PILOT

Pathfinder for an International Large Optical Telescope

FUNCTIONAL & PERFORMANCE REQUIREMENTS DOCUMENT

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CHANGE RECORD

ISSUE	DATE	SECTION/PAGE AFFECTED	PRIMARY EDITOR	REASON/REMARKS
A	30/03/07	All	Will Saunders	
B	24/05/07	All	Will Saunders	Formatting changes; AJM comments not yet included
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D	28/11/07	All	Will Saunders	WS, field of view, cold stop, dome?
E	20/02/08	All	Will Saunders	WS imaging specs
F	11/04/08	All	Will Saunders	Prescriptive and subsystem material split off to System Spec
G	16/07/08	All	Will Saunders	Complete overhaul. Traceability matrix

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1 Scope

1.1 Identification

This FPRD (Functional and Performance Requirements Document) applies to the baseline implementation of PILOT (the Pathfinder for an International Large Optical Telescope), as part of the NCRIS (National Collaborative Research Infrastructure Strategy) funded 2007/8 design study.

1.2 Background and intended use

1.2.1 Aims of PILOT

PILOT is a proposed 2-metre class telescope to be built at Dome C in the Australian Antarctic Territory. The aims of the PILOT telescope are:

1. To demonstrate the feasibility of building and commissioning a large, complex, optical telescope in Antarctica.
2. To demonstrate that the costs and timescales are foreseeable and reasonable.
3. To demonstrate that such a telescope can be routinely operated with reasonable on-sky efficiency.
4. To validate and further characterise the expected excellent natural seeing characteristics of the site.
5. To demonstrate that the anticipated infrared sensitivities can be reached.
6. To demonstrate and characterise the possibilities for diffraction-limited observing from the site.
7. To perform cutting-edge science in its own right.

1.2.2 The NCRIS-funded design study

In late 2006 NCRIS announced an award of A$1M to allow a design study for PILOT to be undertaken. This study is being carried out by AAO and UNSW on behalf of the Australian astronomical community. The aims for this study are:

1. To produce a viable concept design for the system and its components, including identified suppliers for major components.
2. To produce a viable plan for the delivery, assembly and commissioning of the system to Dome C, including identified contractors where required.
3. To produce a lifecycle costing and timescale for the system.
4. To identify major technical risks and mitigation strategies where needed.

This Functional and Performance Requirements Document (FPRD) forms one of the components of that study. It specifies the requirements for the PILOT system, to meet the scientific goals spelt out in the Science Requirements Document (SRD). These in turn derive from the science cases set out in the PILOT Science Case Document. The conditions under which the PILOT facility will operate are set out in the Environmental Conditions Document.

2 Supporting documentation

2.1 Applicable documents

PILOT Science Case Document

PILOT Science Requirements Document

PILOT Environmental Conditions Document

PILOT technical note: pilot_temp_vs_height_vs_time

2.2 Other referenced documents

Science programs for a 2 m-class telescope at Dome C, Antarctica: PILOT, the Pathfinder for an International Large Optical Telescope. Burton *et al.*, 2005. Pub. Ast. Soc. Aust, **22**, 199-235.

3 Definitions, Acronyms and Abbreviations

3.1 General definitions

Interpretation of words shall be according to their definitions in the Macquarie Dictionary (Australian).

Shall expresses a characteristic which is to be present in the item which is the subject of the specification, ie. "shall" expresses a binding requirement.

Should expresses a non-binding preference.

May expresses permissive guidance.

Will expresses a declaration of intent on the part of a party, usually the sponsoring or acquiring organisation. "Will" does not express a binding requirement. "Will" may also be used in cases where the simple future tense is required, for example, "Power for the site will be supplied by the government." Any statement which employs the term "will", if used in the 'Requirements' section, should be present as a note so as to be clearly distinguishable from requirements. Will may also express simple futurity.

3.2 Technical Definitions

Diamond dust	Small, wind-blown ice crystals that are suspended in the air.
Diffraction-limited	An image with Strehl ratio greater than 0.8
d_{50}	Diameter of circle containing half the energy of an image
Free seeing	The seeing above the turbulent surface layer extending to ~100m

Quadrature	Addition (or subtraction) of quantities by squaring, combining, and taking the square root.
Seeing-limited	Images with central intensity at least 80% that given by the seeing alone.
Strehl ratio	Ratio of the central intensity to that given solely by diffraction from the aperture of the telescope
ugriz	Filter set for optical imaging, with centre and (width) given by 350(60), 475(140), 620(140), 760(150), 910(140)nm
$YJHK_dLMNQ$	Filter set for infrared imaging, with centre and (width) given by 1.04(0.20), 1.21(0.26), 1.65(0.29), 2.35(0.23), 3.76(0.65), 4.66(0.24), 10.5(5.3), 20.9(8.8)µm.

3.3 Acronyms and abbreviations

Abbreviation	Description
AAO	Anglo-Australian Observatory
ADC	Atmospheric Dispersion Corrector
AO	Adaptive Optics
fwhm	Full Width Half Maximum
MIR	Mid Infrared
NCRIS	National Collaborative Research Infrastructure Strategy
NIR	Near Infrared
PILOT	Pathfinder for an International Large Optical Telescope
TBC	To Be Confirmed
TBD	To Be Decided
TN	Technical Note
UNSW	University of NSW
wrt	With respect to
ZD	Zenith Distance

4 Environmental conditions

A full description is presented in the Environmental Conditions Document. The parameters presented here are derived from the ECD, except as noted otherwise.

The telescope will be able to operate in normal environmental conditions at Dome C, in both winter and summer. If conditions exceed the limits specified for operating conditions, then the telescope will be secured for survival.

The environmental conditions depend somewhat on elevation. A height of 30m (dome aperture) is assumed here but may be reviewed during detailed design.

4.1 Science operating conditions

In the following conditions, the system shall be capable of meeting the science specifications:

1. Ambient temperature -60C to -30C.
2. Temporal rate of change of ambient temperature in the range ±0.5ºC/minute and ±2.5ºC/hour[1]
3. Vertical rate of change of ambient temperature in the range 0-0.4ºC/m.
4. Air pressure 645 ± 5 hPa
5. Relative humidity 75-150% wrt frost, 50-100% wrt water[2].
6. Wind speed < 12m/s (mean + 1 sigma), from any direction.
7. Wind gustiness < 2% rms.
8. Arbitrary diamond dust accumulation on exposed components.
9. No other precipitation, cloud cover < 25%.
10. Ice condensation onto exposed surfaces colder than 3.5°C above ambient.
11. Sun above or below the horizon, subject only to constraints (e.g. guiding, saturation) caused by higher sky background[3].
12. Atmospheric seeing better than 0.25" at 0.5µm at a height of 100m.
13. Atmospheric seeing better than 0.4" at 0.5µm at a height of 33m.

