Document #: RQD-1.3.3.7-01-X.doc

Created on : Oct 15/10
Last Modified on : Oct 15/10

SCIENCE REQUIREMENTS

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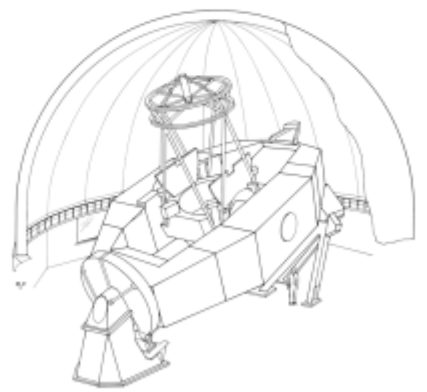
Latest Revision: John Rayner



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Revision History

Revision No.	Author & Date	Approval & Date	Description
Revision 1	John Rayner 1/1/11		Preliminary Release.
Revision 2	John Rayner 2/22/13		Updated

Contents

1 INTRODUCTION

High-level instrument design requirements are derived from the science requirements. This is documented as follows:

1. **Science Case.** This document is written by the science team and edited by the Project Scientist. It consists of a collection of individual science cases written by science team members, each case in the form of an observing proposal consisting of a science case and technical feasibility. For each proposal a list of science requirements is derived.
2. **Science Derived Requirements (SDR).** The Project Scientist writes this document. It captures the high-level science requirements and the top-level technical requirements. The science requirements include parameters such as resolving power, wavelength coverage, sensitivity, slit width, slit length, etc.
3. **Functional Performance Requirements Document (FPRD – or Instrument Specification Document).** The Project Manager writes this document. The FPRD gives the high-level instrument design requirements derived from the science requirements. For example, to produce the sensitivity given in the SRD requires a particular combination of instrument throughput, detector quantum efficiency, detector read noise, image quality, guiding capability, etc. All the science requirements are translated into the high-level instrument requirements that form the FPRD. The general functions of iSHELL are defined and the broad requirements that these place on instrument characteristics described. The FPRD forms the reference document for detailed instrument design. These high-level instrument requirements can then be turned into engineering designs. Instrument verification and validation requirements flow down from these.
4. **Operations Concept Definition Document (OCDD).** The Project Scientist writes this document. It describes the operation of iSHELL as required to carry out the observations described in the science case. It serves a number of purposes. It presents an end-to-end description of iSHELL and the factors affecting observing. The sequence of events required to execute example-observing programs is described (e.g. slew telescope, setup instrument, image target, place target on slit, start guiding, integrate etc.), as a context for developing ideas and operational scenarios. Eventually the operations manual will follow from this document.

The following sections give a summary of the iSHELL preliminary design, and discuss the design requirements derived from the Science Case.

2 PRELIMINARY DESIGN

iSHELL is planned as a replacement for CSHELL. CSHELL provides a maximum resolving power of R ~ 40,000 in single orders ($\delta\lambda \sim \lambda/400$ μm) through the use of a standard echelle grating and 256 x 256 1-5 μm array. iSHELL is being designed for a resolving power of R ~ 70,000 and increased one-shot wavelength coverage ($\delta\lambda \sim \lambda/10$ μm). This is achieved through the use of a cross-dispersed optical design and a 1-5 μm 2048 x 2048 array. Because ISHELL is designed to maximize science return in the areas of planetary science, star formation, the interstellar medium, and galactic astronomy, the instrument is optimized for the *H*, *K*, and *L* bands. The *M* band and part of the *J* band are also accessible. Silicon immersion gratings are used to keep iSHELL manageably small (about the same size as SpeX) and affordable. Absorption in silicon results in a short wavelength cut-off in the *J* band at about 1.15 μm. Availability of large format arrays limits the long wavelength cut-off is to about 5 μm. Slit lengths in the range ~5-25″ are needed for point sources and extended objects (e.g. comets and planets). The minimum slit width to 0.375″ with 3-pixel sampling to match the best seeing at IRTF. Table 1 gives the wavelength coverage per exposure (cross-disperser setting) and the corresponding slit lengths in the current design.

Table 1. List of cross dispersers and spectral formats available in iSHELL.

Exposure name	*Wavelength coverage (μm)*	*Orders covered*	*XD (line/mm)*	*Blaze wavelength (μm)*	*Blaze angle (degrees)*	*Order sorter (μm)*	*Slit length (arcsec)*	*XD tilt (degrees)*
J	1.15-1.35	279-237	800	1.25	29.9	1.05-1.45	5.0	39.4
H	1.50-1.80	211-176	530	1.67	25.7	1.40-1.90	5.0	35.2
K	1.97-2.52	160-125	290	2.19	18.5	1.80-2.60	5.0	28.0
J1	1.15-1.26	280-255	1200	1.2	46.0	1.05-1.45	10.0	56.0
J2	1.25-1.35	255-236	1200	1.2	46.0	1.05-1.45	15.0	61.5
H1	1.50-1.66	211-191	847	1.67	45.0	1.40-1.90	10.0	51.6
H2	1.60-1.75	198-181	847	1.67	45.0	1.40-1.90	15.0	55.0
H3	1.68-1.83	188-173	847	1.67	45.0	1.40-1.90	15.0	57.1
K1	1.84-2.03	171-156	720	1.90	43.1	1.80-2.60	15.0	54.1
K2	2.02-2.18	156-144	720	1.90	43.1	1.80-2.60	15.0	58.9
K3	2.12-2.34	148-135	600	2.16	40.4	1.80-2.60	15.0	51.6
K4	2.32-2.52	135-125	600	2.16	40.4	1.80-2.60	15.0	56.4
L1	2.80-3.10	184-167	450	3.14	45.0	2.70-4.20	15.0	51.3
L2	3.02-3.30	171-157	450	3.14	45.0	2.70-4.20	15.0	55.0
L3	3.14-3.42	164-151	450	3.14	45.0	2.70-4.20	15.0	57.3
L4	3.28-3.67	157-141	360	3.70	42.0	2.70-4.20	15.0	48.5
L5	3.65-4.01	141-129	360	3.70	42.0	2.70-4.20	15.0	53.5
L6	3.84-4.18	134-124	360	3.70	42.0	2.70-4.20	25.0	56.2
M1	4.55-5.27 s	113-98	210	5.0	31.7	4.50-5.50	15.0	40.4
M2	4.55-5.27 l	113-98	210	5.0	31.7	4.50-5.50	15.0	40.4

A complete description of iSHELL's preliminary design can be found in the Operations Concept Definition Documents.

3 DERIVING THE SCIENCE REQUIREMENTS

The Science Case consists of a collection of individual science cases written by science team members, each case is in the form of an observing proposal consisting of a science case and technical feasibility. For each proposal a list of requirements is derived. In developing the Science Case the science team was requested to consider how the instrument and telescope would be used to accomplish the proposed science. Specifically the following issues were addressed:

1. *Target acquisition.* Explain how the target will be positioned on the slit. Assuming the slit viewer is used, explain what filters will be needed, typical integration times, whether sky subtraction is required, etc. Assume the performance of the SpeX slit viewer/guider (OCDD).
2. *Guiding.* The slit viewer will be able to auto guide on spill-over from a point source target in the slit (width about 0.4″) down to *J*, *H*, or *K* magnitudes of about 15. Auto guiding on other point sources in the FOV of the slit viewer works down to *J*, *H*, or *K* magnitudes of about 16. Other guiding options include the off-axis CCD guider which has a guiding limit of $V \approx 15$. The CCD guider is occasionally used with SpeX when the targets are faint (*JHK* > 15) and there are no guide stars in the FOV of the slit viewer. (It is unlikely iSHELL targets will be this faint). However, flexure between the CCD and instrument can lead to the target moving out of the slit during long integrations (> 30 min). On planets, such as Mars, guiding can be done by increasing the size of the slit-viewer guide box to include the disk, and then offsetting the guide box on the slit to place the slit at the desired location on the planet. Jupiter and Saturn are too large to use this technique. In this case non-sidereal telescope tracking plus manual guide corrections using slit viewer images may work. It may be possible to develop auto-correlation methods to guide on disk features but this remains to be demonstrated. Describe what guide filters are needed.
3. *Spectrograph configuration*. Explain what slits (width and length) and cross-dispersers (XDs) are required to achieve the desired resolving power and wavelength coverage. Multiple configurations of the XDs might be needed. Note that most XD settings overlap allowing spectra to be more accurately pieced together (see Table 1).
4. *Detector readout*. Give typical integration times (on-chip integration times, co-adds, number of cycles), and explain any requirements on readout cadence (e.g. minimum time between readouts) and minimum integration time.
5. *Sky subtraction*. Explain if sky subtraction is needed, and if so, how it will be done. In the *L* and *M* bands where the background is higher, the slit is long enough (15″) for point sources to be nodded in the slit. In the *J*, *H*, and *K* bands where the background is lower and more stable, a dark/bias can be subtracted from the target plus sky spectrum, and the sky fitted along a shorter slit (5″?) and then subtracted, leaving the target spectrum.
6. *Standard star calibration*. Dividing the target spectrum by the spectrum of a standard star (ideally a featureless blackbody) serves two purposes. First it corrects for the system throughput as a function of wavelength, and second it removes telluric features. The result is a spectrum of the target in which the continuum shape is preserved, and telluric features are removed (the quality of removal depends on matching the air-mass of the target and standard, and on the S/N). In SpeX (wavelength coverage ~0.8-2.4 μm, and ~2.2-5.0 μm) we do this by observing A0 V stars (accurately known continuum shape), and then removing the hydrogen absorption lines using an A0 V model (Vega). Because the wavelength coverage in CSHELL is so small ($\Delta\lambda \sim \lambda/400$ μm) measuring the continuum conveys little information. Consequently some CSHELL programs just remove telluric features by using an atmospheric model and do not observe a standard star. Explain the requirements for iSHELL observations ($\Delta\lambda \sim \lambda/10$ μm).

