readout noise	<8 electrons	Small enough not to dominate signal-to-noise ratio
Charge transfer efficiency (CTE)	>0.99999 at 40k e^-/pixel >0.99995 at 1620 e^-/pixel	Parallel shifts do not matter, serial shifts do. There are a maximum of 1000 serial shifts. 0.99999^{1000}=0.99, 0.99995^{1000}=0.95
Dark signal	<0.007 e^-/pixel/s	This corresponds to a maximum of 1-2 e^- per spectral channel/s and can be met by cooling the CCD to <-75^{o}C and using MPP (multi-phase pinned).

Telescope Requirements

Parameter	Value	Rationale
Telescope aperture	7.5 cm	Want largest diameter possible to maximize science. All optics are proportional to this value and it largely drives the size and mass of the system (and the cost).
Telescope vertical field of view	0.05 degrees	This is about 1/2 of a scale height and maximizes the number of photons collected while minimizing the altitude smearing.
Telescope horizontal field of view	2.50 degrees	Want this to be as large as possible. Limited by horizontal gradients.
Telescope primary roughness	<2.0 nm rms	The telescope primary roughness determines the amount of scattered light collected by the system. Scattered light decreases the signal-to-noise and increased the error.
Light baffle	baffle length = 42.76 cm, critical baffle diameter = 9.5 cm	Keep direct sun off the primary for sun angles of greater than 15 degrees.
Telescope f number	5.7	Required to meet the numerical aperture of the fibers.

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Filter Requirements - 1

Parameter	Value	Rationale
Bandwidth	0.3 - 4.0 nm, depends on spectral region	Want good spectral isolation to minimize background effects. Bandwidth must be wide enough to accept modest temperature changes.
Effective index of refraction	1.8-2.0	Want large to minimize angular spectral shifts. Values of ~2 are the practical limit in the visible.
Thermal drift	0.002 nm/°C	Want small values to allow filter temperature to vary. Use of refractory oxide leads to about a factor of 10 improvement over old filter types.
Blocking range	200-1200 nm	Need to be blocked over the range the CCD is sensitive.

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Filter Requirements - 2

Parameter	Value	Rationale
Operating temperature	20±5°C	Operating range of instrument. Leads to maximum thermal drift of 0.01 nm.
Size	diameter = 1.370 in (+0.0/-0.01 in), clear aperture = 1.310 in, thickness no greater than 0.098 in	Clear aperture matches optics, thickness as small as possible to minimized moment of inertia.
Field of view	2.25°, F/12.7	Matches optics.
Tilt	1 degree	Moves reflected light out of optical path.

TIDI Filter Wheel #1

Position	Wavelength (nm-air)	FWHH (nm)	Feature	Notes
1	867.13	0.3	$O_2(^1\Sigma)$ (0-1) P11 pair (11531.7989 cm^{-1} and 11536.7235 cm^{-1}) and Ar (866.79 nm)	O_2 and calibration filter for winds and rotational temperatures (60 - 85 km) w/ 866.12 nm
2	763.68	0.3	$O_2(^1\Sigma)$ (0-0) P9 pair (13093.6407 cm^{-1} and 13091.6958 cm^{-1}) and Ar (763.51 nm)	O_2 and calibration filter for winds and rotational temperatures (85 - 120 km) w/ 765.07 nm
3	557.8	0.5	OI (^{1}S)	green line filter for winds (90 - 250 km) and Doppler temperatures (100 - 150 km)
4	OG 515	N/A	high pass filter	high transmission above 515 nm, removes UV and blue light
5	630.1	0.5	OI (^{1}D) and Ne (630.48 nm)	red line and calibration filter winds and Doppler temperatures (200 - 300 km)
6	765.07	0.3	$O_2(^1\Sigma)$ (0-0) P15 pair (13069.9459 cm^{-1} and 13068.0662 cm^{-1})	O_2 for winds and rotational temperatures (80 - 125km) w/ 763.68nm
7	866.12	0.3	$O_2(^1\Sigma)$ (0-1) P7 pair (11545.2971 cm^{-1} and 11543.3255 cm^{-1}) and Ar (866.79 nm)	O_2 and calibration filter for winds and rotational temperatures (60 - 85 km) w/ 867.13 nm
8	892.1	0.5	OH Meinel (7-3) P1(3) pair and Ne(891.95 nm)	OH and calibration filter nocturnal winds and temperatures (80 - 90 km)

TIDI Filter Wheel #2

Position	Wavelength (nm-air)	FWHH (nm)	Feature	Notes
1	OG 515	N/A	high pass filter	high transmission above 515 nm, removes UV and blue light
2	732.1	0.5	OII (^{2}P) pair	plasma drift winds (170 - 300 km)
3	844.8	0.5	O triplet	auroral winds (150 - 300 km)
4	557.2	0.5	OI (^{1}S) cal filter Kr (557.03 nm)	green line calibration filter
5	589.4	1.0	NaD doublet and Ne (590.25 nm)	sodium for nocturnal and auroral winds and temperatures (85 - 95 km)
6	779.5	0.5	OH Meinel (9-4) P1(2) pair	OH for nocturnal and auroral winds and temperatures (80 - 90 km)
7	764.0	4.0	$O_2(^1\Sigma)$ (0-0) P branch and Ar (763.51nm)	band brightness w/ 761.0 nm
8	761.0	2.0	$O_2(^1\Sigma)$ (0-0) R branch and Kr (760.15 nm)	band brightness w/ 764.0 nm

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Important Scattering Terms: BRDF

Bidirectional Reflective Distribution Function (BRDF) describes the scattering pattern

$$\mathrm{BRDF}(\theta) = \frac{b}{\theta^c}$$

b and c are constants.

