PRECISION RADIAL VELOCITY SPECTROMETER

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CHANGE RECORD

Issue	Date	Section affected	Change Description
0.1	29 April 2006		First draft by JTR with comments from team incorporated by DWL.
0.2	9 August 2006		Second draft by JTR
0.3	5 September 2006		Third draft by JTR. RV surveys and GRB scenario added. Comments by HRAJ, AJL, and AV. Final edit by DWL.
0.4	12 September 2006		Fourth draft by JTR. Comments by Hermine plus some minor changes.
1.0	16 September 2006		Final issue for Gemini review - dwl

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List of Abbreviations

A&G	Gemini acquisition and guidance system
FPRD	Functional and Performance Requirements Document
FOV	Field of view
FV	Fibre viewer
GCAL	Gemini facility calibration unit
H2RG	Hawaii 2 RG detector array
HR	High (spectral) resolution
OAP	Off-axis parabola
OCDD	Operation Concepts Definition Document
PRVS	Precision Radial Velocity Spectrometer
PSF	Point spread function
R	Spectrograph resolving power
RMS	root mean squared
SRF	Spectral Response Function
RV	Radial velocity
XD	Cross-dispersed

Definitions

TBD	To Be Defined : a requirement to be developed during the preliminary design stage of the instrument.
TBC	To Be Confirmed : a requirement that is correct with the current design information but requires confirmation during the preliminary design stage of the instrument.
TBR	To Be Reviewed : a requirement specified to meet the PRVS top-level requirements, but which might over-constrain the design.

1. PURPOSE

This document describes the operation of the Gemini Precision Radial Velocity Spectrometer (PRVS) as required to carry out the observations described in the science case. It serves a number of purposes. It presents an end-to-end system level description of PRVS, the factors affecting the observing and a context for developing ideas and operational scenarios. The document will be updated as work progresses. The values given in this document for top-level requirements should be considered provisional at this time as further detailed modelling & analysis will be done to confirm these values before the document is re-issued for final submission to Gemini. This is not a requirements document and the content is for information only. Eventually the operations manual will follow from this document.

2. APPLICABLE AND REFERENCE DOCUMENTS

Reference	Document Title	Document Number	Issue
AD01	PRVS Science Case	PRVS-SPEC-00004-0001	1.0
AD02	PRVS Initial Functional and Performance Requirements Document	PRVS-SPEC-00003-0001	1.0
AD03	PRVS Science Requirements	PRVS-SPEC-00005-0001	1.0

3. SCIENCE REQUIREMENTS SUMMARY

The science requirements are derived from the science described in the Science Case. To make the requirements most useful it is assumed that PRVS is a fibre-fed echelle spectrograph.

The primary science aim of PRVS is to conduct a survey of mid- to late-M dwarfs stars to search for terrestrial mass planets (~ 1-10 M_{earth}). To be useful we have concluded that several hundred stars need to be observed over multiple epochs and that the survey needs to be completed in about five years. This results in three fundamental science requirements:

- Radial velocity precision (SR_1)
- Sensitivity (SR_2)
- Observational efficiency in conducting the radial velocity survey (SR_3)

Further requirements are developed from these three fundamental requirements. The requirements derived from the three fundamental requirements have some dependence on the instrument design. By modelling the Doppler information in M dwarfs we have derived requirements for resolving power (SR_4), number of pixels per spectral resolution element (sampling) (SR_5), and simultaneous wavelength range (SR_6) required to obtain the necessary radial velocity precision. This also requires the instrument SRF to remain stable in shape and position within certain limits over the course of an individual observation and over longer periods (SR_7).

Sensitivity is a requirement for signal/noise (S/N) and therefore results in requirements for instrument throughput (SR_8) and fibre field-of-view (SR_9) (to minimize 'slit losses'), and instrument background sources through their noise contribution (SR_10). A requirement related to throughput, stability, and observational efficiency, is for acquisition and guiding to put the target star in the centre of the fibre and to keep it there during an observation (SR_11 and SR_12). Good image quality of the target star on the entrance to the fibre is required to meet the required throughput (SR_13). Good image quality at the spectrograph detector is required to meet the required resolving power (SR_14). The cosmetic quality of the array needs to be such that the number of bad pixels does not significantly reduce the number or quality of detectable spectral features (SR_15).

The requirements of the other science cases are consistent with the science requirements derived from the primary science case for PRVS.

A complete description of the science requirements can be found in the Science Requirements document.