7. *Spectro-photometry*. Absolute flux calibration of spectra might be important for some programs. This is normally done by observing the target and a flux standard through a wide slit. Explain requirements for absolute flux calibration of spectra.
8. *Scientific imaging*. The slit viewer will be capable of relatively high quality imaging and photometry. Discuss any needs for observing programs (filters, photometric accuracy, astrometry, etc.).
9. *Calibration*. Wavelength calibration will be done using arc lamps (*JHKL*) and telluric features (*LM*). If the slit is not moved between observation and arc lamp exposure, wavelength calibration should be accurate to better than one pixel (the minimum slit width is three pixels and this is matched to R=70,000). At *JHK* higher precisions should be obtainable by using telluric features (e.g. methane in the *K* band). Telluric features are stable to ~20 m/s. Radial velocity programs requiring higher precisions will be able to use a gas cell. Internal flat fielding and detector linearity should reduce systematic errors to less than 1%. Observing programs requiring errors less than 1% (i.e. S/N >100) should be noted.
10. *Radial velocity stability*. Experiments with CSHELL (Chris Johns-Krull) have demonstrated one-sigma RV precisions of ≈ 80 m/s over a period of eight days (8 epochs). iSHELL should do equally well and probably better since instrument stability will be a design consideration. With a gas cell the limiting precision will be ~10 m/s. Discuss required precisions and timescales for any RV programs.

In the following section we discuss the instrument requirements derived from the Science Case.

3.1. SCIENCE DERIVED REQUIREMENTS

3.1.1 Resolving Power

The majority of the science considered can be achieved at the proposed resolving power of R=70,000. For *L* band observations of thick disks and comets resolving powers up to about 100,000 are optimum because of the high line density and the need to discriminate these features against the rich telluric spectrum, even at the cost of reduced wavelength coverage. For measurements of optically thin disks using the fundamental CO transitions in the *M* band resolving powers from 20,000 to 50,000 will measure gas over a range of radii, while resolving powers up to 100,000 (3 km s^{-1}) are optimum for measuring velocities in disks and in proto-stellar cores (line profiles). Other science cases involving magnetic effects (Zeeman splitting and velocity measurements in outer planet atmospheres) also benefit from high resolving powers. In the *H* and *K* bands where telluric contamination is much reduced some stellar science (intrinsic widths 3-6 km/s) might profit from the increased wavelength coverage (more features, simultaneous line ratios) and improved sensitivity resulting from working at lower resolving powers (e.g. R=50,000). Our simulations find that the optimum resolving power for radial velocity observations of cool stars in the near infrared is about 70,000.

An important question for iSHELL on IRTF is does the estimated sensitivity at these resolving powers permit useful numbers of targets to be observed? The Science Case finds that there are sufficient targets for excellent science over the expected life the instrument (10 years).

3.1.2 Wavelength Coverage

While the ideal instrument should cover as much wavelength range as possible, practical considerations require a trade-off of wavelength coverage with resolving power, slit length, spectral sampling, and finite array size. To get high resolving power (R~70,000) on IRTF with an instrument of manageable size requires a silicon immersion grating. Silicon has a short wavelength limit of about 1.15 μm. The best available large format infrared array (2046x2048 Hawaii-2RG) is sensitive out to 5.1-5.4 μm (depending on particular array). Therefore iSHELL can cover the range 1.15-5.3 μm. At the short wavelength end of this range iSHELL has the sensitivity to do excellent stellar spectroscopy. At the long wavelength end of this range iSHELL has the resolving power and sensitivity to measure several molecular lines in-between the ubiquitous contaminating telluric features, in the atmospheres of Jupiter and Saturn (e.g. NH_3 at 5.1867 μm and 5.2521 μm).

The simultaneous (one-shot) wavelength coverage of iSHELL in the preliminary design is given in Table 1. More one-shot wavelength coverage can be obtained by using shorter slit lengths however the science team prefer longer slits (typically 15″) for improved background (sky, scattered light, and dark/bias backgrounds) subtraction. Given the numerous number of lines that iSHELL will need to cover it is important that iSHELL have the ability to put any wavelength at the center of the array with the exception of wavelengths close to the short and long wavelength limits.

3.1.3 Sensitivity

To be useful the instrument must also meet sensitivity requirements. Sensitivity is a requirement for S/N and therefore results in requirements for instrument throughput, instrument background sources through their noise contributions (e.g. cold optical bench temperature, cold stop in front of the slit), and detector properties (e.g. QE, dark current, and read noise). To optimize sensitivity the slit width is matched to the seeing.

3.1.4 Velocity Resolution

Using the CO band-head in young stars and telluric features for the wavelength fiducial, CSHELL is currently achieving RV precisions of about 80 m/s over a period of a month (Chris Johns-Krull and collaborators). Through the use of a gas cell and scaling to its broader wavelength range iSHELL should approach RV precisions of 10 m/s. However, the limiting precision is difficult to predict since it will determined by instrument stability. Instrument stability is a design consideration but iSHELL is not optimized for stability since it is mounted at cassegrain focus and has several moving mechanisms (including slits and cross dispersers). The goal is for a long-term precision of about 10 m/s over a period of months.

3.1.5 Cadence and Data Rates

Several science programs require taking spectra at frequencies of up to about once per minute. The resulting requirement is that the detector readout be much shorter than one minute in order to maintain this cadence. To keep read noise low the pixel read-out rate of H2RG detectors is 100 kHz. H2RG detectors are available with one, four, or thirty-two outputs (channels), with corresponding read-out times of 42 s, 10s, and 1.3 s respectively. Fast read-out times are even more important for SpeX and

NSFCAM2, and since iSHELL will share the same array controller we have decided to wire-up all the IRTF H2RG arrays for thirty-two outputs.

The data size of a 2048 x 2048 frame is 8.4 MB. A reasonable estimate for the highest data rate comes from asteroseismology projects where the fast cycle time of infrared arrays is exploited. In this case using a minimum exposure time (~2 s) and a cycle time of 6 s would give a data rate of 3.8 GB per hour and a total of 30 GB per night if sustained for 8 hours. More typical would be a rate of one frame per minute given a data rate of 0.5 GB per hour and about 5 GB per night.

3.1.6 Slit Width, Optical Efficiency, and Sampling

The resolving power, R, is given by

$$R = \frac{2d}{\phi D} n \tan\delta,$$

where d is the collimated beam diameter, D is the diameter of the telescope primary mirror, ϕ is the slit width (radians), n is the refractive index of the immersion material, and δ is the blaze angle of the grating. To achieve good optical efficiency at the desired resolving power of R=70,000, the nominal slit width is set to 0.375″ to match the best uncorrected seeing at IRTF. The practical requirements to keep the instrument small enough to mount at cassegrain focus (d < 25 mm), and for good sub-pixel optical aberrations in the spectrograph (f/38 collimator), dictate the use of an R3 ($\tan\delta$ =3) silicon (n =3.4) immersion grating. R3 format is the standard (lower risk) format offered by the University of Texas at Austin who are fabricating the immersion gratings for us. Increasing slit width to improve the optical efficiency in more typical seeing would mean either increasing the instrument size (*d)* or increasing the immersion-grating format ($\tan\delta$), neither of which are practical. Matching the slit width to the best seeing is also preferred for spatial sampling of resolved targets such as planets.

Nyquist (i.e. two-pixel) sampling of the slit width is the absolute minimum needed. Experience shows that sampling > 2.5 pixels are required for good telluric division while sampling of > 4 pixels is optimum to measure the PSF for high precision radial velocity observations. Good telluric cancellation and precision radial velocity observations are requirements. Decreasing sampling improves sensitivity in the detector performance limited regime but reduces sensitivity when sky background limited (see Table 4.5), but it also increases wavelength coverage per exposure. We have concluded that a reasonable compromise is for a sampling of three pixels per smallest slit width (0.125″ per pixel).

3.1.7 Slit Length and Orientation

The science case indicates that iSHELL will be used predominantly to observe point sources at *J, H*, and *K*, and both point sources and extended objects at *L* and *M*. Experience with SpeX on IRTF has shown that with a slit length of 15″ point sources can be comfortably nodded within the slit to simultaneously subtract sky, any scattered light, and dark/bias, without the need for separate sky and dark/bias exposures and subsequent loss of observing efficiency. H2RG arrays are known to have stable biases. At the resolving power of iSHELL the only sky background at *JHK* is from sky emission lines while at *LM* the background is dominated by thermal emission from the telescope and sky. If the dark/bias is stable enough to be measured before or after an observation then nodding along the slit is not needed and the slit just needs to be long enough to fit the seeing-dependent PSF of the object spectrum, plus additional space to fit the background on either side of the extracted object spectrum, from which a bias/dark exposure has been subtracted. Under these circumstances a slit length of about 5″ is acceptable. The shorter the slit, the more orders that can be placed on the array, and the more the simultaneous wavelength coverage. With a slit length of 5″ the entire *K, H*, or *J* bands can be covered in one setting. However, the science team have put a higher premium on accurate background and dark/bias subtraction than the potential for increased simultaneous wavelength coverage. Consequently, we have set a primary requirement for a minimum slit length of about 15″ so that point sources can be nodded within the slit. A secondary requirement is for a minimum slit length of about 5″ for increased wavelength coverage, if it can be accommodated. A slit length of 15″ is also a good compromise between wavelength and spatial coverage of extended objects (e.g. comets and planetary disks in the *L*-band). In addition, a slit length of 25″ is required for H_3^+ observations across the disk of Jupiter at ~3.9-4.1 μm. Compared to CSHELL, which uses a slit length of 30″ across 1-5 μm and works in single-order mode, this does result is some loss of capability. A partial solution would be to provide a set of single-order filters for important lines (e.g. 1.27 μm O_2 airglow observations of Venus). The slit length would still be limited to 25″

The science case requires that iSHELL have the capability to orientate its slit at any position angle. For example, aligning the slit meridian of Mars or latitude of Jupiter. As demonstrated with SpeX the best way to do this is with an internal K-mirror image rotator.

3.1.8 Signal to Noise Ratio

Most of the science cases can be accomplished with S/N ≈ 200. However, exoplanet characterization studies require S/N >1000. In this regime systematic errors due array issues including linearity, persistence, cross-talk, and stability, need to be carefully considered since they may be the limiting factors.