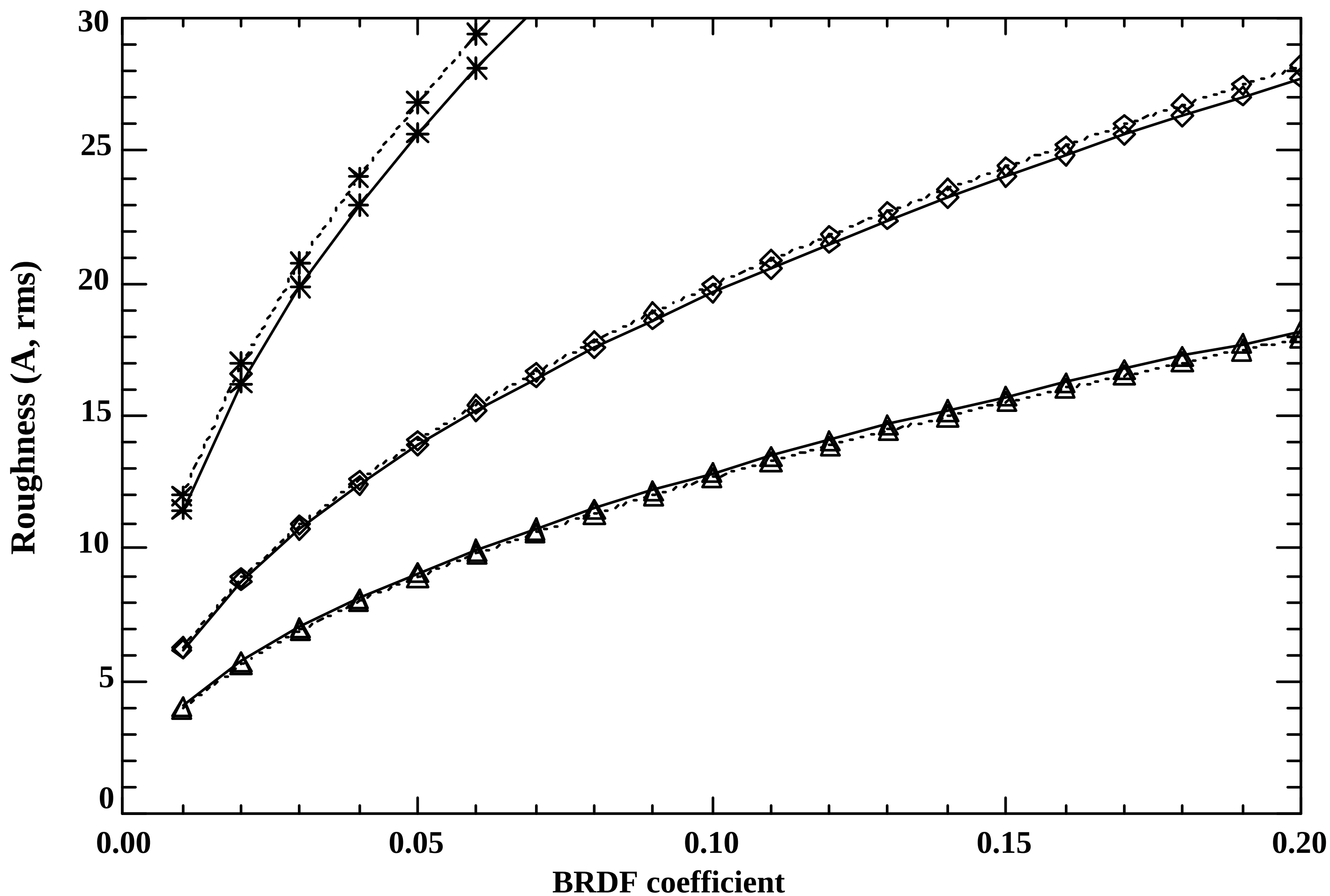
If c = 2, then approximately

$$\sigma = \frac{\lambda}{360}\left(\frac{\pi b}{2}\ln\left[\frac{\theta_{max}}{\theta_{min}}\right]\right)^{\frac{1}{2}}$$

If c ° 2, then

$$\sigma = \frac{\lambda}{2}\left(\frac{\pi}{180}\right)^{\frac{c}{2}}\left(\frac{b}{2\pi(2-c)}\left[\theta_{max}^{2-c} - \theta_{min}^{2-c}\right]\right)^{\frac{1}{2}}$$