4.2 Safe operating conditions

In the above conditions, modified as follows, the telescope will be capable of taking data.

1. Ambient temperature -65C to -25C.

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[1] From preliminary GIVRE2 tower temperature data for Autumn 2008. TBC.

[2] It is likely that an enclosure will be provided, with interior humidity < 100% wrt frost, homogeneous interior temperature, and outflow of air to prevent entry of diamond dust.

[3] Daytime seeing drops to values comparable with nighttime each afternoon when temperatures stabilise

2. Temporal rate of change of ambient temperature in the range ±1ºC/minute and ±5ºC/hour.
3. Wind speed < 16m/s (mean + 2 sigma).

4.3 Survival conditions

In the above conditions, modified as follows, the telescope and all associated hardware (tower, dome, electronics) must be able to survive safely for an indefinite period.

1. Ambient temperature -85C to +35C.
2. Rate of change of ambient temperature < 20ºC/hr.
3. Air pressure 600-1050 hPa.
4. Relative humidity wrt ice 0-165%.
5. Wind speed < 30m/s.
6. Snow precipitation < 15mm/hr water equivalent.
7. Windblown snow accumulating arbitrarily on all exposed surfaces.
8. Total external power failure.

Note that there is negligible seismic activity and no lightning at Dome C.

5 Requirements

5.1 General requirements

1. The PILOT telescope shall have aperture diameter between 1.8m and 2.5m, with preference for the largest size possible.
2. The telescope may be installed at a height above the ice surface sufficient to meet the imaging requirements.
3. The telescope will have an enclosure, to protect the telescope from frost and snow and to allow maintenance.
4. All normal data-taking operations, including calibrations, mosaicing, micro-stepping, shall be possible remotely.
5. Focus and M1-M2 alignment shall be testable and adjustable remotely.
6. Instrument change between mounted instruments will be possible remotely..
7. There will be provision for fast guiding via movement of M2 or M3.
8. The telescope shall be able to track sources at sidereal and solar system rates, with a preference for also allowing tracking of low-Earth-orbit objects.
9. Each mode of use will contain provision for guiding at an accuracy commensurate with the required image quality in that mode.
10. Each mode of use will contain provision for optical alignment of the telescope and instrument to an accuracy commensurate with the required image quality in that mode.

11. Each mode of use will contain provision for taking the calibration data commensurate with being photon or sky-noise limited.

5.2 Scientific system requirements

1. The telescope shall be designed for use from 0.4-40µm.
2. There is a preference for allowing use in the TeraHertz region from 40-450µm.
3. There is a preference for allowing use in the UV from 0.35-0.4µm.
4. The system shall be optimised for wide-field use at 2.4µm.
5. The focal length of the telescope will be such as to allow 1.5-2.5 pixel sampling of the Airy disc at 2.4µm[4].
6. The unvignetted field of view shall have a diameter at least 40 arcmin, with a preference for at least 1 degree.
7. The total emissivity of the system will be less than 5% at 2.4µm[5].
8. The system shall be designed to allow diffraction-limited imaging at 1µm in ideal conditions[6].
9. The system shall be designed to allow wide-field diffraction-limited imaging at 2.4µm in good conditions[7].
10. The design shall allow free-seeing-limited, wide-field optical use in good conditions.
11. The design shall not preclude an upgrade path to diffraction-limited imaging down to 500nm in good conditions, with the use of an AO system.
12. The design shall not preclude an upgrade path to allow diffraction-limited imaging at *YJHK*, in normal[8] conditions with an AO system.

5.3 Pointing, slewing, tracking

1. The telescope shall be able to point to all elevations greater than 20° at all azimuths, with a preference for 15°[9].

[4] For a 2.4m telescope and 18µm pixels, this translates to a focal length 22.1-36.9m, and a focal ratio f/9.2 – f/15.4.

[5] Based on 1% x 3 mirrors, plus spider and other non-optical sructures.

[6] Here and throughout, ideal conditions are taken to mean science operating environmental conditions, perfect seeing, no wind, no rate of temperature change, astronomical darkness, ZD=0°, any moon phase.

[7] Here and throughout, good conditions are taken to mean science operating environmental conditions, 25% quartile seeing, wind speed and rate of temperature change, astronomical darkness, elevation > 45°, any moon phase.

[8] Here and throughout, normal conditions are taken to mean science operating environmental conditions, astronomical darkness, median seeing, elevation > 30°, any moon phase..

[9] To reach the equator. At this zenith distance, the seeing is still comparable with temperate sites, while the NIR background is still up to an order of magnitude darker. Also required for efficient debris tracking.

2. The telescope shall be capable of at least 540° rotation in azimuth.
3. The telescope will be able to point to an elevation of 0° at (at least) a single azimuth, to allow top end changes and other top end maintenance to be carried out.
4. The telescope shall point to better than 20", with a preference for 5".
5. In all modes, the time taken to slew from and to anywhere on the sky, acquire a new guide star, and start observing, shall be less than 3 minutes.
6. The telescope shall be able to track at sidereal and solar-system rates.
7. The telescope shall be able to track at sidereal rates at all elevations less than 89°.
8. Subject to elevation and azimuth limits, the telescope shall allow indefinite tracking of sidereal and solar-system sources.
9. The telescope shall be capable of tracking sidereal or solar-system sources, without guiding, with a pointing error of less than 0.2" for a period of 10s[10].
10. There is a preference for a capability to track objects in low-earth orbits, requiring a tracking rate of 1°/s.
11. There will be an instrument rotator at each Nasmyth focus.
12. When tracking sidereal sources, the accumulated angular error on the instrument rotator will be less than 10μrad/hr.

5.4 Guiding, offsetting

1. Guiding commands will be driven from within each instrument. Guiding may use a combination of the fast tip-tilt capability (for small amplitude fast guiding) and the telescope drive motors (for longer timescales or larger offsets).
2. In each mode, guide star acquisition shall take less than 1 minute.
3. In each mode, the capture field of view of the guiding system shall be larger than the combined telescope pointing error and tower flexure.
4. In each mode, it shall be possible to use the guiding system to offset the telescope position by arbitrary amounts, subject only to guide star availability for the offset position, with an accuracy better than 1/10 pixel or 1%, whichever is larger[11].
5. Blind offsetting (unguided) shall be possible by arbitrary amounts with accuracy 0.05"+2% of the offset.[12]
6. The secondary mirror will have a fast guiding capability. The minimum throw will be at least ±1" in either direction[13]. The minimum frequency will be at least 30Hz, with a preference for 100Hz[14].

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[10] For daytime use.

[11] For micro (sub-pixel) dithering.

[12] For dithering and mosaicing.