3.1.9 *Scattered Light*

Scattered light is an unwanted background source at the detector array and reduces the effective S/N of the data. Here we list potential sources of scattered light and preventative measures:

Table 2. Sources and mitigation of scattered light

Source	Light distribution	Mitigation
Instrument thermal background	Diffuse	Cool instrument enclosure (80 K) Cool detector baffle (38 K)
Off-axis scattered light	Diffuse	Cold stop Baffles
Surface scattering	Diffuse	Smooth and clean optical surfaces
Surface irregularity	Dependent	By design - specify for low scatter Lower aberrations affect core of PSF Higher order aberrations affect wider wings of PSF
Optical ghosts	Diffuse and structured	Ideally use all mirror design Minimize the number of refractive elements Optimize broad-band anti-reflection (BBAR) coats Optimize lens curvatures to avoid in-focus ghosts Optimize to avoid lenses close to the detector Tilt filters High detector QE (good BBAR coat)
Immersion grating substrate (IG) ghosts	In focus	Wedge appropriate IG surfaces to steer ghosts out of the beam Optimize anti-reflection coats
Grating flatness	Dependent	By design – specify for low scatter Lower aberrations affect core of PSF Higher order aberrations affect wider wings of PSF
Grating groove errors	Diffuse ('grass') Diffuse Ghost lines	Minimize random errors in groove pattern Minimize micro-roughness Minimize periodic errors in groove pattern

Quantitative spectroscopy requires the measurement of equivalent width defined as follows:

$$W_\lambda = \int \frac{I_c - I_\lambda}{I_c} d\lambda$$

where the intensity in the line and continuum are I_c and I_λ respectively. While in the presence of scattered light I_s:

$$W_\lambda = \int \frac{I_c - I_\lambda}{I_c + I_s} d\lambda$$

The accuracy required for equivalent width measurements depends on the application but a reasonable goal is for accuracies better than about 5% (tbc) (e.g stellar atmospheres and abundances). Since the low order grating aberrations only scatter light to within a few pixels of the wings this is not a significant concern for equivalent width measurements. Of more concern is light scattered many instrumental profile widths into the wings. This arises from the diffuse scatter sources given in Table 2.

An example of a measured infrared echelle instrumental profile is illustrated in Figure 1 (courtesy of Villanueva, Kaüfl, Smette, and Mumma from CRIRES R≈ 70,000). This is just for one spectral line.

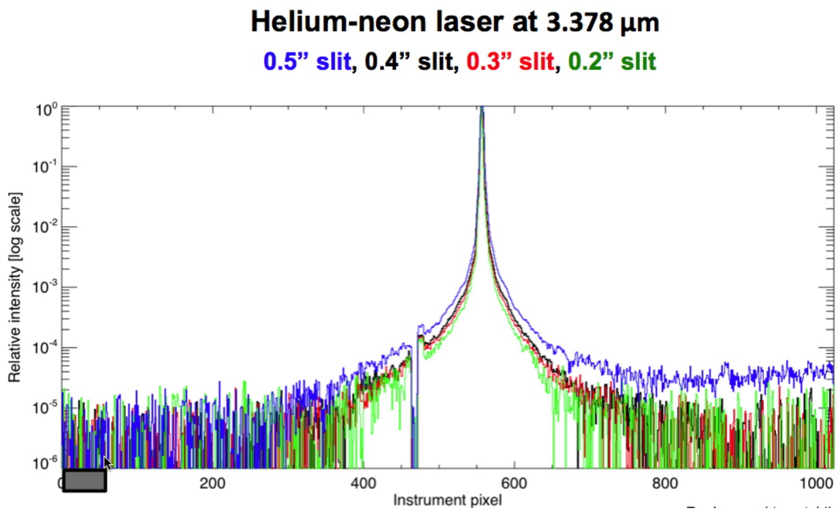

Figure 1. CRIRES instrumental profile showing scattered light in the wings of the spectral PSF

When the 'continuum' of lines across a spectral order is added in the scattered light level can reach a few per cent. By measuring the line cores of opaque telluric features scattered light reaches about two per cent in CRIRES (see Figure 2).

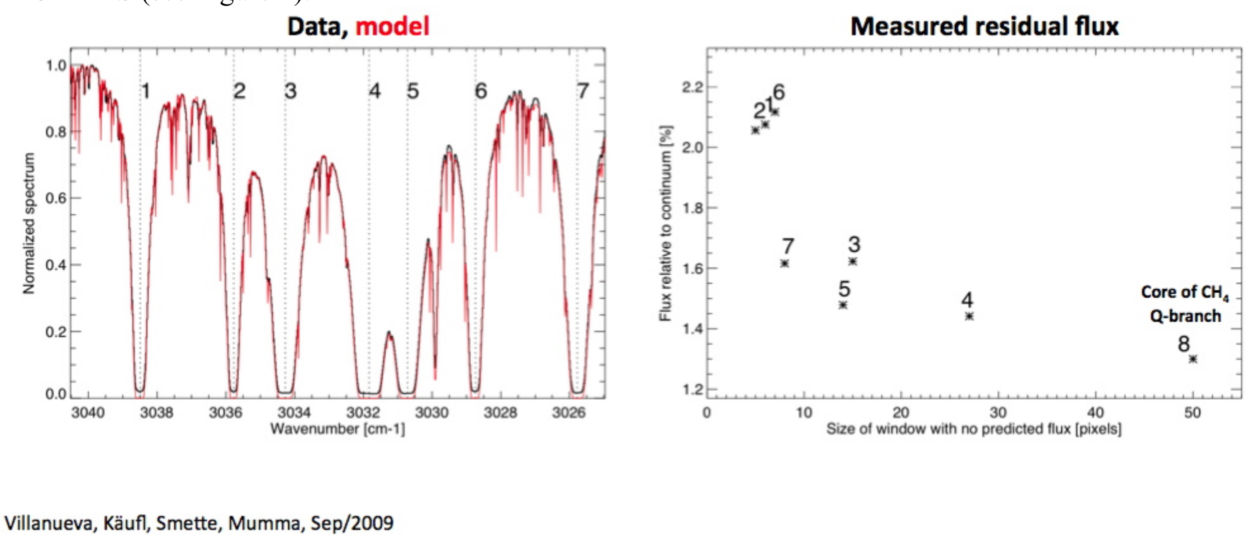

Figure 2. CRIRES measured residual flux in opaque telluric features

By comparison CSHELL and SpeX achieve a relative intensity of roughly 10^{-5} in the far wings of the spectral PSF for individual lines (dispersion direction), and SpeX sees a scattered light background of about one per cent in the gap between orders from the continuum. Modelling by Villaneuva et al. indicated that a residual flux of two per cent (see Figure 2) limits the S/N to about 200 that can be improved to about 1000 by fitting the instrument profile with a suitably wide kernel.

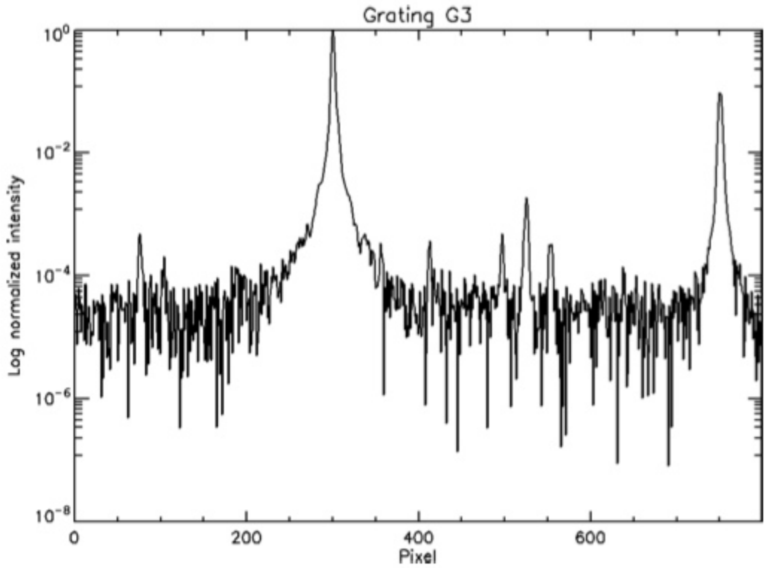

Figure 3. Sum of several thousand exposures of G3 silicon immersion grating at λ=0.5435 μm from Marsh et al. 2007 (AO 46, 17, 3413). The level of grass is < 10^{-4} of the strongest diffraction peak. Lyman ghosts between the orders are less than 0.1% of the peak.

The best immersion gratings being produced by UT compare well with the best commercial front-surface echelle gratings (see Figure 3) with the exception of repetitive errors introduced in the photolithographic patterning process causing some grating ghosts. Should iSHELL receive similar quality gratings the scattered light issues should be similar those for CRIRES, CSHELL, and SpeX. See the paper by Marsh et al. 2007 (Applied Optics 46, 17, 3413) for a quantitative discussion of immersion gratings being produced by our collaborator Dan Jaffe's group at UT, Austin.

To first order uncorrected scattered light (including ghost reflections) at the level of 1% contributes to a 1% uncertainty in the level of the continuum and therefore to a S/N limit of 100. Consequently to reach a S/N of 1000 requires scattered light to be less than 0.1% or that measures be taken to remove it. Since the scattered light background is usually diffuse and relatively unstructured, nodding a source within a slit does a good job of subtracting the background, as does fitting the background along the slit if there is sufficient space on either side of the source. This cannot be done for sources that fill the slit (e.g. planets) and in these cases the instrument profile has to be fitted as discussed above. Ideally scattered light is minimized in the design by employing mitigating measures as described in Table 2.

3.1.10 Spectral Calibration

To achieve the proposed science the data needs to flat fielded (S/N>1000) and wavelength calibrated (≈1 km/s for non-RV science, ≈10 m/s for RV science). Calibration needs to done fast and efficiently and ideally at the telescope position of the science targets to allow for any flexure in the instrument. This is best done with an instrument-mounted calibration unit comprising flat-field lamps and arc lamps. We anticipate that a gas cell will be used for RV calibration. Telluric features will be used to supplement arc lamps for wavelength calibration at thermal wavelengths (>3 μm) where arc lines become less frequent and more difficult to detect.