BRDF vs. Surface Roughness



Dotted = analytical, Solid=numerical
star = -1.5, diamond= -2, triangle = -2.5

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TIS and Scattered Light

- **Total Integrated Scatter (TIS) describes the total amount of scattering**

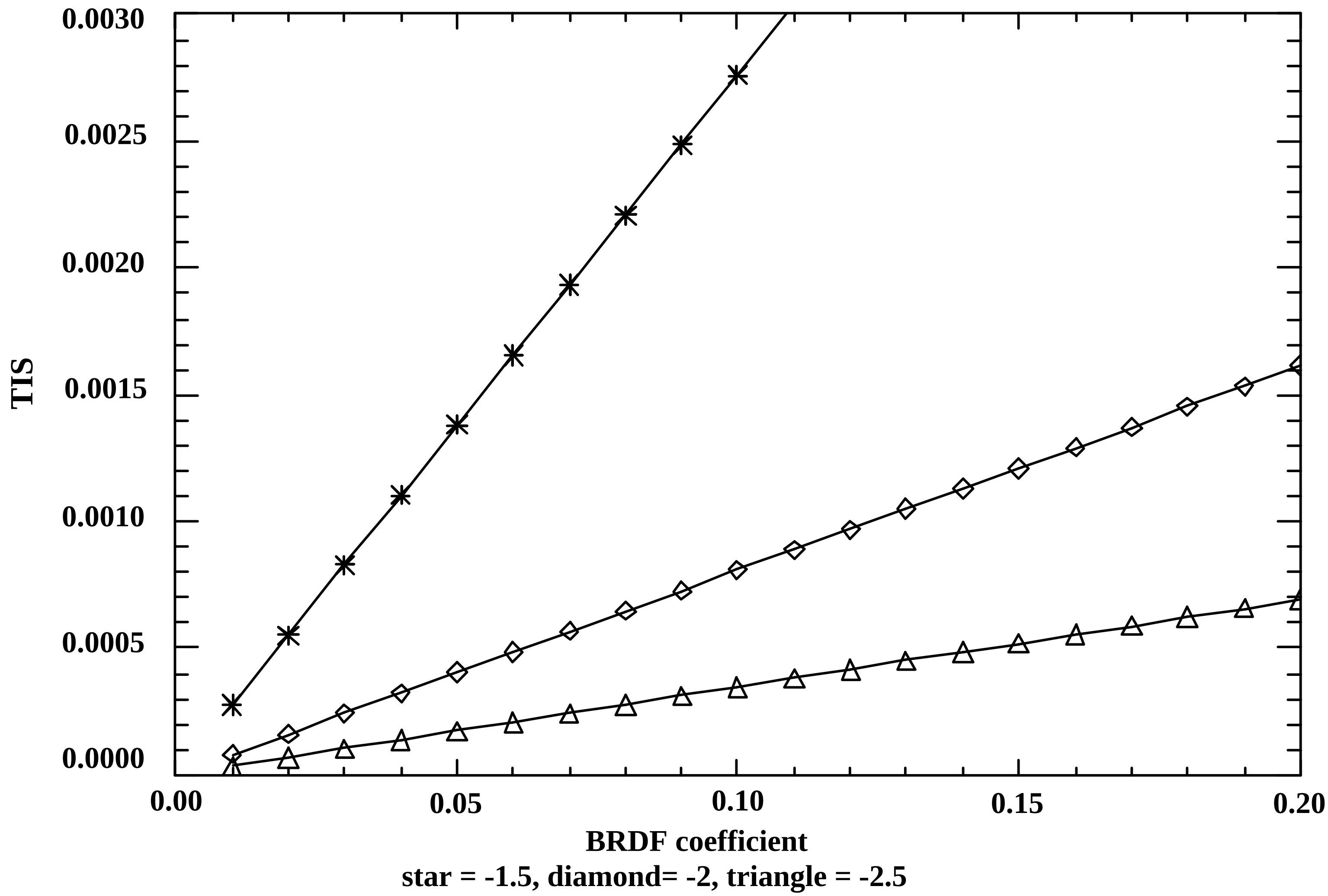
$$\mathrm{TIS} = \left(\frac{4\pi\sigma}{\lambda}\right)^2$$

σ is the roughness, λ is the wavelength.

- **The scattered light, B_{scat}, is given by (for c = 2)**

$$B_{scat}(\theta_b) = 2kb \int_0^{\frac{\theta_h}{2}} \int_{-\frac{\theta_v}{2}}^{\frac{\theta_v}{2}} \frac{B_{Ray}(\theta_b + \theta_v)\phi(\theta_h, \theta_v, r_{primary}, r_{baffle}, d_{baffle})\, d\theta_h\, d\theta_v}{(\theta_h^2 + \theta_v^2)}$$