[13] Based on expected rms windshake of ~0.2" and fwhm image motion 0.2-0.3”

7. There will be provision for chopping, with a throw of at least 1', at a rate of at least 1Hz, with no greater than 10% lost time due to telescope motion. All these specifications are nominal and subject to revision during detailed design.

5.5 Core modes

The PILOT system shall be capable of the following modes of use: wide-field NIR (1-5μm) seeing-limited imaging; high resolution NIR (1-5μm) diffraction-limited imaging; wide-field (1°) seeing-limited optical imaging; Fast (>10Hz) diffraction-limited optical (0.4-1μm) imaging; wide-field MIR imaging and low resolution spectroscopy.

5.5.1 Wide-field Near-Infrared imaging

1. There will be a capability for wide-field imaging over 1-5μm, optimised at 2.4μm.
2. Filters will include at least $YJHK_dLM$. At least 12 filters will be permanently available.
3. The detector area shall be at least 75mm x 75mm, with a preference or upgrade path for 120mm x 120mm [15].
4. The pixel scale shall be in the range 1.5-2.0 pixels per diffraction-limited resolution element (1.22λ/D) at 2.4μm. For a 2.4m telescope and 18μm pixels, this translates to a focal length 22.1-29.5m, a focal ratio f/9.2 – f/12.3, and a pixel scale 0.12-0.168"/pixel.
5. All optics below M3 shall be part of, or included inside, the dewar. An exception may be made for a dichroic beamsplitters allowing simultaneous optical/NIR or NIR/MIR use.
6. The total degradation to the image quality delivered by the system in normal conditions, over the entire detector area and in bands $YJHK_dLM$, shall be a 50% encircled energy diameter better than 0.2", or 1/3 of the Airy disc diameter, whichever is larger. The baseline is an idealised diffraction-limited telescope with unobscured primary, perfect imaging and atmospheric dispersion correction, and no local or boundary layer seeing degradation. The calculated degradation is to include all other effects, combined in quadrature.
7. The delivered PSF under median seeing conditions must be uniform and symmetric to within 10% in FWHM across the total field of view, and must be modellable to within 0.5% for colour or position-dependent errors.
8. The efficiency of the system (top of telescope to detected photons), shall be greater than 50%, over the entire detector area and in all bands.

[14] Based on 10 x the Tyler frequency of 3-5Hz, and the tower fundamental windshake frequency 2-3Hz.

[15] Based on a 4 x 2048x2048 Hawaii-2RG18 array with 18μm pixels, or 4 x 4096x4096 Hawaii-4RG15 array with 15μm pixels.

9. The thermal background from the instrument, telescope, ground, non-imaged sky, and out-of-band imaged sky, as seen by the detectors, will amount to not more than 10% of in-band imaged sky at 2.4μm or 100% at 4.66μm[16].
10. Baffles, Narcissus mirrors, undersized secondary and cold stops are acceptable, as long as the vignetting introduced does not amount to more than 10% anywhere within the field, for any of the primary modes of use.
11. A fast guiding system will be specified, such as to allow at least 95% sky coverage, with a target of 99%. Field rotation and field recentering may be allowed to reach this target.
12. The guiding system will allow sub-pixel micro-stepping.
13. Calibration facilities will be specified, allowing flat-fielding of the data at a level better than the photon or sky noise, with lost science time less than 5%.
14. Provision will be made for allowing periodic measurement and adjustment of focus and alignment of camera and telescope, at a level allowing the image quality specifications to be met.
15. The data storage and reduction facilities should be capable of reducing and storing a maximum number of 10000 frames per day, for up to 200 days use.

5.5.2 Near-Infrared diffraction-limited mode

1. The PILOT system shall be capable of delivering well-sampled, diffraction-limited images at 1-2.5μm, should environmental conditions (seeing, thermal stability, windshake) allow.
2. Filters will include at least $YJHK_d$. At least 12 filters will be permanently available.
3. In this mode, the useable detector area shall be at least 37.5mm x 37.5mm[17], with a preference for the largest size possible.
4. The pixel scale shall be in the range 2.0-3.0 pixels per diffraction-limited resolution element (1.22λ/D) at 1μm. For a 2.4m telescope and 18μm pixels, this translates to a focal length 70.8-106.2m, a focal ratio f/29.5 – f/44.3, and a pixel scale 0.035-0.052"/pixel,
5. All optics below M3 shall be part of, or included inside, the dewar. An exception may be made for a dichroic beamsplitters allowing simultaneous optical/NIR or NIR/MIR use.
6. There is a preference for this mode to use the same focal station and detector as the wide-field NIR imaging mode, with interchangeable optics within the instrument.
7. The total degradation to the image quality delivered by the system in good conditions, over the entire detector area and in bands $YJHK_d$, shall be a 50% encircled energy

[16] Equating to 6.6% total telescope emissivity at -46°C for fiducial values for the sky background of 100μJy at 2.4μm and 0.5Jy at 4.66μ (Burton et al. 2005).

[17] Based on a single 2048x2048 Hawaii-2 detector with 18μm pixels.

diameter better than 0.12", or 1/3 of the Airy disc diameter, whichever is larger. The baseline is an idealised telescope with unobscured primary, perfect fast tracking, imaging and atmospheric dispersion correction, and no local seeing effects. The calculated degradation is to include all other effects. It is to be taken in quadrature and including diffraction.

8. An upgrade path will be specified to an adaptive optics system allowing these specifications to be met in normal conditions.
9. The efficiency of the system (top of telescope to detected photons), shall be greater than 25% over the entire detector area and in all bands.
10. The thermal background from the instrument, telescope, ground, non-imaged sky, and out-of-band imaged sky, as seen by the detectors, will amount to not more than 20% of imaged sky at 2.4μm.
11. Baffles, Narcissus mirrors, undersized secondary and cold stops are acceptable, as long as the vignetting introduced does not amount to more than 20% anywhere within the field.
12. A fast guiding system will be specified, such as to allow at least 90% sky coverage, with a target of 99%. Field rotation and field recentering may be allowed to reach this target.
13. Calibration facilities will be specified, allowing flat-fielding of the data at a level better than the photon or sky noise, with lost science time less than 5%.
14. Provision will be made for allowing periodic measurement and adjustment of focus and alignment of camera and telescope, at a level allowing the image quality specifications to be met.
15. The data storage and reduction facilities should be capable of reducing and storing a maximum number of 10000 frames per day, for up to 200 days use, shared with wide-field NIR mode.

5.5.3 Wide-field Optical Imaging

1. The system will allow wide-field optical imaging, over a wavelength range 400nm-1000nm, with a preference for 350nm-1000nm. The system will be optimised for 800nm.
2. The filter set will include at least *griz* filters, and a very broadband filter designed to maximise faint galaxy S/N. There is a preference for *u* also. At least 4 and preferably 6 filters will be available at any time, and filters must be interchangeable.
3. The detector area for wide-field optical imaging shall be at least 450cm^2, with a preference for at least 900cm^2 [18].