3.1.11 Observing Efficiency

iSHELL will be used for surveys of relatively bright targets (integration times of ~ 600 s). Consequently for efficient use of observing time target acquisition, positioning in the slit, and guider setup must done on times of ~ 60 s. This requires the use of an infrared slit viewer and guider similar to the SV being used very successfully in SpeX. Also, the instrument reconfiguration time should be ~ 60 s to not adversely effect observing efficiency.

3.1.12 Object Acquisition, Guiding, Absolute Flux Calibration, Science Imaging

The fundamental requirements of the slit viewer are to focus the telescope onto the slit, and for object acquisition and guiding in the near-IR. Targets need to be acquired and placed on the slit. For point sources guiding can be done on spill-over from the target in the slit. For extended objects (such as Mars) the guide box size can be increased to include the object and locate a selected region in the slit, provided the objects fits into the FOV and is bright enough.

A further requirement is for ≈1% imaging photometry with the slit viewer across the range ~1-5 μm. Although it is not a fundamental requirement, science imaging with the slit viewer is very desirable, both to support iSHELL programs and to support non-iSHELL programs that would otherwise require an instrument change on the multiple instrument mount. Science imaging with iSHELL will require a standard set of 1-5μm filters and additional calibration (e.g. linearity correction).

Absolute flux calibration of spectra can be made possible by providing a wide slit (about 3″). However, high-resolution echelle spectrographs do not usually measure the shape of the continuum and there is no strong science requirement for this, although the high-resolution spectral library is a possible exception. Measuring the shape of the continuum may also complicate calibration and data reduction. This issue is still under consideration.

3.1.13 Instrument Accessibility

iSHELL should have an operational life of at least a decade. It is therefore to be expected that the types of science done with the instrument will change. The instrument should be flexible enough to accommodate any changes where possible. The most likely changes would be in the spectral formats. This would involve new cross-dispersing gratings and order sorters, and possibly new immersion gratings and slits. It is also likely that imaging filters in the slit viewer will change as the science evolves.

Consequently, a reasonable requirement of the science case is make the mechanisms that mount these components accessible with a minimum amount of disassembly and interference with the rest of the instrument. This is also a requirement for instrument assembly and maintenance.

3.1.14 Quick Look Data Viewer

A requirement is for observers to view data as it is being acquired to assess data quality. A quick-look viewer should allow images to be displayed as they are received and allow simple arithmetic analysis using frame buffers. The image display options should include header information, line cuts, and statistics. Interactive features should include drawing guide boxes and offsetting the telescope using cursor or keyboard inputs, and automatic focus routines. The Data Viewer (DV) currently in use already provides this functionality with IRTF facility instruments. iSHELL will use DV.

An add-on component to DV should allow spectra to be extracted from spectral images using a simplified version of the spectral extraction package and default extraction parameters so that S/N can be estimated in real time.

3.1.15 Data Reduction Tool

It is important that iSHELL have an easy-to-use data reduction tool for fast accurate reduction of data. iSHELL produces cross-dispersed spectral images very similar to those produced by SpeX but at higher resolving power. The required functionality of the data reduction package required for iSHELL is therefore similar to that built for SpeX ('Spextool'). The following data frames are required:

- Target spectrum
- Telluric standard spectrum
- Arc lamp spectrum and/or sky telluric spectrum for wavelength calibration
- Flat field frames
- Dark and bias frames
- Bad pixel image
- Linearity data

3.2. SENSITIVITY MODELING

The sensitivity of iSHELL is estimated using a system model coded in IDL. The instrument parameters that are needed to estimate sensitivity are given in Tables 3 and 4. More details of the sensitivity model are discussed in the OCDD. The effects of detector performance and pixel sampling are discussed in the following sections. For comparison with iSHELL, the sensitivity of CSHELL is estimated using the same model.

Table 3. Instrument sensitivity parameters: spectrograph

Parameter	**CSHELL**	**iSHELL**
Resolving power (max)	40,000	70,000
Spectral sampling	2.5 pixels per slit width	3 pixels per slit width
Wavelength coverage	1.0-5.4 μm	1.15-5.3 μm
Spatial sampling	0.2″ per pixel	0.125″ per pixel
Slit width (min)	0.50″	0.375″
Detector	256x256 InSb	2040x2040 H2RG
Read noise (multiple reads)	25 e RMS (measured)	5 e RMS
Dark current	1 e/s (measured)	0.1 e/s
Throughput	0.125 (measured average)	0.10 (average)

Table 4. Instrument sensitivity parameters: slit viewer

Parameter	**SpeX**	**iSHELL**
Detector	512x512 Aladdin 2 InSb	512x512 Aladdin 2 InSb
Wavelength coverage	0.8-5.4 μm	0.8-5.4 μm
Pixel scale	0.12″ per pixel	0.1″ per pixel
Field-of-view	60″x60″	42″ diameter
Read noise (CDS)	60 e RMS	60 e RMS
Dark current	1 e/s	1 e/s
Throughput	0.20	0.25

3.2.1 Sky and Instrument Background

The atmospheric transmission code ATRAN was used to compute a telluric transmission spectrum (R=70,000) for an air mass of 1.15 (60° elevation) and 2 mm of precipitable water (average for Mauna Kea). Thermal emission from the sky was calculated by assuming a sky emissivity (1 – sky transmission) and a sky temperature of 263 K. Estimates of the non-thermal continuum are from Maihara et al. (1993). Sky emission lines (nearly all OH) are included even though they only cover at most 0.5% of pixels in any particular waveband (maximum in the *H*-band) at an instrument resolving power of R=70,000. Thermal background from the telescope and cryostat window was calculated assuming a temperature of 273 K and an emissivity of 0.1 (typical measurements are about 0.06 for IRTF). The thermal background from the instrument must be small compared to the dark current. For example, the flux from a 77 K cold optical bench is kept to a level of about 0.01 e /s by restricting the field-of-view of the detector to a half-angle of 15 degrees with a 100 mm long baffle connected to the detector mount (temperature 38 K). See Figures 4 and 5.

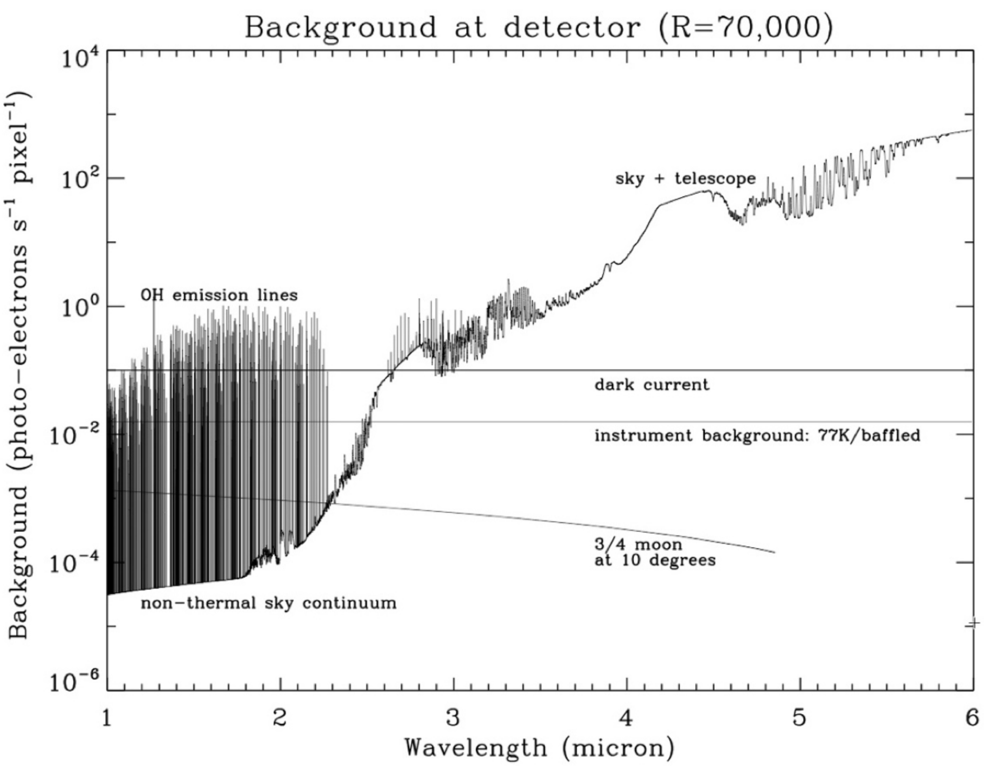

Figure 4. Predicted background at the array in iSHELL assuming a resolving power of R=70,000 matched to a 0.375″ slit, a slit efficiency of 0.4 (0.7″ seeing at *K*), and an average instrument throughput of 0.1