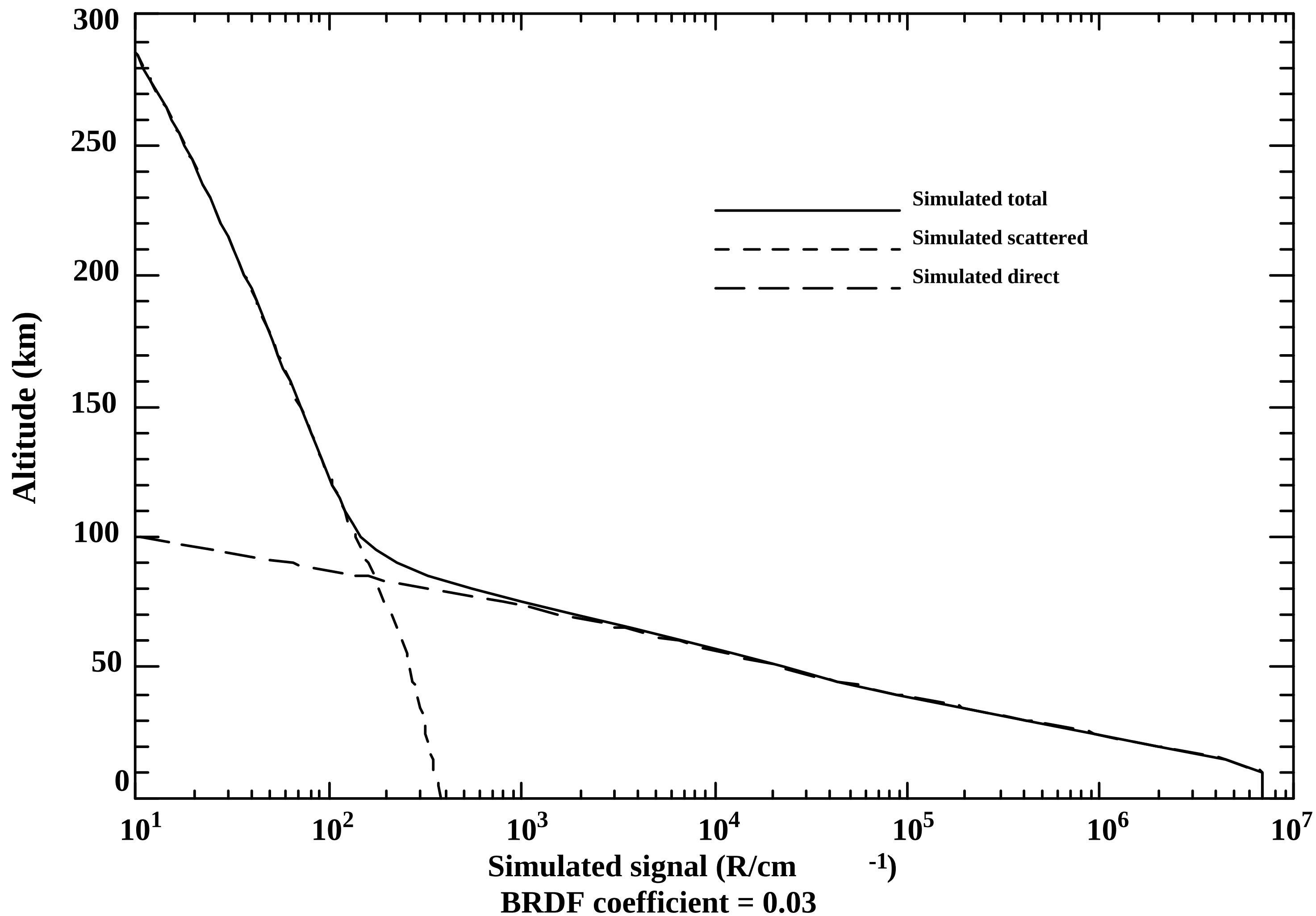
Total Integrated Scatter vs. BRDF



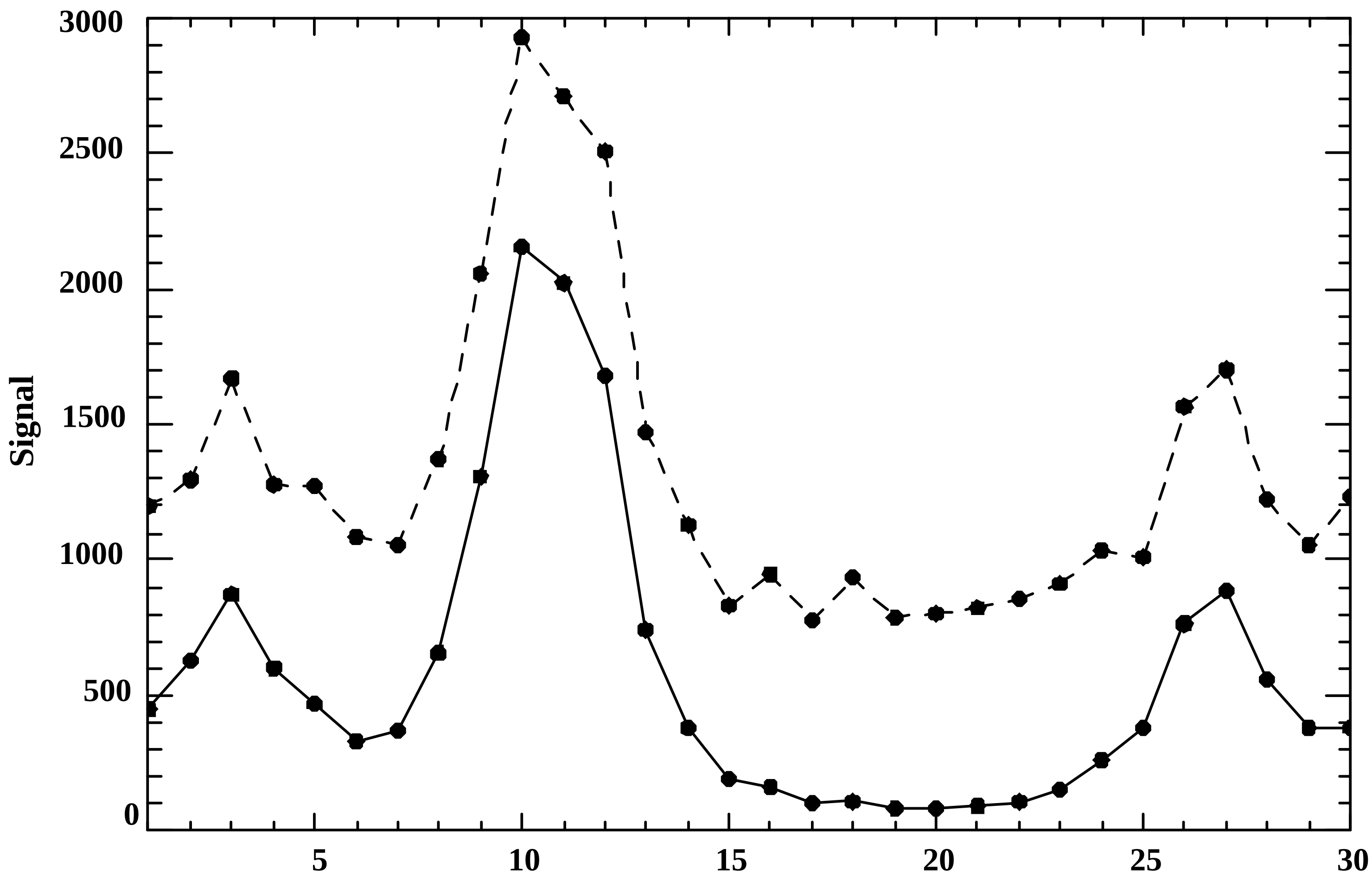
Parameters Used in Telescope Scattering Calculation