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[18] Allowing, e.g., 10 x STA1600A 10K x 10K detectors, or at 1000cm^2, allowing the PanSTARRS 1.4Gpix array

4. The plate scale will be 2-3 detector resolution elements per expected median tip-tilt-corrected seeing fwhm at 800nm. The detector resolution element is defined as one pixel, as broadened by charge diffusion. The median expected tip-tilt corrected seeing at 800nm is taken to be 0.3"[19]. For a 2.4m telescope and a pixel size of 12μm with negligible charge diffusion, this translates to a focal length 19.7-29.5m, a focal ratio f/8.2– f/12.3, and a pixel scale 0.1-0.15"/pixel.
5. The total degradation to the image quality delivered by the system in the normal conditions, over the entire detector area and in *griz* bands, shall be a 50% encircled energy diameter better than 0.2", or 1/3 of the Airy disc diameter, whichever is larger. The baseline is an idealised telescope with unobscured primary, perfect tracking, imaging and atmospheric dispersion correction, and no local seeing effects. The calculated degradation is to include all other effects. It is to be taken in quadrature and including diffraction.
6. The delivered PSF under median seeing conditions must be uniform and symmetric to within 5% in FWHM across the total field of view, and must be modellable to within 0.25% for colour and position-dependent errors.
7. An ADC will be included, allowing correction for atmospheric dispersion to a ZD of at least 70°.
8. The efficiency of the system (top of telescope to detected photons), shall be greater than 50%, over the entire detector area for $\lambda > 0.5\mu m$, and greater than 25% at 0.4μm.
9. A fast guiding system will be specified, such as to allow at least 95% sky coverage, with a target of 99%. Field rotation and field recentering may be allowed to reach this target.
10. Provision will be made for allowing periodic measurement and adjustment of focus and alignment of camera and telescope, at a level allowing the image quality specifications to be met.
11. Calibration facilities will be specified, allowing flat-fielding of the data at a level better than the photon or sky noise, with lost science time less than 5%.
12. There is a preference that differential field distortion due to temperature effects and due to atmospheric dispersion be each less than 2 pixels across the detector
13. The data storage and reduction facilities should be capable of reducing and storing a maximum number of 500 frames per day, for up to 200 days use.

5.5.4 Optical diffraction-limited mode

1. The system will allow for low noise, high speed optical imaging from 0.4-1μm.
2. Filters will include at least *griz*.
3. In this mode, the detector area shall be at least 13mm x 13mm[20].

[19] Subject to review in light of further site testing.

[20] Based on 1K x 1K E2V L3Vision CCD201 detector

4. The pixel scale shall be in the range 2-3 detector resolution elements per diffraction-limited resolution element (1.22λ/D) at 500nm. For a 2.4m telescope and 15µm pixels and detector resolution elements, this translates to a focal length 118-177m, a focal ratio f/49 – f/74, and a pixel scale 0.021-0.031"/pixel.
5. The total degradation to the image quality delivered by the system in good conditions, over the entire detector area and in *griz* bands, shall be a 50% encircled energy diameter better than 0.12", with a target of 0.09".The baseline is an idealised telescope with unobscured primary, perfect tracking, imaging and atmospheric dispersion correction, and no local seeing effects. The calculated degradation is to include all other effects. It is to be taken in quadrature and including diffraction.
6. The efficiency of the system (top of telescope to detected photons), shall be greater than 25%, across the entire detector and in *griz* bands.
7. A guiding scheme will be specified, such as to allow at least 50% sky coverage, with preference for the largest value possible. Field rotation and field recentering are allowed to reach this target.
8. The frame rate for the entire detector will be at least 20Hz, with a preference for 50Hz. Frame rates of 100Hz must be achievable for full-width windowed portions of the detector.
9. An ADC will be included.
10. An upgrade path will be specified to an adaptive optics system allowing diffraction-limited imaging into the optical, with a target of 500nm, in good conditions.
11. Calibration facilities will be specified, allowing flat-fielding of the data at a level better than the photon or sky noise, with lost science time less than 10%.
12. Provision will be made for allowing periodic measurement and adjustment of focus and alignment of camera and telescope, at a level allowing the image quality specifications to be met.
13. The data reduction facilities should be capable of storing and reducing the PLIC data in real time (i.e., select, register and co-add frames). The maximum storage of data should be 50GB/day (compressed) for up to 200 days.

5.5.5 Mid-Infrared imaging and spectroscopic mode

1. The system shall allow diffraction-limited imaging and low resolution spectroscopy at 10-20µm, with a preference for 7-40µm.
2. Available filters will include broad-band filters at N, Q bands; narrow-band filters for the molecular hydrogen rotation lines at 12.3µm and 17.0µm, with a preference for also NeII 12.8µm, at resolution at least R=3000, with a preference for R>10000; and grisms giving narrow-band spectral resolution not less than R=100, with a preference for R=1000, for the entire wavelength range. At least 8 filter slots will be available for each detector.
3. The field of view will be not less than 1024 x 1024 pixels for 7-20µm, and not less than 256 x 256 pixels for 20-40µm..

4. The pixel scale will be 1.5–2.5 pixels per diffraction limited resolution element at 17 μm and 30 μm.
5. The image quality will allow diffraction-limited imaging at all wavelengths in median conditions.
6. The efficiency of the system (top of telescope to detected photons), shall be greater than 50%, across the entire detector and in all bands.
7. The phase shift across the field for narrow-band imaging will be less than 1/1000, with a preference for 1/3000.
8. The thermal background from the instrument, telescope, ground, non-imaged sky, and out-of-band imaged sky, as seen by the detectors, will be no greater than 50% of in-band imaged sky in narrow-band use at 17.0 μm.
9. A guiding system will be specified, such as to allow at least 95% sky coverage, with a target of 99%. Field rotation and field recentering may be allowed to reach this target.
10. Calibration facilities will be specified, allowing flat-fielding of the data at a level better than the photon or sky noise, with lost science time less than 10%.
11. Provision will be made for allowing periodic measurement and adjustment of focus and alignment of camera and telescope, at a level allowing the image quality specifications to be met.
12. The data storage and reduction facilities should be capable of reducing and storing a maximum number of 10,000 frames per day, for up to 200 days use.

5.5.6 Interchange and simultaneous use

1. The NIR and fast optical cameras will be permanently mounted on the telescope. Other instruments may be changed according to season.
2. Interchange to the NIR or fast optical cameras shall be possible, in normal operation, in less than 5 minutes.
3. Interchange from or between any other instruments shall be possible in less than 1 working day.
4. There is a preference for simultaneous wide-field Optical/Near-Infrared use.
5. There is a preference for simultaneous wide-field Near-Infrared/Mid-Infrared use.
6. There is a preference for all 4 instruments to be mounted simultaneously.
7. There is a preference for future instruments to be mountable.