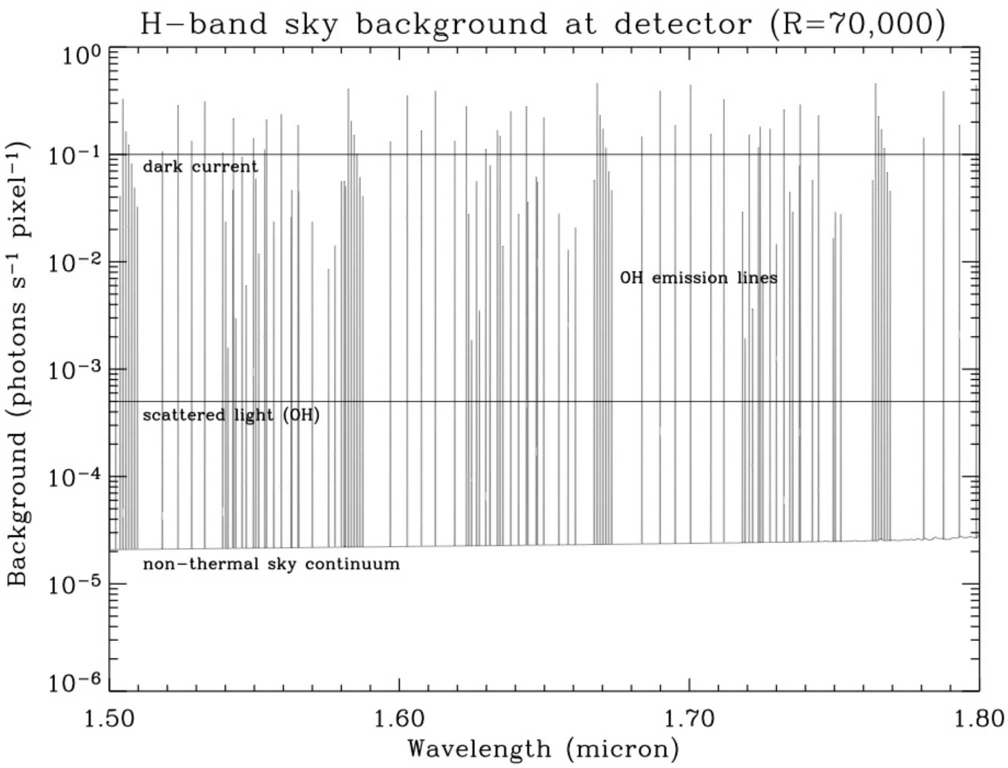

Figure 5. The modelled iSHELL *H*-Band sky background at the detector. An estimate of the background due to internal optical scatter of the OH sky emission lines is included

3.2.2 Detector Performance

Due to the high dispersion (*R*=70,000) and small pixel-field-of-view (0.125 ″/pix), the sensitivity of iSHELL is limited by detector performance at wavelengths shorter than 2.5 μm. Hawaii-2RG detectors have advertised dark currents of less than 0.1 e/s and should achieve a read noise of better than 5 e RMS with multiple non-destructive reads (NDRs). The quantum efficiency of the array is about 80%. See Table 7 of the OCDD for details of H2RG array performance.

By comparison the 256x256 InSb array currently in CSHELL achieves a dark current of about 1 e/s and a read noise of about 25 e RMS with 8 NDRs (maximum). The quantum efficiency of the array is about 90%.

3.2.3 Spectrograph Sensitivity

The effect of detector performance, specifically read noise and dark current, on sensitivity is tabulated in Table 5. A realistic expectation for the performance is ~5 e RMS for the read noise (multiple NDRs) and a dark current of 0.1 e/s (higher than measured dark currents of ~0.01 e/s to allow for residual image effects).

Table 5. Effect of detector performance on ISHELL point source sensitivity (one-hour 100σ, R=70,000, seeing 0.7″, throughput 0.10)

Read noise (e RMS)	Dark (e/s)	*J*	*H*	*K*	*L*	*M*
20	1.00	9.33	8.84	8.44	7.01	5.03
10	0.10	10.18	9.68	9.28	7.36	5.03
10	0.01	10.34	9.85	9.45	7.40	5.03
5	0.10	10.43	9.94	9.53	7.41	5.03
5	0.01	10.77	10.28	9.87	7.45	5.03

Pixel field-of-view and the number of pixels sampling the slit also have an effect on sensitivity. Finer pixels and finer sampling are better for sampling the image PSF and spectral features. Finer pixels reduce sensitivity when observations are detector performance limited (*JHK*) but increase sensitivity when sky background limited (*LM*), and vice versa. See Table 6.

Table 6. Effect of pixel size and slit sampling on sensitivity (one-hour 100σ, R=70,000, seeing 0.7″, throughput 0.10, read noise 5 e RMS, dark current 0.1 e/s)

Slit width	pfov	Pixels per slit width	Magnitude (Vega)				
			J	*H*	*K*	*L*	*M*
0.375″	0.125″	3	10.43	9.94	9.53	7.41	5.03
0.375″	0.188″	2	10.71	10.22	9.81	7.25	4.81

Table 7. Effect of resolving power (R) on sensitivity (one-hour 100σ, seeing 0.7″, throughput 0.12, read noise 5 e RMS, dark current 0.1 e/s, slit 0.25″, pfov 0.083″)

Resolving Power	Magnitude (Vega)				
	J	*H*	*K*	*L*	*M*
100,000	10.19	9.70	9.29	7.26	4.90
70,000	10.47	9.94	9.53	7.41	5.03
50,000	10.94	10.45	10.04	7.71	5.29

The effect of resolving power on point-source sensitivity is tabulated in Table 7.

The sensitivities of iSHELL and CSHELL are compared in Table 8. With a 0.75 ″ wide slit iSHELL and CSHELL have very similar resolving powers. The estimated throughput of iSHELL is slightly less than the measured throughput of CSHELL due to the additional elements required for the factor of ~70 increase in simultaneous wavelength coverage (cross dispersion, off-blaze grating illumination needed for wide wavelength coverage). A significantly improved detector and improved slit efficiency (due to the wider slit) more than compensate for this. The result is that, for the same resolving power, iSHELL is over half a magnitude more sensitive than CSHELL. In practice CSHELL does not normally achieve these sensitivities possibly because of low-level systematic noise in the readout. Also, since it dose not have a slit viewer, guiding is less effective.

Table 8. Comparison of iSHELL and CSHELL sensitivities (one-hour 100σ)

Instrument	R	Magnitude (Vega)				
		J	*H*	*K*	*L*	*M*
iSHELL	39,000	11.5	11.0	10.6	8.4	6.0
CSHELL	40,000	10.8	10.3	9.9	7.5	5.5

3.2.4 Multiplex Advantage

Using the product of resolving power, one-shot wavelength coverage, and the S/N in a given integration time required to reach a star of the same brightness (R x δλ x S/N) as a measure of the relative overall observing efficiency, Table 9 gives the relative efficiencies of CSHELL and iSHELL.

Table 9. Relative observing efficiencies of CSHELL and iSHELL

Wavelength range	Observing efficiency	
	CSHELL	iSHELL
J	1	70
H	1	60
K	1	60
L	1	75
M	1	75

This figure of merit assumes a linear relationship between the parameters that is not always useful. For example, some observing programs which are feasible at R=70,000 are not feasible at R=40,000. Also, slit length has been ignored, and so the comparison is most appropriate for point sources.

3.2.5 Slit Viewer Sensitivity

The slit viewer in iSHELL will have roughly the same sensitivity for guiding and imaging as the slit viewer in SpeX. The reduced sensitivity of iSHELL compared to SpeX due to the finer pixel scale will compensated for by the higher throughput (SpeX has more fore-optics). The magnitude limit for guiding on spill over from a target in the slit is JHK~15 in ~10 s in median seeing. The imaging sensitivity is given in Table 10.

Table 10. Slit viewer sensitivity 60s 10σ

Magnitude (Vega)			
J	***H***	***K***	***L′***
18.1	17.2	16.7	11.7

4 LISTING OF HIGH-LEVEL INSTRUMENT REQUIREMENTS

The highest-level instrument requirements are requirements dictated by facility needs. The decision to build a high-resolution infrared spectrograph for IRTF comes from overall strategic plans, the availability of funding and resources, and not solely from scientific considerations. We call these requirements Facility Requirements (FR). The Science Case and Science Derived Requirements (SR) flow from the decision to build a high-resolution 1-5 μm spectrograph, and from these the top-level engineering requirements (TR) are derived. The Top-Level Requirements are the starting point for the Functional Performance Requirements Document (FPRD).

4.1 Facility requirements

4.1.1 High Resolution 1-5 μm Spectroscopy [FR_1]

iSHELL shall be a ~1-5 μm high-resolution echelle spectrograph for use at the cassegrain focus of IRTF. It will employ silicon immersion gratings to keep the instrument sufficiently compact to mount at this focus. Dan Jaffe's group at the University of Texas, at Austin, shall provide the silicon immersion gratings. iSHELL shall replace CSHELL.

4.1.2 One Hawaii-2RG Array [FR_2]

iSHELL shall use one Teledyne Hawaii-2RG 2048 x 2048 detector array for spectroscopy.

4.1.3 Data Reduction [FR_3]

The iSHELL project shall provide users with a complete data reduction tool similar in capability to Spextool, which was developed for use with SpeX data.

4.2 SCIENCE DERIVED REQUIREMENTS

The requirements tabulated below are derived directly from the Science Case and include a description of the requirement, its value or specification, priority (essential and optimal), and the source of the requirement. The level of the maturity of the requirement: stable, firm, open, or under review (in that order of decreasing confidence) is indicated. Proof of compliance explains how the value of the requirement will be confirmed. Also included in the description are related requirements and any important assumptions.