Parameter	Value
Satellite altitude	625 km
Primary radius	3.85 cm
Critical baffle radius	4.75 cm
Primary-Critical baffle distance	42.46 cm
b	0.03
c	2

TIDI Simulated Limb Brightness at 865 nm

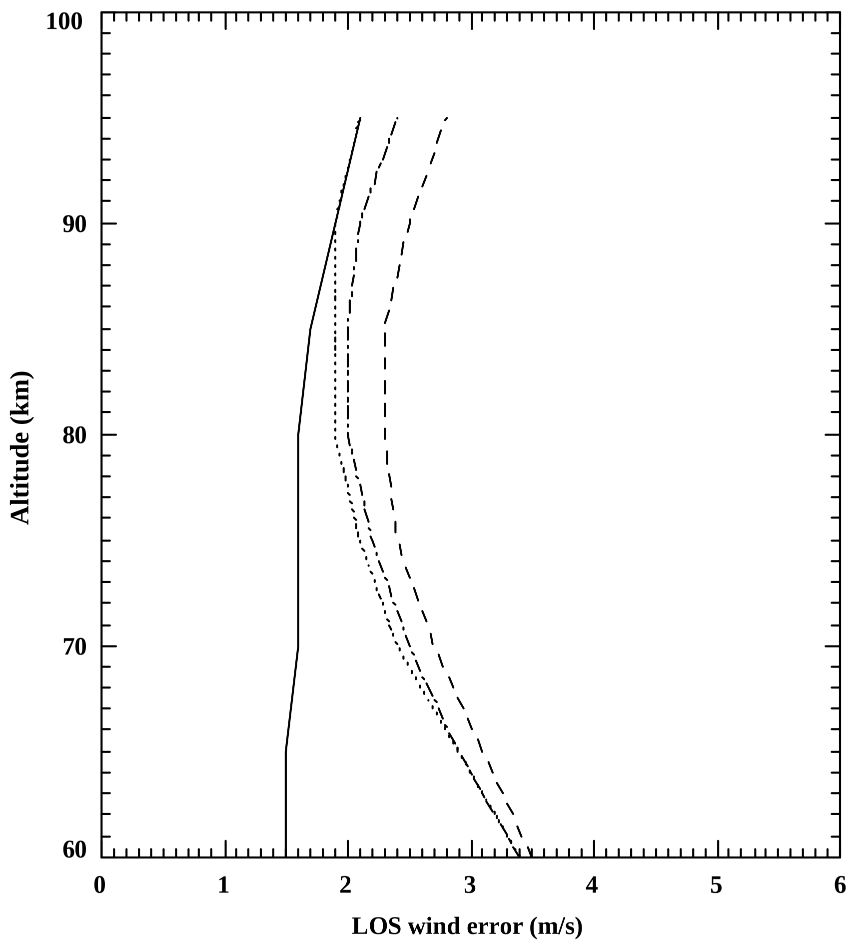


Simulated O_2 (0,1) Signal
Tangent Altitude: 85.0 km



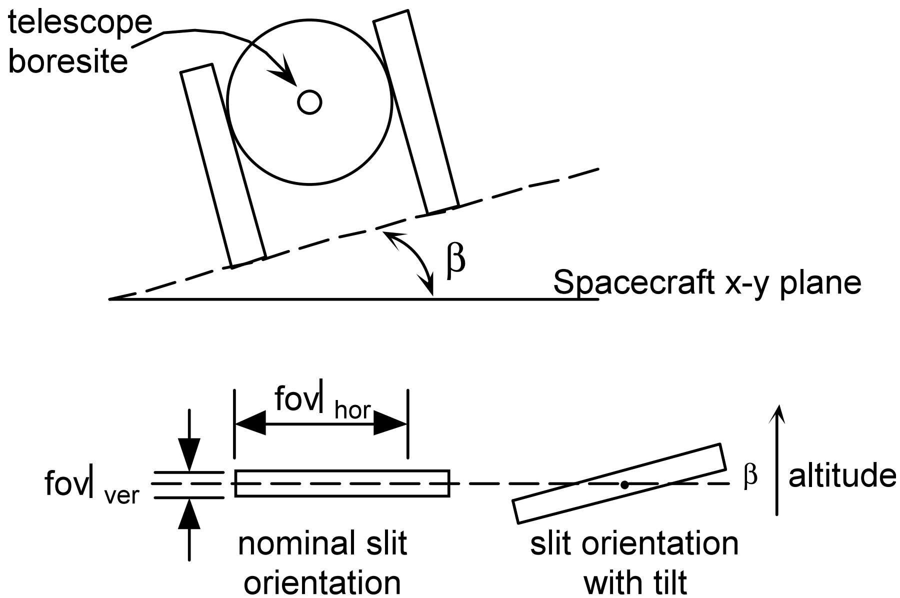
Solid = without scattered light, Dashed = with scattered light