5.5.7 First light and commissioning instruments

1. A small-field optical camera shall be the commissioning instrument. This may be the fast readout, high resolution optical camera.

The preferred first major instrument (Optical wide-field, NIR imager, MIR imager) depends on detector availability, funding and design contributions.

5.6 *Other potential modes of use*

5.6.1 Potential Terahertz use

Dome-C is a superb site for Terahertz astronomy, and PILOT is in principal able to perform at these wavelengths.

1. The system shall not unnecessarily preclude use at 40-450μm.

5.6.2 Potential use for tracking space debris

The PILOT telescope is well-suited (in terms of geographic location and aperture) for the tracking of space debris during the extensive twilight. The following additional requirements will not be precluded:

1. A fast wide-field optical camera.
2. Tracking for arbitrary near-earth orbits, at rates up to ~1°/s.
3. Greatly increased data handling capabilities, and an ability to keep data entirely separate for proprietary reasons.

5.7 *Image quality error budget*

1. The baseline for determining image degradation is the diffraction limit from the unobscured primary, convolved with the optimally tip-tilt-corrected free atmospheric seeing.
2. The contributions to image quality to be taken into consideration shall include, at least, all of the following:

   (a) Effect of secondary and baffles on diffraction pattern;

   (b) Differential refraction;

   (c) Optical aberrations assuming ZEMAX parameters;

   (d) Deviations from ZEMAX surface parameters on manufacture;

   (e) Deviations from ZEMAX surface parameters caused by gravity, wind, and temperature variation;

   (f) Surface roughness;

   (g) Inhomogeneity within transmissive optics;

   (h) Misalignment of optics;

   (i) Pixellation, including charge diffusion;

   (j) Atmospheric seeing (where explicitly specified);

   (k) Tip-tilt correction (where explicitly specified);

   (l) Mirror seeing;

(m) Telescope seeing[21];

(n) Dome seeing[22];

(o) Surface layer turbulence;

(p) Guiding errors;

(q) Windshake.

5.8 Site monitoring requirements

Environmental conditions will be monitored continuously, both to determine the optimal program and for system protection.

1. The facility shall contain sufficient site-testing instrumentation to enable a continuous monitoring of seeing or turbulence, cloud and atmospheric emission monitor, humidity, and snowfall.

[21] i.e. thermal effects within the dome

[22] i.e.thermal effects at the dome aperture

6 Operational Functionality and Performance

6.1 Operations

1. The system will be capable of indefinite continuous operation.
2. Normal operations shall require no more than a single operator, who will in general be remote from the telescope.
3. Normal operations, including calibrations and instrument changes between mounted instruments, shall be possible unsupervised, for indefinite periods, via observing scripts generated by an automated system based on current conditions.
4. Normal operations shall not require physical access to any part of the system.
5. Operations support for normal operations and for routine maintenance, defined as those tasks scheduled more often than annually, shall require no more than a single technical assistant.
6. The system will be designed for maximum reliability and minimal human intervention.
7. Downtime due to routine maintenance shall not exceed 5% of useable night time or 10% of useable day time.
8. Foreseeable major maintenance tasks (e.g. mirror recoating) requiring more than a single person shall be specified, quantified, and a procedure for doing them specified.

6.2 System control

1. The telescope shall be provided with a computer controlled Telescope Control System.
2. System control (opening up, slewing to a field, acquiring a guide-star, data-taking, calibrations, instrument changes, closing up) shall be possible in three modes:
   - by a local operator at Concordia or in the dome.
   - remotely from outside Antarctica.
   - under computer control via a user-supplied script.
3. In all operating modes, interlocks (e.g. snow alarm, zenith limits, turnkey access to telescope) shall prevent unsafe operation.
4. Routine survey operations shall be possible by technical staff without specific astronomical training.
5. Requirements for the data transfer required for remote operation from outside Antarctica shall be specified in the design study.

6.3 Observational setup selection

1. A method shall be specified for selection of the observational setup and target selection, at all times when useful data-taking is possible.

2. This method shall include selection of programs suitable for any given time of day or year.
3. This method shall include procedures for deciding between programs in real time, and for determining all observational parameters (e.g. filters, calibration frames, exposure times, field pointings), dependent on current and projected environmental and astronomical conditions.
4. These procedures shall not require expert astronomical expertise.

6.4 Data rates, handling and storage

1. Computing facilities shall allow data taking at the fastest expected rates for normal use of any instrument or expected combination of instruments.
2. Computing facilities shall allow data to be pipeline processed, including mosaicing and dithering, into reduced image frames and image catalogues, in real time[23].
3. Computing facilities shall allow a week's worth of data to be stored online.
4. Computing facilities shall allow an entire year's worth of raw and reduced data to be stored.
5. There shall be a separate system for data re-reduction
6. All raw, reduced and extracted data shall be automatically backed up to two copies of removable physical media in real time.
7. The data handling system shall store the two backup copies in different buildings.

6.5 Data reduction

1. All normal data-taking operations will be provided with a data reduction pipeline.
2. The Data Reduction Pipeline shall automatically produce fully calibrated (photometrically and astrometrically), mosaiced and coadded images.
3. The Data Reduction Pipeline shall automatically produce lists of extracted sources together with basic properties.
4. The Data Reduction Pipeline shall complete its automated pipeline tasks faster than the expected daily-averaged rate at which data is acquired.
5. The Data Reduction Pipeline shall be able to merge lists taken at different wavelengths or pointings into single catalogues.
6. The Data Reduction Pipeline shall be capable of automatically detecting and flagging temporal changes in reobserved fields.

[23] Fast optical imaging excepted

6.6 Data transfer

It is not expected that data transfer in real time will be feasible. However transfer of extracted lists of sources and selected data subsets is possible and desirable. In addition, the routine operation of the telescope will require transfer of housekeeping and quality-control information.

1. A method of transferring test data for quality verification shall be specified.
2. A method for extracting and transferring 'postage stamp' data for current and/or any previous observations of selected areas shall be specified.
3. Allowance for data transfer of up to 500 MB/day is required[24].
4. A method for transporting all raw and reduced PILOT data from Dome-C to outside Antarctica shall be specified.
5. A system for checking, storing and archiving PILOT data products outside Antarctica shall be specified.
6. A method shall be specified for the world-wide dissemination of all non-proprietary PILOT data.

[24] Corresponding to a single satellite channel in continuous use.