4.2.1 Resolving Power [SR_1]

Title	Spectral resolving power	**Reference**	SR_1
Description			
Spectral resolving power is defined as $R=\lambda/\Delta\lambda$ where: λ is wavelength $\Delta\lambda$ is the smallest resolved wavelength interval (Rayleigh criterion) The spectral resolving power at the center of the waveband shall be: (1) $R \geq 70{,}000$ (2) $R = 80{,}000$			
Priority	(1) Essential (2) Optimal		
Source	Science Case		
Maturity	Stable		
Proof of compliance	Demonstrate compliance with lab observations of arc spectra prior to delivery		
Related requirements	SR_2 Sensitivity SR_4 Simultaneous wavelength range SR_5 Slit width SR_811Radial velocity precision		
Assumptions	Spectral lines are considered to be resolved if they satisfy the Rayleigh criterion		
Comment	The spectral resolving power varies slightly with wavelength (i.e. incident grating angle) hence the specification applies at the center wavelength. Set by optical design. The smallest slit (0.375″ and three detector pixels wide) is matched to R=80,000. Optical aberrations broaden the diffraction profile to R=70,000-80,000 depending on wavelength and location on the array		

4.2.2 Sensitivity [SR_2]

Title	Sensitivity	**Reference**	SR_2
Description			
iSHELL shall have a point-source sensitivity of: (1) $J \geq 10.5$, $H \geq 10.0$, $K \geq 9.5$, $L' \geq 7.4$, $M' \geq 5.0$ for S/N =100 in 3600 s at R=70,000 (Vega magnitudes) (2) $J \geq 10.7$, $H \geq 10.2$, $K \geq 9.8$, $L' \geq 7.7$, $M' \geq 5.3$ for S/N =100 in 3600 s at R=70,000			
Priority	(1) Essential (2) Optimal		
Source	Science Case		
Maturity	Firm		
Proof of compliance	Sensitivity will be verified during on-sky commissioning using observations of standard stars. Contributing factors (e.g. throughput, read noise, dark current) will be verified in the lab during testing		
Related requirements	SR_1 Resolving power SR_5 Slit width SR_6 Sampling SR_7 Slit length		
Assumptions	The sensitivity estimates are based on a model that includes the following assumptions: R=70,000 matched to a slit width of 0.375″ Sampling of 3 pixels per slit width (spectral resolution element) Average throughput 0.1 (1) or 0.125 (2) (which includes the telescope, optics, and detector) 0.7″ seeing at *K* 5 e RMS read noise (with multiple NDRs) 0.1 e/s dark current (including persistence) 0.01 e/s instrument background S/N > 200 in flat field A cold stop to minimize background sources Baffling to minimize the effects of scattered light The Science Case is based on the essential sensitivity estimate		
Comment	The sensitivity is dependent on parameters outside the instrument (e.g. seeing, telescope and sky temperature). Assumptions must be made about these		

4.2.3 *Continuous Wavelength Range [SR_3]*

Title	Simultaneous wavelength range	**Reference**	SR_3
Description			
(1) The instrument shall have the capability to position any wavelength in the range 1.2-5.2 μm in the center of the array cross-dispersion axis and the simultaneous wavelength (SR_4) range shall be continuous			
Priority	(1) Essential		
Source	Science Case		
Maturity	Firm		
Proof of compliance	By design		
Related requirements	SR_1 Resolving power SR_4 Simultaneous wavelength range SR_7 Slit length		
Assumptions	Array size 2048 x 2048		
Comment	Set by optical design and cross-disperser mechanism.		

4.2.4 *Simultaneous Wavelength Range [SR_4]*

Title	Simultaneous wavelength range	**Reference**	SR_4
Description			
The simultaneous (i.e. one-shot) wavelength coverage, $\delta\lambda$, is the continuous wavelength range covered in one setting of the instrument: (1) $\delta\lambda \leq \lambda/10$ (2) $\delta\lambda \leq \lambda/5$ where λ is the central wavelength setting of the instrument			
Priority	(1) Essential (2) Optimal		
Source	Science Case		
Maturity	Firm		
Proof of compliance	Demonstrate compliance with lab observations of arc spectra prior to delivery		
Related requirements	SR_1 Resolving power SR_3 Continuous wavelength range SR_6 Sampling SR_7 Slit length SR_11 Radial velocity precision		
Assumptions	Array size 2048 x 2048		
Comment	Set by optical design		

4.2.5 *Slit width [SR_5]*

Title	Slit width	Reference	SR_5
Description			
The slit width matched to R=70,000 shall be: (1) 0.375″ A selection of wider slits shall be available for better sensitivity in a range of seeing conditions and for improved sensitivity when higher resolving power is not needed: (1) 0.75″ (R=39,000) (1) 1.50″ (R=20,000) (1) 3.00″ (R=10,000; wide slit for absolute spectro-photometry)			
Priority	(1) Essential		
Source	Science Case		
Maturity	Stable		
Proof of compliance	Demonstrate compliance with lab observations prior to delivery		
Related requirements	SR_1 Resolving power SR_2 Sensitivity		
Assumptions	Smallest point source size (best seeing) is about 0.3″ (FWHM), typical is about 0.7″ (FWHM)		
Comment	Set by optical design		

4.2.6 *Sampling [SR_6]*

Title	Sampling	Reference	SR_6
Description			
(1) The smallest spectral resolution element (R=70,000) shall be sampled by 3.0 pixels			
Priority	(1) Essential		
Source	Science Case		
Maturity	Stable		
Proof of compliance	Demonstrate compliance with lab observations prior to delivery		
Related requirements	SR_1 Resolving power SR_2 Sensitivity SR_4 Simultaneous wavelength range SR_5 Slit width SR_11 Radial velocity precision		
Assumptions	Intra-pixel response function		
Comment	Set by optical design		

4.2.7 Slit length [SR_7]

Title	Slit length	Reference	SR_7
Description			
A selection of slit lengths shall be provided: (1) 10.0″ (1) 15.0″ (1) 25.0″ (2) 5.0″			
Priority	(1) Essential (2) Optimal		
Source	Science Case		
Maturity	Firm		
Proof of compliance	Demonstrate compliance with lab observations prior to delivery		
Related requirements	SR_2 Sensitivity SR_4 Simultaneous wavelength range		
Assumptions			
Comment	Set by optical design. The length of the slit in pixels at the spectrograph array is affected by anamorphic magnification effects introduced by the cross disperser. For each slit length several slit width requirements must also be satisfied (see SR_4)		

4.2.8 Slit orientation [SR_8]

Title	Slit orientation	Reference	SR_8
Description			
(1) The slit must be capable of alignment to any position angle on the sky			
Priority	(1) Essential		
Source	Science Case		
Maturity	Stable		
Proof of compliance	By design		
Related requirements			
Assumptions	The field will be rotated on the slit by an internal K-mirror image rotator similar to SpeX		
Comment	iSHELL is too big to use the cassegrain image rotator		

4.2.9 S/N Limit [SR_9]

Title	S/N limit	Reference	SR_9
Description			
(1) Systematic noise effects shall not limit the measured S/N to less than 100 (2) Systematic noise effects shall not limit the measured S/N to less than 1000			
Priority	(1) Essential (2) Goal		
Source	Science Case		
Maturity	Firm		
Proof of compliance	The limiting S/N in extracted spectra will be measured both in the lab and at the telescope		
Related requirements			
Assumptions	Flat fielding and linearization of data is assumed. It is assumed that any instrument flexure is small enough to not introduce systematic noise effects to this level after any required calibration is done		
Comment	Potential noise sources include unstable fixed pattern noise in the detector, electrical pickup, scattered light effects, optical fringing, etc. Scattered light effects may require fitting if the instrumental profile to achieve a S/N of 1000		

4.2.10 Wavelength Measurement [SR-10]

Title	Wavelength measurement	Reference	SR_10
Description			
(1) Wavelength shall be measurable to a precision of better than 1/10 of the smallest slit width (0.3 pixels at the spectrograph detector) (2) The wavelength solution shall be stable (months) to better than one pixel			
Priority	(1) Essential (2) Goal		
Source	Science Case		
Maturity	Firm		
Proof of compliance	Related functional requirements will be demonstrated in the lab (e.g. instrument configuration, moving mechanisms etc.). Full compliance will require all-up testing at the telescope		
Related requirements	SR_11 RV Precision TR_11 Image Stability at the Spectrograph Detector TR_13 Image Stability and Positioning at the Slit TR_17 Position of the Spectrograph Detector TR_18 Calibration unit		
Assumptions	Wavelength calibration with arc lamps and telluric features		
Comment	Flexure and repositioning requirements can be met by more frequent calibration		

4.2.11 Radial Velocity Precision [SR_11]

Title	Radial velocity precision	**Reference**	SR_11
Description			
iSHELL shall enable the measurement of radial velocity of (1) ≤ 20 m/s (2) ≤ 10 m/s (3) ≤ 5 m/s The radial velocity measurement shall be stable over a period of months			
Priority	(1) Essential (2) Optimal (3) Desirable		
Source	Science Case		
Maturity	Firm		
Proof of compliance	Compliance based on known RV stable stars measured during commissioning		
Related requirements	SR_1 Resolving power SR_4 Simultaneous wavelength range (gas cell) SR_6 Sampling SR_12 Spectral Response Function (SRF)		
Assumptions	Dependent upon the amount of Doppler information in the science target. The use of a gas cell is assumed		
Comment	Radial velocity precision is sensitive to changes in the SRF due to instability in the instrument (e.g. flexure, temperature)		

4.2.12 Spectral Response Function (SRF) [SR_12]

Title	Spectral response function	Reference	SR_12
Description			
To achieve a radial velocity precision about 10 m/s RMS the skewness, defined by the dimensionless third moment μ_3, must be known at all times to within ± 0.01. This requires: (1) a. that provision shall be made to measure μ_3 to ± 0.01 (arc lines or laser fringes); b. that μ_3 of the instantaneous optical SRF shall be stable between measurements (e.g. daytime calibration) to this precision or better; c. that μ_3 for the effective SRF, being the combination of the optical SRF in b. and any smearing brought about by image drift during the course of an observation, shall be kept stable to within the same to ± 0.01; this requires the image motion across the face of the detector be ≤ 0.1 pixel during an observation			
Priority	(1) Essential		
Source	SR_1 and Science Case (PRVS)		
Maturity	Open		
Proof of compliance	Demonstrate that the requirement is met through lab testing prior to delivery		
Related requirements			
Assumptions	Daytime calibration to measure the SRF will be made at intervals of days to months depending on the change in skewness with time, and following any instrument maintenance (i.e. requiring a cold cycle)		
Comment	This requirement sets the spatial and temperature stability of the instrument (see the FPRD)		

4.2.13 Cadence [SR_13]

Title	Cadence	Reference	SR_13
Description			
(1) The instrument shall be capable of taking and storing full array data at a sustained rate of up to 10 full data frames per minute (2) The instrument shall be capable of taking and storing full array data at a sustained rate of up to 30 full data frames per minute			
Priority	(1) Essential (2) Optimal		
Source	Science Case		
Maturity	Firm		
Proof of compliance	Demonstrate the requirement is met through lab testing prior to delivery		
Related requirements			
Assumptions	Array size of 2048 x 2048 pixels and data size 2 Bytes per pixel. Data to be transferred to and stored on the network disk		
Comment			