Simulated O_2 (0,1)
Line-of-Sight Wind Errors



Solid: no scattering   Dotted b=0.0 (direct scattering only)
Dot-dashed: b=0.03 (roughness = 1 nm rms)
Dashed b=0.1 (roughness = 2 nm rms)

Telescope Boresite Tilt About Telescope x Axis



- **Requirement:**

The tilt will not increase vertical extent of the field of view by more than 20%

- **Equation:**

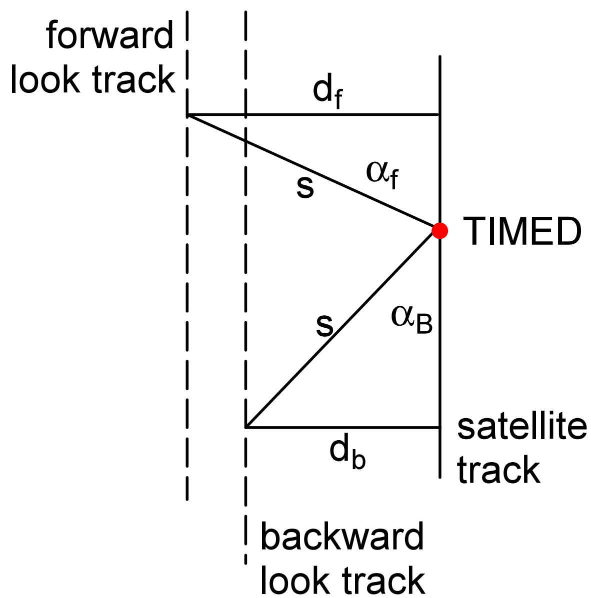
$$\beta < \frac{f \; fov|_{ver}}{fov|_{hor}}$$

- **Results:**

f=0.2; $fov|_{ver}$=0.05°; $fov|_{hor}$=2.5°
β<800 arc-sec=0.23°

Telescope Alignment:
Rotation About Telescope z Axis

- **Effects:**
  Spacecraft velocity component in measured velocity is a strong function of this angle. This is a systematic effect and is included in zero wind term.
- **The viewing track distance from the spacecraft changes.**



$d \cong s \sin\alpha \qquad s = \sqrt{(z_s - z_T)(2R_e + z}$

$z_s = 625\,\text{km} \quad z_i = 60\,\text{km} \quad R_e = 63$

$s \cong 2700\,\text{km} \quad \Delta d < 100\,\text{km}$

$\Delta s \cos\alpha \Delta\alpha$

$\Delta\alpha = \frac{\Delta d}{s \cos\alpha} = 3°$

- **Position the telescopes about the spacecraft z axis to ~1° keeps the two fields effectively overlapped.**

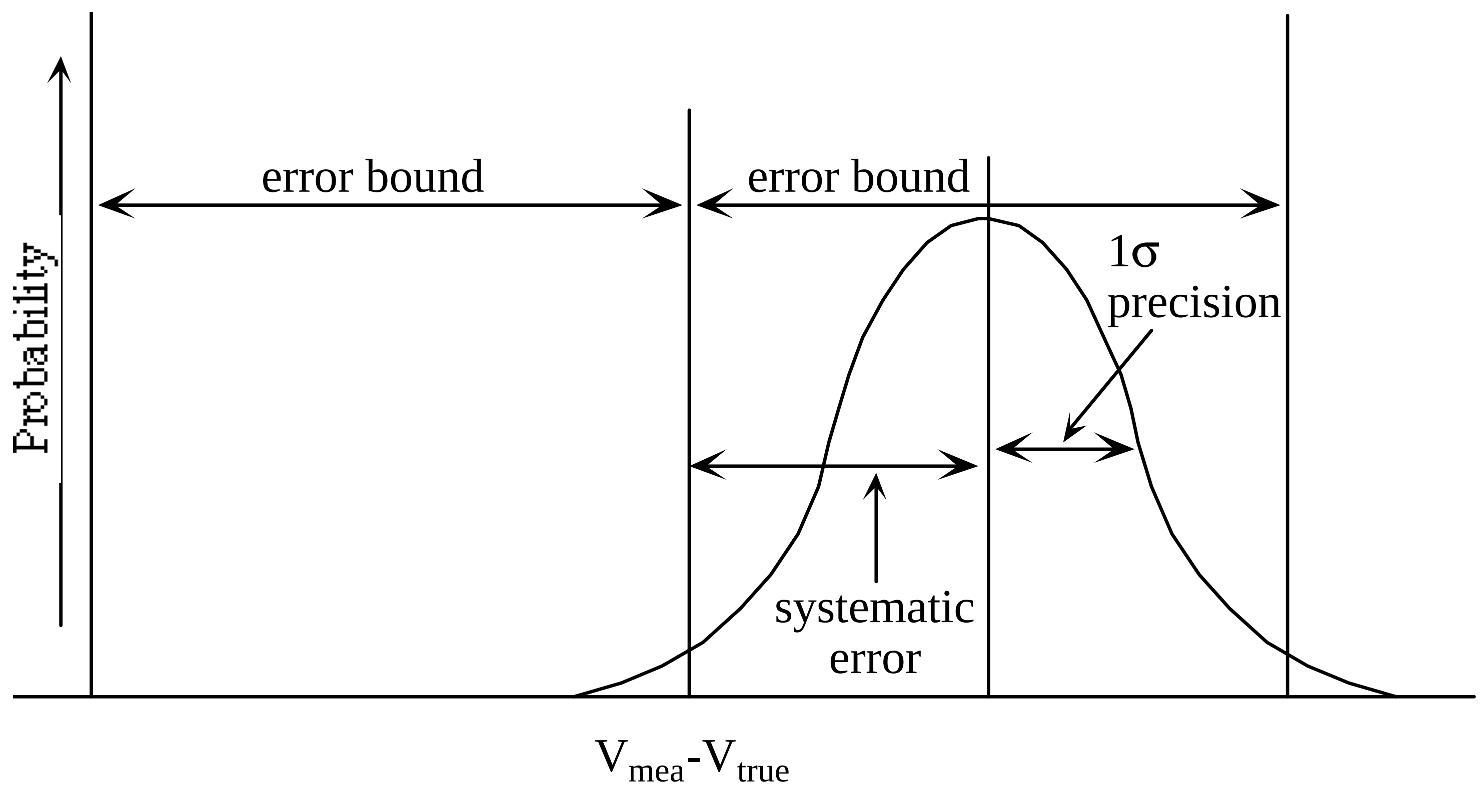
Telescope Alignment:
Rotation About Telescope y Axis