7 Environmental Functionality and Performance

1. The facility shall meet its functional and performance requirements in the specified ‘science operating conditions’ (Section 4.1).
2. The facility shall be able to operate safely under the specified ‘safe operating conditions’ (Section 4.2).
3. With the telescope enclosure closed, the facility shall survive without damage the specified ‘survival conditions’ (Section 4.3).
4. For components where periodic clearing of diamond dust is required, a procedure for doing so shall be identified.
5. All exposed components shall be able to function, or safe recovery procedures specified, after snowfalls of 20mm water equivalent with drifting.
6. The telescope shall function safely at the coldest expected temperatures. Manufacture, partial assembly and possibly partial testing of the telescope will take place at room temperatures. The temperature specification for mechanical functionality is -85C to +30C.
7. Any exhaust heat and gases from telescope, dome, electronics or any other components must have negligible effect on optical coatings.
8. All coatings and other surface materials must be designed to withstand any diesel fumes or other pollutants that are likely to be present at Dome C. The level of these pollutants is still to be determined.
9. During operations, no more than 400W of heat loading shall be released within the space envelope prescribed by the closed telescope enclosure.
10. During operations, no unventilated exposed surface within the space envelope prescribed by the closed telescope enclosure shall have a product of area and temperature differential larger than $2m^2$°C.
11. Any exhaust heat and gases from telescope, dome, electronics or any other components, injected into the dome, will be less than $10W/m^2$.

8 System reliability, maintainability, durability

8.1 Reliability

1. The target for time lost due to hardware, software or procedural faults shall be no more than 5% of astronomical dark time and 25% of other time.
2. The target mean time between failures requiring human intervention for the entire system shall be greater than 1 week of continuous use.
3. The target risk of catastrophic failure entailing more than a month's downtime shall be less than 5%/year.

8.2 Maintainability

1. Plug-in spares will be provided for all components with estimated risk of failure greater than 5% per year.
2. The service interval will be multiples of 12 months for all components.
3. Provision shall be made for warming the telescope and enclosure to safe working temperature for maintenance.
4. Provision shall be made for removing and reinstalling or exchanging each of the telescope mirrors.
5. Provision shall be made for removing and reinstalling or exchanging all the instruments.

8.3 Durability

1. The design life of the system is 10 years.
2. All components with estimated risk of failure greater than 5% within this lifetime will have repair or replacement procedures specified.

9 Interfaces

9.1 Internal interface requirements

All subsystem designs shall identify and include all interfaces with the other subsystems. This identification and interface definition shall form part of the subsystem FPRDs.

These interfaces shall be separately checked for consistency and redesigned as needed.

9.2 External interface requirements

PILOT external interfaces have been identified as indicated in Figure 1. Each of these interfaces shall be rigorously defined in an ICD (Interface Control Document).

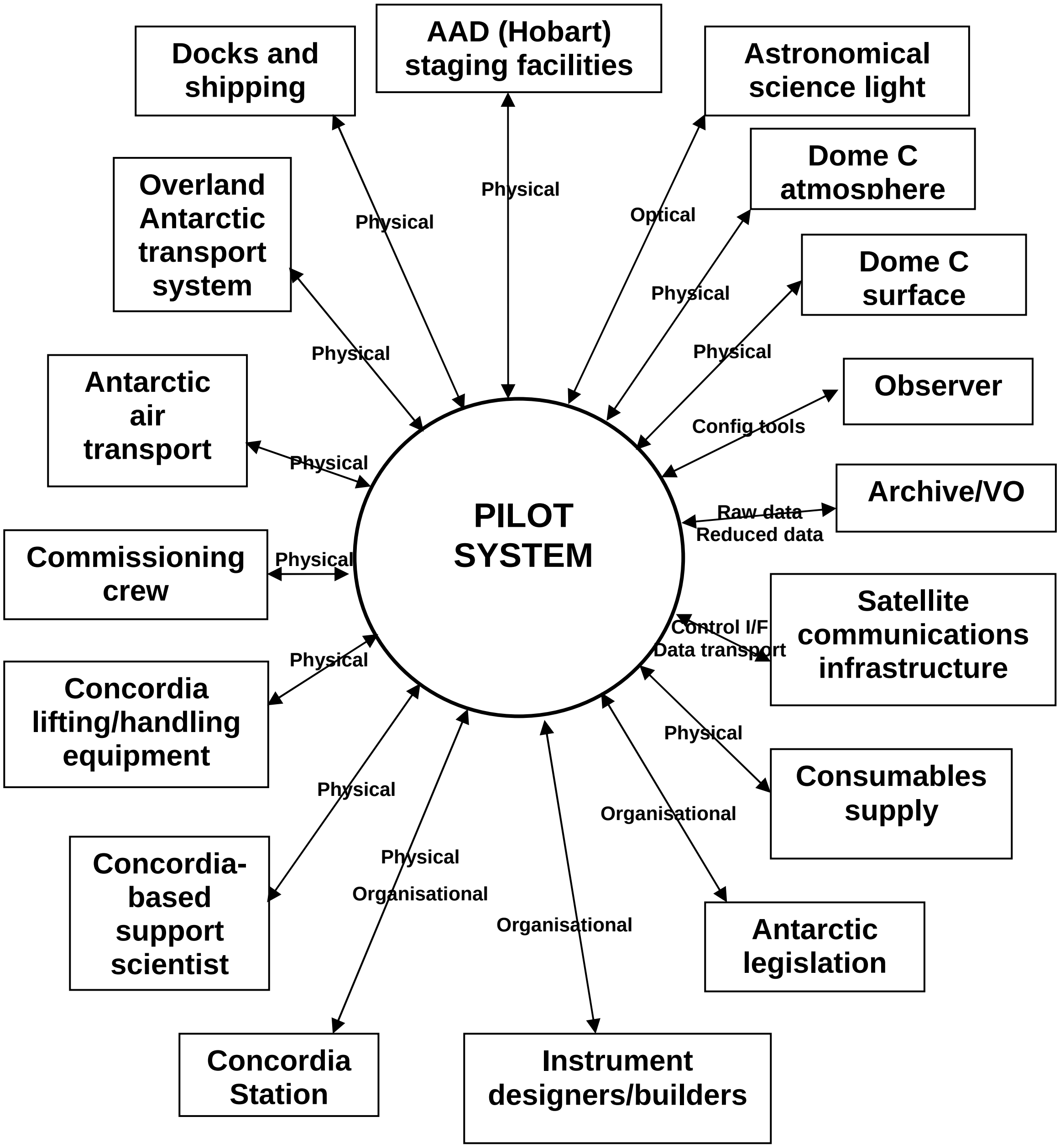

Figure 1. PILOT system external interfaces.

9.3 System environmental requirements

There are no system-level environmental requirements.

Note that subsystems and specific interfaces will certainly incur their own environmental requirements; for example the ICD controlling the interface with Concordia Station will necessarily specify requirements on RF interference from PILOT subsystem to the station, and vice versa, and on allowable levels of light emission from the station that reach the telescope.