4.2.14 Observing Efficiency [SR_14]

Title	Observing efficiency	Reference	SR_14
Description			
iSHELL shall have "open shutter" efficiencies of (3) a. ≥ 67 % for 10 min observation b. ≥ 92 % for a one-hour observing block			
Priority	(1) Essential		
Source	Science Case and OCDD (instrument configuration)		
Maturity	Firm		
Proof of compliance	Related functional requirements will be demonstrated in the lab (e.g. instrument configuration, moving mechanisms etc.). Full compliance will require all-up testing (slew, acquisition, and guide setup) at the telescope		
Related requirements	TR_8 Slit viewer (acquisition and guiding) TR_15 Calibration unit		
Assumptions	• Overheads taken to include: telescope slew, acquisition, guider setup, and instrument configuration • Overheads do not include calibration (flats, arcs etc.), and observations of standard stars • Efficiency = total exposure time / total elapsed time		
Comment	Typical exposure times are between 10 and 60 mins		

4.2.15 Instrument Accessibility [SR_15]

Title	Instrument accessibility	**Reference**	SR_15
Description			
(1) To accommodate changes in the science case over the lifetime of the instrument, iSHELL shall be designed for easy accessibility			
Priority	(1) Essential		
Source	Science Case		
Maturity	Stable		
Proof of compliance	By design		
Related requirements	Ease of access is understood to mean no disturbance of the optical alignment, a minimum of disassembly, and replacement of components not requiring more than a few hours work		
Assumptions			
Comment	From the science case the highest priority mechanisms are the cross-disperser wheel and the SV filter wheel. Ease of accessibility is also required for instrument assembly and maintenance. The closed-cycle cooler should also be easily accessible for replacement		

4.2.16 Absolute flux [SR_16]

Title	Observing efficiency	**Reference**	SR_14
Description			
iSHELL shall enable measurement of absolute flux to an accuracy of (1) 2% (2) 1%			
Priority	(1) Essential (2) Optimal		
Source	Science Case		
Maturity	Firm		
Proof of compliance	Photometry of standard stars		
Related requirements	TR_9 Cold stop and pupil viewer TR_19 Calibration unit		
Assumptions	Movement between object and standard stars < 15 degrees		
Comment			

4.3 TOP-LEVEL REQUIREMENTS

The top-level requirements flow down from the science derived requirements and are the starting point for the FPRD.

4.3.1 Throughput [TR_1]

Title	Throughput (spectrograph)	**Reference**	TR_1
Description			
Average throughput shall be (3) ≥ 0.05 (4) ≥ 0.10 This includes the telescope, instrument, and detector QE but excludes the atmosphere			
Priority	(1) Essential (2) Optimal		
Source	SR_2		
Maturity	Stable		
Proof of compliance	The throughput will be measured during commissioning at the telescope		
Assumptions	The throughput used in modelling sensitivity is based on most likely performance (BBAR coats, grating efficiency, detector QE etc.).		
Comment			

4.3.2 Read Noise [TR_2]

Title	Read noise (spectrograph)	**Reference**	TR_2
Description			
Read noise shall be (1) a. ≤ 5 e RMS with NDRs and read out overhead < 30.0 s b. ≤ 15 e RMS with NDRs and read out overhead < 1.0 s c. ≤ 100 e RMS with NDRs and read out overhead < 0.1 s (2) a. ≤ 2 e RMS with NDRs and read out overhead < 30.0 s b. ≤ 7 e RMS with NDRs and read out overhead < 1.0 s c. ≤ 50 e RMS with NDRs and read out overhead < 0.1 s			
Priority	(1) Essential (2) Optimal		
Source	SR_2, Controller Requirements Document		
Maturity	Stable		
Proof of compliance	The read noise will be measured in the lab and at the telescope. The read noise of the spectrograph should be measured while the slit viewer is guiding		
Assumptions	Read noise includes noise contribution of the SGIR controller		
Comment			

4.3.3 Dark Current [TR_3]

Title	Dark current (spectrograph)	**Reference**	TR_3
Description			
Dark current shall be (1) ≤ 0.1 e/s (2) ≤ 0.01 e/s			
Priority	(1) Essential (2) Optimal		
Source	SR_2, Controller Requirements Document		
Maturity	Stable		
Proof of compliance	The dark current will be measured in the lab and at the telescope and the blank-off in position		
Assumptions	Measured at optimum temperature (~38K) and includes persistence		
Comment			

4.3.4 Spectrograph Detector Cosmetics [TR_4]

Title	Spectrograph detector cosmetics	**Reference**	TR_4
Description			
The number of bad pixels shall be (1) ≤ 1.0 % (2) ≤ 0.5 %			
Priority	(1) Essential (2) Optimal		
Source	Modelling affect of bad pixels on spectral extraction		
Maturity	Satble		
Proof of compliance	Bad pixel mask/map		
Assumptions	Bad pixels are defined as those pixels more than 3σ away from the mean in the flat field images and dark current images. The combination of these are entered into the bad pixel mask/map		
Comment			

4.3.5 Pixel-Field-of-View (PFOV) [TR_5]

Title	PFOV (spectrograph)	**Reference**	TR_5
Description			
PFOV shall be (1) 0.125″ per pixel in dispersion direction			
Priority	(1) Essential		
Source	SR_5, SR_6		
Maturity	Stable		
Proof of compliance	The PFOV will be measured at the telescope		
Assumptions	F/38 beam from the telescope		
Comment	In the cross-dispersion direction the PFOV will be affected by anamorphic magnification by the XD gratings		

4.3.6 Instrument Background [TR_6]

Title	Instrument background (spectrograph)	**Reference**	TR_6
Description			
The instrument shall be (1) ≤ 0.01 e/s/pixel			
Priority	(1) Essential		
Source	SR_2		
Maturity	Stable		
Proof of compliance	At a level of 0.01 e/s/pixel the instrument background is difficult to measure. Lab measurements should confirm that the background is ≤ 0.1 e/s/pixel. Using measurements of internal temperatures and light leaks, modelling should establish that the requirement is met		
Assumptions	Optical bench temperature < 80 K and adequate detector baffling (< 40 K) to restrict FOV at the spectrograph array. Dark current < 0.1 e/s		
Comment			

4.3.7 Image Rotator [TR_7]

Title	Pupil viewer	**Reference**	TR_7
Description			
(1) iSHELL shall have an image rotator to allow alignment of the slit to any position angle on the sky. For efficient target acquisition the optical and mechanical axes of the image rotator shall be co-aligned such that the field is not displaced by more than 10% of the diameter of the field-of view of the Slit Viewer upon rotation (2.2 mm at the slit plane, 1.1 mm at the slit-viewer array)			
Priority	(1) Essential		
Source	Science case, SR_8		
Maturity	Stable		
Proof of compliance	By design		
Assumptions	The field will be rotated on the slit by an internal K-mirror image rotator similar to SpeX . FOV is 42″ diameter and the pixel scale 0.1″ per pixel.		
Comment	The requirement that the field should not move by more than 10% of the diameter is so that the view of the field is not offset significantly when the rotator is used to avoid confusion by moving objects at the edge of the field in and out view. This is equivalent to a tilt of the rotator unit by 0.175 degrees, which gives 1.1 mm at the SV array.		

4.3.8 Cold Stop and Pupil Viewer [TR_8]

Title	Pupil viewer	**Reference**	TR_8
Description			
(1) iSHELL shall have a pupil viewer to ensure correct alignment of the internal cold stop with the telescope entrance pupil (center cold stop with reimaged pupil) a. cold stop must be co-aligned with the pupil image to achieve a transmission of ≥ 95% (equivalent to co-alignment to within 0.25 mm) b. cold stop alignment must maintain absolute throughput within 1% between observations of a target and its standard for 1% absolute photometry (0.1 mm) c. consequently the image quality of the re-imaged pupil at the cold stop shall be better than 0.1 mm 50% EED			
Priority	(1) Essential		
Source	SR_2		
Maturity	Firm		
Proof of compliance	By design		
Assumptions	The instrument mounting allows for tilt adjustment to align the cold stop with the entrance pupil (secondary mirror). Flexure requirements assume best case cold stop transmission of 100% or pupil image and cold stop are not centered		
Comment	Proper alignment is required to maximize throughput (signal) and minimize unwanted thermal background and scattered light from the telescope. The image quality requirement limits the tilt of a spherical collimating mirror to no more than 5 degrees		

4.3.9 Slit Viewer [TR_9]

Title	Slit viewer	Reference	TR_9
Description			
(1) iSHELL shall have a slit viewer to ensure proper telescope focus at the slit, and for efficient acquisition and guiding			
Priority	(1) Essential		
Source	Science Case, SR_2, SR_14		
Maturity	Stable		
Proof of compliance	By design		
Assumptions	To satisfy the requirements for focus, and acquisition and guiding the SV is assumed to have the following performance: Average throughput > 0.2 Aladdin 2 InSb 512 x 512 array Read noised 60 e RMS CDS and 25 e RMS with multiple NDRs Dark current about 1 e/s Image scale about 0.1″ per pixel (under review) FOV 30″ x 30″ (under review) Full complement of filters (JHKL′M′ broad-band filters plus several narrow-band filters)		
Comment	The SV will also function as a 1-5 μm science imager		

4.3.10 Image Quality at the Spectrograph Detector [TR_10]

Title	Image quality (IQ) at the spectrograph detector	**Reference**	TR_10
Description			
The image quality at the spectrograph detector shall not degrade the diffraction-limited spectra resolving power by more than 10%. This requires: (1) a. 50% EED ≤ 1.37 pixels (24.7 μm) b. 80% EED ≤ 2.74 pixels (49.3 μm) Specified in the dispersion direction (x-axis). Lower IQ in the cross-dispersion direction (y-axis) does not affect spectral resolving power. c. Immersion grating flatness < 0.1 μm RMS measured in air/vacuum at 0.63 μm (2) The spectrograph optics should be diffraction limited (Strehl S>0.8)			
Priority	(1) Essential (2) Goal		
Source	SR_1		
Maturity	Stable		
Proof of Compliance	Demonstrate compliance with lab observations of arc spectra prior to delivery.		
Assumptions	Diffraction-limited resolving power is R=80,000 (FWHM≡50%EED) matched to 3-pixel wide slit. In an ideal instrument this is defined by the width of the re-imaged rectangular slit onto the spectrograph detector. Refocusing of the spectrograph detector with wavelength is allowed. Detector crosstalk will not further degrade this requirement		
Comment	The requirement includes room for fabrication errors. IQ is dominated by the performance of the spectrograph camera lens and diffraction of the slit image at the immersion grating. EED addresses low frequency surface errors. Strehl addresses high frequency surface errors.		