- Effect:
  Rotation about the y axis rotates the elevation angle. This decreases the overscan available.
- There is an overscan of 5° on either side of the operational range.
- Placing the telescopes within 0.5° in this axis uses 10% of the overscan.

TIDI Error Overview

- **Errors are comprised of two types:**
  - 1. Systematic - Error biases that are constant (e.g. telescope placement), change slowly (e.g. instrument drift), or are step changes that occur once (e.g. 1-g effects, launch shifts).
  - 2. Random - Errors that change from measurement to measurement and are characterized by a probability distribution, usually Gaussian.
- **A error bound is a range that, to a certain probability, will include the error from an individual measurement, e.g."the error in the measurement has a 68% chance of being within 3 m/s."**
- **Most science studies combine data in some form (e.g., averaging, fitting). This has the effect of reducing random errors by approximately 1 over the square root of the number of data points.**

TIDI Systematic and Random Errors



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TIDI Top Level Error Budget

Error type	Value
Random	2.5 m/s
Systematic	2.0 m/s
Error bound (68%) [1-σ Gaussian uncertainty equivalent]	3.2 m/s

Systematic Errors

- Systematic effects are lumped into the "zero wind." This is the average velocity the instrument would measure if the atmosphere were not in motion. Systematic effects cause this value to be non-zero.

- Measurement of the zero wind correction requires a long, detailed, and difficult validation process.
  - On-board lamps provide information of long-term instrument drifts, changes in instrument sensitivity, and spectral resolution.
  - Known information about geophysical conditions provides useful constraints that can get the zero wind correction close.
  - Other measurements (other satellite instruments, ground-based instruments, or in-situ measurements) can provide direct comparisons.

    It is essential to know the characteristics of the data used in the comparison.

Random Noise Budget

Effect	Value	Comments
Photon noise	2.0 m/s	Integration time can be adjusted to obtain this value. Besides counting statistics, this includes noise components such as CCD read noise, CCD thermal noise, and background (both direct and telescope scattered).
Spacecraft velocity component uncertainty	1.5 m/s	Includes precision of telescope pointing knowledge and spacecraft attitude errors.
Interferometer temperature uncertainty	0.5 m/s	Typical drift is 50 m/s/°C. A precision of 0.01 degrees is required.
total	2.55 m/s	

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Spacecraft Velocity Components and Errors

The spacecraft velocity component knowledge requirement drives the azimuth error.

The component of the spacecraft velocity along the line of sight is given by

$$v_c = v_{sc}\left[\cos\varepsilon\cos\alpha - \psi\cos\varepsilon\sin\alpha + \theta\sin\varepsilon\right]$$

and the error by

$$\sigma^2_{v_c} = v^2_{sc,0}\left[\sigma^2_\varepsilon \sin^2\varepsilon_0 \cos^2\alpha_0 + \sigma^2_\alpha \cos^2\varepsilon_0 \sin^2\alpha_0 + \alpha^2_\psi \cos^2\varepsilon_0 \sin^2\alpha_0 + \sigma^2_\theta \sin^2\varepsilon_0\right] + \sigma^2_{v_{sc}} \cos^2\varepsilon_0 \cos^2\alpha_0$$

Tangent Altitude and Errors

The Tangent altitude knowledge requirement drives the elevation error.

The tangent altitude is given by

$$z_T = (R_e + z_s)\cos\beta - R_e$$

and the angle, β, is given by

$$\sin\beta = \sin\varepsilon + \phi\cos\varepsilon\sin\alpha + \theta\cos\varepsilon\cos\alpha$$

The error is

$$\sigma_{z_T}^2 = (R_e + z_s)^2\left[\sigma_\phi^2\sin^2\alpha_o + \sigma_\theta^2\cos^2\alpha_o + \sigma_\varepsilon^2\right]\sin^2\varepsilon_o$$

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Error Components

Component	Value	Comment
Roll knowledge error	0.01 deg (1-σ) 36 arc-sec	spacecraft value
Pitch knowledge error	0.01 deg (1- σ) 36 arc-sec	spacecraft value
Yaw knowledge error	0.01 deg (1- σ) 36 arc-sec	spacecraft value
Elevation knowledge error	0.018 deg (1- σ) 65 arc-sec	required to meet altitude knowledge
Azimuth knowledge error	0.0083 deg (1- σ) 30 arc-sec	required to meet spacecraft velocity component knowledge
Spacecraft speed knowledge error	0.25 m/s (1- σ)	spacecraft value