9.4 External resource utilization requirements

No specific system-level external resource utilization requirements have been identified. Customer requirements documents may subsequently impose such requirements (for example, requirements to use resources from specific national Antarctic agencies, or limitations on fossil fuel consumption).

9.5 System physical requirements

No system-level physical requirements have been identified. The requirement to locate the telescope subsystem at Dome C is explicit in the project definition. Subsystems will inherit physical requirements from interface definitions in the relevant ICDs.

10 Design and construction requirements

10.1 General design and construction constraints

1. There is a strong design preference for the use of standard or existing components.
2. Wherever applicable, use will be made of design standards (including internal data standards, workmanship requirements, production techniques).
3. The design, construction and decommissioning plan shall comply with the Madrid Protocol.

Appendix A. Traceability Matrix

This section details traceability of each requirement specified in this document, from each source requirement in the OCD, contract Statement of Work, science requirements documents, customer requirements documents, or ICDs.

Each FPRD requirement should trace to one or more higher level requirements, as applicable; or alternatively reference to the document which contains requirements traceability information.

Note: Higher level requirements are requirements which are source requirements contained in source documents. Source documents may include operational requirements documents, policy documents, standards, legislation, requirements clarification records, etc, or the specification (including applicable IRSs/ICDs) of the higher level element of which the item is a part.

Qualification methods aimed at verifying the requirements have been met may include:

a. **test**. The operation of the system, or a part of the system, using instrumentation or other special test equipment to collect data for later evaluation;

b. **demonstration**. The operation of the system, or a part of the system, that relies on observable functional operation not requiring the use of instrumentation, special test equipment, or subsequent analysis;

c. **analysis**. The processing of accumulated data obtained from other qualification methods. Examples are reduction, interpolation, or extrapolation of test results;

d. **inspection**. The visual examination of system components, documentation, etc;

e. **special qualification methods**. Any special qualification methods for the system, such as special tools, techniques, procedures, facilities, acceptance limits, use of standard samples, preproduction or periodic production samples, pilot models, or pilot lots.

X is wild card for any integer.

Requirement	Description	Origin	Qualification	Comment
1.2.1.X	PILOT goals	Project Plan	b	
1.2.2.X	Design study goals	Project Plan	b	
4.X.X	Environmental conditions	ECD	c	
5.1.1	Telescope size	SRD 2.1.1	d	
5.1.2	Tower height	SRD 2.1.5	d	

Requirement	Description	Origin	Qualification	Comment
5.1.3	Enclosure	ECD	d	Frost, wind, ΔT protection
5.1.4	Remote operation	Functional utility	b	
5.1.5	Focus, alignment	Functional utility	c	
5.1.6	Instrument switching	SRD 2.1.8	b	GRB's
5.1.7	Fast guiding	SRD 2.1.5, SRD 3.X.4	b	Seeing, Tower shake
5.1.8	Tracking	SRD 2.1.7	b	
5.1.9	Guiding	SRD 2.1.5, SRD 3.X.4	b	
5.1.10	Alignment	SRD 2.1.5, SRD 3.X.4	b	
5.2.1-3	Wavelength coverage	SRD 2.1.2	c	
5.2.4	Optimisation at 2.4μm	SRD 3.2.1	c	
5.2.5	Focal length	SRD 3.2.02	c	
5.2.6	FOV	SRD 2.1.4	c	
5.2.7	Emissivity	SRD 2.1.6	c	
5.2.8	Image quality at 1μm	SRD 3.2.04	b	Also pathfinding
5.2.9	Image quality at 2.4μm	SRD 3.2.04	b	
5.2.10	Image quality in optical	SRD 3.1.04	b	
5.2.11,12	AO upgrade paths	Observing efficiency	d	Also pathfinding
5.3.1	Elevation limit	SRD 2.1.3	b	Also debris tracking
5.3.2	Azimuth limit	Observing efficiency	b	
5.3.3	Elevation limit	System Utility	b	Top end

Requirement	Description	Origin	Qualification	Comment
				changes
5.3.4	Pointing	Observing efficiency	b	
5.3.5	Slewing time	SRD 2.1.6	b	Also observing efficiency
5.3.6	Tracking	SRD 2.1.7	b	
5.3.7	Zenith blind spot	Observing efficiency	b	
5.3.8	Tracking	SRD 2.1.7	b	
5.3.9	Tracking without guiding	SRD 3.3.11	b	Also TeraHertz
5.3.10	Tracking LEO objects	SRD X.X.X	b	For space debris
5.3.11	Instrument rotators	Functional utility	b	
5.3.12	Rotator accuracy	SRD 3.1.5	c	0.05" across field in 1 hr
5.4.1	Guiding from instruments	Functional utility	b	
5.4.2	Acquisition time	Observing efficiency	b	
5.4.3	Guide window	Functional utility	c	
5.4.4	Microstepping	SRD 2.2.5, SRD 3.3.4	b	Barely sampled PSF's for max FOV
5.4.5	Offsetting		b	Mosaicing, spectral acquisition
5.4.6	Fast Guiding	SRD 3.1.5, SRD 3.2.5	b	Wind shake + image motion
5.4.7	Chopping		b	Nominal spec, subject to review
5.5.1.1	PNIRC WF λ	SRD 3.2.1	d	

Requirement	Description	Origin	Qualification	Comment
5.5.1.2	PNIRC WF filters	SRD 3.2.7	d	
5.5.1.3	PNIRC WF FOV	SRD 3.2.3	c	
5.5.1.4	PNIRC WF pixel scale	SRD 3.2.2	c	
5.5.1.5	PNIRC WF cold optics	SRD 3.2.10	d	
5.5.1.6	PNIRC WF image quality	SRD 3.2.4, SRD 3.2.5	a	
5.5.1.7	PNIRC PSF stability	SRD 3.2.7	a	
5.5.1.8	PNIRC WF throughput	SRD 3.2.9	a	
5.5.1.9	PNIRC WF thermal background	SRD 3.2.10	a	
5.5.1.10	PNIRC WF baffling	SRD 3.2.9	d	
5.5.1.11	PNIRC WF sky coverage	Functional utility	d	
5.5.1.12	PNIRC WF micro-stepping	SRD 3.2.5	c	
5.5.1.13	PNIRC WF calibration	Observing efficiency	d	
5.5.1.14	PNIRC WF focus/alignment	SRD 3.2.5	b	
5.5.1.15	PNIRC WF data rates	SRD 3.2.11	b	
5.5.2.1	PNIRC HR λ	SRD 3.2.1	b	
5.5.2.2	PNIRC HR filters	SRD 3.2.7	d	
5.5.2.3	PNIRC HR FOV	SRD 3.2.3	d	
5.5.2.4	PNIRC HR pixel scale	SRD 3.2.2	d	
5.5.2.5	PNIRC HR cold	SRD 3.2.10	d	