4.3.11 Image Stability at the Spectrograph Detector [TR_11]

Title	Image stability at the spectrograph detector	**Reference**	TR_11
Description			
(1) Flexure: a. Wavelength calibration should be repeatable to within 1/10 of the slit width at the array (0.3 pixels). This is equivalent to an angular precision of 4.2 arc-seconds at the cross disperser (dispersion direction). b. In the cross-dispersion direction the orders should be repeatable to an accuracy of one pixel so that a spectrum does not move relative to bad pixels. This is equivalent to an angular precision of 10.1 arc-seconds at the cross disperser (cross dispersion direction). Requirements a. and b. should be met for at least one hour of observing time, i.e. about 15 degrees of telescope movement. (2) Repositioning: a. Wavelength calibration should be repeatable to within 1/10 of the slit width at the array (0.3 pixels). b. In the cross-dispersion direction the orders should be repeatable to an accuracy of one pixel so that a spectrum does not move relative to bad pixels. This is equivalent to an angular precision of 7.4 arc-seconds (18 μm in 0.5 m) at the cross disperser.			
Priority	(1) Essential, (2) Goal		
Source	SR_1, SR_10		
Maturity	Open		
Proof of Compliance	Demonstrate compliance with lab observations of arc spectra and flexure tests prior to delivery.		
Assumptions	Diffraction-limited resolving power is R=80,000 (Rayleigh criterion) matched to 3-pixel wide slit.		
Comment	Flexure and repositioning and flexure at these levels do not affect image quality. If the repositioning requirement is not met then calibration will be done at the telescope position of the observation.		

4.3.12 Image Quality at the Slit [TR_12]

<table>
<tr><td>Title</td><td>Image quality (IQ) at the slit</td><td>Reference</td><td>TR_12</td></tr>
<tr><td colspan="4">Description</td></tr>
<tr><td colspan="4">The image quality at the slit must not degrade the best seeing-limited PSF by more than 5%. This is met with:
(1) a. 50% EED ≤ 70 μm
b. 80% EED ≤ 140 μm
The smallest slit subtends 0.375″ and is about 208 μm wide (normal to the incoming f/38 beam)

The foreoptics should be diffraction limited (Strehl S>0.8)</td></tr>
<tr><td>Priority</td><td colspan="3">(1) Essential</td></tr>
<tr><td>Source</td><td colspan="3">SR_2</td></tr>
<tr><td>Maturity</td><td colspan="3">Stable</td></tr>
<tr><td>Proof of Compliance</td><td colspan="3">By design and by ensuring fore-optics specifications are met. By comparing the IQ of targets in the TFP and in the slit plane, both made with the SV, the IQ at the slit can be determined</td></tr>
<tr><td>Assumptions</td><td colspan="3"></td></tr>
<tr><td>Comment</td><td colspan="3">The requirement includes tolerancing. At the telescope the IQ at the slit is dominated by seeing; best image FWHM about 0.4″ at K (220 μm). IRTF is focused by measuring the FWHM at K. Typical fabrication tolerances for fore-optics powered surfaces give 50% EED ≤ 30 μm.

EED addresses low frequency surface errors. Strehl addresses high frequency surface errors.</td></tr>
</table>

4.3.13 Image Stability and Positioning at the Slit [TR_13]

Title	Image stability at the slit	**Reference**	TR_13
Description			
(1) a. Any flexure must not move the image on the slit by more than 1/3 of the smallest slit width (0.125″) during one hour of observing, i.e. about 15 degrees of telescope movement (e.g. the collimator must not flex by more than 0.05 degree or 40 μm at its edge). b. The absolute position of the center of the slit/s should be within 0.5 mm of the ideal optical axis. c. The slits shall be aligned east-west within 0.1 degrees in the slit wheel d. The top and bottom of the re-imaged slit should be aligned within one pixel of a SV detector column (position angle within 0.6 degrees).			
Priority	(1) Essential		
Source	SR_2, SR_4, SR_10		
Maturity	Open		
Proof of Compliance	By FEA design and flexure testing.		
Assumptions	F/38.3 onto the slit plane and smallest slit width 0.375″. For point sources the default position angle of the slit is east-west so that the star does not drift out of the slit due to any non-sidereal tracking errors.		
Comment	The tolerance can be looser if guiding is done with a rigid slit viewer but off-instrument (telescope) guiders should also be accommodated. The requirements for absolute alignment are to position the blaze wavelength in the center of the spectrograph and the re-imaged slit in the center of the SV field of view.		

4.3.14 Image Quality at the Slit Viewer Detector [TR_14]

Title	Image quality (IQ) at the slit viewer	**Reference**	TR_14
Description			
The image quality at the SV array must not degrade best images (about 0.4″ FWHM at *K*) by more than10%. This is met with: (1) a. 50% EED ≤ 1.8 pixels (48 μm) b. 80% EED ≤ 3.6 pixels (97 μm) The slit viewer optics should be diffraction limited (Strehl S>0.8)			
Priority	(1) Essential		
Source	Science Case, SR_2, SR_14		
Maturity	Stable		
Proof of compliance	By design and by ensuring fore-optics specifications are met. Measure IQ of the slit image at the SV array		
Assumptions	Image scale about 0.1″ per pixel and 27 μm pixels (InSb Aladdin 2 array in SV), FOV 42″ diameter		
Comment	IRTF is focused by measuring the FWHM at *K*. The requirement includes tolerancing. EED addresses low frequency surface errors. Strehl addresses high frequency surface errors.		

4.3.15 Image Stability at the Slit Viewer Detector [TR_15]

Title	Image stability at the SV detector	**Reference**	TR_15
Description			
(1) a. Any flexure must not move the image of the slit on the SV detector by more than one pixel (27 μm or 0.1″) during one hour of observing, i.e. about 15 degrees of telescope movement (e.g. the slit mirror must not flex by more than 0.001 degree about the axis of the slit wheel or 1.0 μm at its edge). b. The absolute position of the center of the re-imaged slit/s should be within 0.5 mm of the ideal optical axis (i.e. within 20 pixels of the center of the SV detector for symmetric FOV).			
Priority	(1) Essential		
Source	SR_2, SR_14		
Maturity	Firm		
Proof of compliance	By FEA design and flexure testing.		
Assumptions	Image scale at SV detector 0.1″/pixel (27 μm pixel).		
Comment	The SpeX SV, which has the same requirement and a very similar layout to iSHELL, achieves a flexure of less than about one pixel at 60 degrees tilt.		

4.3.16 Position of the Slit Viewer Detector [TR_16]

Title	Position of the SV detector	**Reference**	TR_16
Description			
(1) a. The center of the SV detector shall be aligned within 0.1 mm of the ideal optical axis (i.e. within about 4 SV detector pixels). b. SV detector columns or rows (TBD) shall be aligned within 0.1 degrees of re-imaged east-west			
Priority	(1) Essential		
Source	SR_2, SR_14		
Maturity	Firm		
Proof of compliance	By design, and through optical and mechanical alignment.		
Assumptions			
Comment			

4.3.17 Position of the Spectrograph Detector [TR_17]

Title	Position of the SV detector	**Reference**	TR_17
Description			
(1) a. The center of the spectrograph detector shall be aligned within 0.1 mm of the ideal optical axis (i.e. within about 6 spectrograph detector pixels). b. Spectrograph detector columns or rows (TBD) shall be aligned within 0.1 degrees of re-imaged east-west c. The spectrograph detector is mounted on a focus stage to allow for focusing (± 2 mm)			
Priority	(1) Essential		
Source	SR_2, SR_10		
Maturity	Firm		
Proof of compliance	By design, and through optical and mechanical alignment.		
Assumptions			
Comment	Required focus range comes from chromatic performance of the spectrograph camera lens including tolerancing		

4.3.18 Stray Light at the Spectrograph Detector [TR_18]

Title	Stray light at the spectrograph detector	Reference	TR_18
Description			
(1) The stray light background at the spectrograph detector should be less than 1% of the spectral continuum for S/N > 100. (2) The stray light background at the spectrograph detector should be less than 0.1% of the spectral continuum for S/N > 1000.			
Priority	(1) Essential (2) Goal		
Source	SR_9		
Maturity	Firm		
Proof of compliance	Stray light will be measured both in the lab and at the telescope		
Assumptions			
Comment	(1) Can be achieved by taken measures to minimize stray light (optimizing BBAR coats and surface irregularity) (2) Can be achieved nodding along slit to remove background or by fitting the instrument profile if the slit is no long enough		

4.3.19 Calibration Unit [TR_19]

Title	Calibration unit	Reference	TR_19
Description			
(1) iSHELL shall have a spectral calibration unit for efficient acquisition of high S/N flat field and arc line images			
Priority	(1) Essential		
Source	SR_2, SR_10, SR_14		
Maturity	Stable		
Proof of compliance	By design		
Assumptions			
Comment	The calibration unit is mounted to the instrument and comprises flat-field lamps and arc lamps. At wavelengths longer than about 3 μm telluric features will supplement lamp lines for wavelength calibration. Gas cell used for precision RV observations		

4.3.20 Quick Look Data Viewer [TR_20]

Title	Quick look data viewer	**Reference**	TR_20
		Description	
(1) iSHELL shall have a means to view and perform simple arithmetic on images and data in real time			
Priority	(1) Essential		
Source	SR_2, SR_14		
Maturity	Stable		
Proof of compliance	By design		
Assumptions	Largest array size 2048 x 2048 pixels		
Comment	The functionality of the quick data viewer will be very similar to the data viewer (DV) used for SpeX and NSFCAM2		