Spacecraft Velocity Component Error Budget

Component	Value	Comment
Spacecraft speed error component	0.16 m/s	
Yaw knowledge error	0.85 m/s	
Roll knowledge error	0.00 m/s	no influence to 1^{st} order
Pitch knowledge error	0.51 m/s	
Elevation angle knowledge error	0.65 m/s	driven by altitude requirement
Azimuth angle knowledge error	0.71 m/s	only free parameter
Total velocity component error	1.4 m/s	budget value = 1.5 m/s

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Tangent Altitude Error Budget

Component	Value	Comment
Yaw knowledge error	0.00 km	no influence to 1^{st} order
Roll knowledge error	0.34 km	
Pitch knowledge error	0.34 km	
Elevation angle knowledge error	0.86 km	dominate term
Azimuth angle knowledge error	0.00 km	no influence to 1^{st} order
Tangent altitude precision	0.98 km	budget value = 1 km

End-to-End Azimuth and Elevation Errors

Azimuth error

$$\sigma^2_{\alpha'} = \sigma^2_{\alpha_o} + \sigma^2_{\psi} + \sigma^2_{\phi}\cos^2\alpha_o\tan^2\varepsilon_o + \sigma^2_{\theta}\sin^2\alpha_o\tan^2\varepsilon_o$$

Elevation error

$$\sigma^2_{\varepsilon'} = \sigma^2_{\varepsilon} + \sigma^2_{\phi}\sin^2\alpha_o + \sigma^2_{\theta}\cos^2\alpha_o$$

TIDI Azimuth and Elevation Knowledge Errors

Parameter	Azimuth	Elevation	Comment
Roll knowledge	11 arc-sec	25 arc-sec	Based on 0.01 deg (36 arc-sec) precision and view geometry.
Pitch knowledge	11 arc-sec	25 arc-sec	Based on 0.01 deg (36 arc-sec) precision and view geometry.
Yaw knowledge	36 arc-sec	0 arc-sec	Based on 0.01 deg (36 arc-sec) precision and view geometry.
LVDT random error	0 arc-sec	25 arc-sec	SPRL measurement.
Telescope random error - elevation, $\sigma_{e,1}$	0 arc-sec	$\sqrt{\sigma_{e,1}^2 + \sigma_{e,2}^2} \leq 60$ arc-sec	Based on elevation angle precision in S/C frame of 65 arc sec to meet altitude knowledge requirement.
Telescope pedestal to S/C error - elevation, $\sigma_{e,2}$			
Telescope random error - azimuth, $\sigma_{a,1}$	$\sqrt{\sigma_{a,1}^2 + \sigma_{a,2}^2} \leq 30$ arc-sec	0 arc-sec	Based on azimuth angle precision in S/C frame of 30 arc sec to meet S/C velocity component knowledge.
Telescope pedestal to S/C error - azimuth, $\sigma_{a,2}$			
Total	**49 arc-sec**	**74 arc-sec**	

Comparison of Alignment Requirements

	Altitude Error (km)
Total Zenith Error = 75 arc seconds	1.0
Total Zenith Error = 100 arc seconds	1.3

	S/C Velocity Component Error (m/s)	Total Random Error
Total Azimuth Error = 50 arc seconds	1.4	2.55
Total Azimuth Error = 80 arc seconds	2.15	3.00

Variable Definition

Parameter	Description
v_c	component of spacecraft velocity in viewing direction
v_{sc}	spacecraft velocity (~7500 m/s)
$v_{sc,o}$	nominal spacecraft speed
Δv_{sc}	error in spacecraft speed
$\sigma_{v_{sc}}$	standard deviation of spacecraft speed knowledge, ~0.25 m/s
ε	viewing angle depression angle (0 = horizontal viewing), nominally ~23° in the spacecraft frame
ε_o	nominal viewing depression angle, i.e. what the angle is assumed and supposed to be
$\Delta\varepsilon$	error in the depression angle
α	azimuth angle of observation ±45°, ±135° to x axis of spacecraft
α_o	nominal azimuth angle, i.e. what the angle is assumed and supposed to be
$\Delta\alpha$	error in the azimuth angle
ψ	yaw of spacecraft about z axis from the local horizontal, local vertical frame
σ_ψ	standard deviation of yaw knowledge, ~0.01 degrees
θ	pitch of spacecraft about y axis from the local horizontal, local vertical frame
σ_θ	standard deviation of pitch knowledge, ~0.01 degrees
ϕ	roll of spacecraft about x axis from the local horizontal, local vertical frame
σ_ϕ	standard deviation of roll knowledge, ~0.01 degrees
z_T	tangent altitude (60-300 km)
R_e	Earth radius (mean = 6371 km)
z_s	spacecraft altitude (625 km)
β	angle between look direction and z axis in the local horizontal, local vertical frame
$z_{T,o}$	nominal tangent point altitude

SPACE PHYSICS RESEARCH LABORATORY

TIDI

TIDI Reference Parameters

Parameter	Value
Earth radius[1]	6371.00 km (mean) 6378.14 km (equator) 6356.755 km (pole)
Satellite altitude	625 km
Altitude viewing range	60-300 km
Viewing angles (from horizon)	24.4 degrees (0 km) 23.2 degrees (60 km) 17.5 degrees (300 km)
Distance from spacecraft to tangent point	2829.3 km (0 km tangent height) 2690.2 km (60 km tangent height) 2023.0 km (300 km tangent height)
Inclination	74.2 degrees
Precession rate	~-3 degrees/day
Satellite speed	~7.55 km /s
Orbital period	~97.06 minutes
Number of orbits per day	~14.8