Requirement	Description	Origin	Qualification	Comment
	optics			
5.5.2.6	PNIRC HR/WF	SRD 3.2.2.	d	
5.5.2.7	PNIRC HR image quality	SRD 3.2.4, SRD 3.2.5	a	
5.5.2.8	PNIRC HRAO upgrade		d	Pathfinding
5.5.2.9	PNIRC HR throughput	Observing efficiency	a	
5.5.2.10	PNIRC HR thermal background	SRD 3.2.10	a	
5.5.2.11	PNIRC HR baffling	SRD 3.2.9	d	
5.5.2.12	PNIRC HR sky coverage	Functional utility	b	
5.5.2.13	PNIRC HR calibration	SRC 3.2.12	d	+ Observing efficiency
5.5.2.14	PNIRC HR focus/alignment	SRD 3.2.5	b	
5.5.2.15	PNIRC HR data rates	SRD 3.2.11	b	
5.5.3.1	PVISC λ	SRD 3.1.1	b	
5.5.3.2	PVISC filters	SRD 3.1.7	d	
5.5.3.3	PVISC FOV	SRD 3.1.3	d	
5.5.3.4	PVISC pixel scale	SRD 3.1.2	c	
5.5.3.5	PVISC image quality	SRD 3.1.4, SRD 3.1.5	a	
5.5.3.6	PVISC throughput	SRD 3.1.9	a	
5.5.3.7	PVISC ADC	SRD 3.1.12	a	
5.5.3.8	PVISC sky coverage	Observing efficiency	b	
5.5.3.9	PVISC focus/alignment	SRC 3.1.4, SRC 3.1.5	b	+ Observing efficiency

Requirement	Description	Origin	Qualification	Comment
5.5.3.10	PVISC calibration	SRD 3.1.14	d	
5.5.3.11	PVISC field distortion	SRD 3.1.12	d	
5.5.3.12	PVISC data rates	SRD 3.1.10	b	
5.5.4.1	PLIC λ	SRD 3.4.1	b	
5.5.4.2	PLIC filters	SRD 3.4.5	d	
5.5.4.3	PLIC FOV	SRD 3.4.3	d	
5.5.4.4	PLIC pixel scale	SRD 3.4.2	c	
5.5.4.5	PLIC image quality	SRD 3.4.4	a	
5.5.4.6	PLIC throughput	SRD 3.4.8	a	
5.5.4.7	PLIC sky coverage	SRD 3.4.7	b	
5.5.4.8	PLIC frame rate	SRD 3.4.12	b	
5.5.4.9	PLIC ADC	SRD 3.4.6	d	
5.5.4.10	PLIC AO upgrade		d	Pathfinding
5.5.4.11	PLIC calibration	SRD 3.4.11	b	
5.5.4.12	PLIC focus/alignment	SRD 3.4.4	b	
5.5.4.13	PLIC Data rate	SRD 3.4.9	b	
5.5.5.1	PMIRIS λ	SRD 3.3.1	b	
5.5.5.2	PMIRIS Filters/grisms	SRD 3.3.6	d	
5.5.5.3	PMIRIS FOV	SRD 3.3.3	c	
5.5.5.4	PMIRIS pixel scale	SRD 3.3.2	c	
5.5.5.5	PMIRIS image quality	SRD 3.3.4	a	
5.5.5.6	PMIRIS throughput	SRD 3.3.7	a	
5.5.5.7	PMIRIS phase	SRD 3.3.6	a	

Requirement	Description	Origin	Qualification	Comment
	shift			
5.5.5.8	PMIRIS background	SRD 3.3.8	a	
5.5.5.9	PMIRIS sky coverage	Observing efficiency	b	
5.5.5.10	PMIRIS calibration	SRD 3.3.12	d	
5.5.5.11	PMIRIS focus/alignment	SRD 3.3.4	b	
5.5.5.12	PMIRIS Data rate	SRD 3.3.9	b	
5.5.6.1	Mounted instruments	SRD 2.1.10	d	
5.5.6.2	Change time	SRD 2.1.08	b	
5.5.6.3	Change time	SRD 2.1.09	b	
5.5.6.4	PVISC+PNIRC	SRD 2.1.11	d	
5.5.6.5	PNIRC+PMIRIS	SRD 2.1.11	d	
5.5.6.6	Instrument mounting	SRD 2.1.10	d	
5.5.6.7	Future instruments	SRD 2.1.12	d	
5.5.7.1	First light instrument	Commissioning requirements	d	
5.6.1.1	Terahertz use	Pathfinding	d	
5.6.2.X	Space debris monitoring	SRD XXX	d	
5.7.1	Error budget		d	Methodology only
5.8.1	Weather station	SRD 2.2.7	b	
6.1.1	Continuous use	SRD 2.2.2	b	
6.1.2	Single operator	Functional efficiency	b	
6.1.3	Automated	SRD 2.2.1, SRD	b	

Requirement	Description	Origin	Qualification	Comment
	operation	2.1.8		
6.1.4	Remote operation	SRD 2.2.1	b	
6.1.5	Single technician	Functional efficiency	b	
6.1.6	Reliability	SRD 2.2.2	c	
6.1.7	Maintenance time	SRD 2.2.2	c	
6.1.8	Major maintenance	Functional efficiency	d	
6.2.1	TCS	SRD 2.2.1	d	
6.2.2	Control modes	SRD 2.2.1	b	
6.2.3	Interlocks	OH&S	a	
6.2.4	Operator expertise	Functional efficiency	b	
6.2.5	Remote communications	Functional efficiency	d	
6.3.X	Observational setup	SRD 2.2.1	d	
6.4.1-5	Data hardware pipeline	Functional efficiency	c	
6.4.6,7	Data backups	Data security	d	
6.5.1-5	Reduction pipeline	Functional efficiency	b	
6.5.6	Transient flagging	SRD 2.2.5	b	
6.2.1	Transferring test data	Functional efficiency	d	
6.2.2	Postage stamps	SRD 2.2.5	b	
6.2.3-6	Data transfer	System utility	c, d	
7.1-8	Environmental functionality	System utility	a, c	
7.9-11	Heat load in dome	SRD 3.1.4/5, SRD 3.2.4/5	c	
8.1.1-3	Reliability	SRD 2.2.2	c	

Requirement	Description	Origin	Qualification	Comment
8.2.1	Plug-in spares	SRD 2.2.2	d	
8.2.2	Maintainability	System functionality	d	
8.3.X	Durability	System functionality	c	
9.X.X	Interfaces	System functionality	d	
10.X.X	Design and construction	System functionality	d	