The science requirements are turned into detailed instrument requirements through the process of instrument design. This process is described in the relevant instrument design documents. The detailed instrument requirements are given in the Initial Functional Performance Requirements Document (FPRD). An overview of the resulting design of PRVS is described in the following section.

4. INSTRUMENT DESCRIPTION

4.1 OVERVIEW

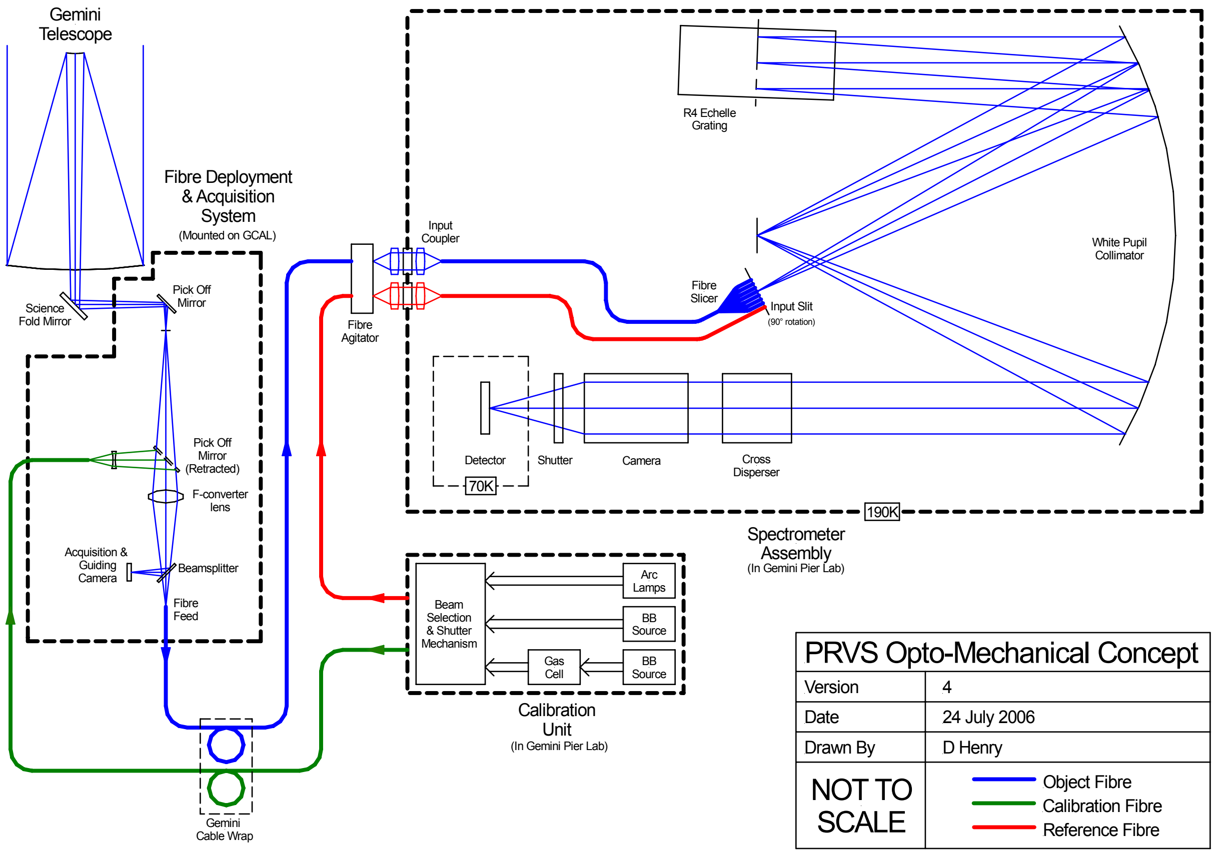

Figure 1. Schematic layout of PRVS

Light from the telescope is re-imaged onto the entrance of an optical fibre located in the Fibre Deployment and Acquisition System (FDAS) which is mounted on the ISS near to the GCAL unit at the f/16 cassegrain focus. A CCD fibre-viewing camera is used for acquisition and guiding. The 60 m long 'object' fibre runs from the FDAS through the telescope cable wrap down to the telescope pier laboratory and into a bench-mounted spectrograph. For environmental stability the spectrograph is contained inside a vacuum jacket and is temperature controlled. The bulk of the spectrograph is cooled to 190 K. A second 'reference' fibre runs from a calibration unit located next to the cryostat into the spectrograph. A third 'calibration' fibre feeds calibration light up to the FDAS so that calibration light can also be transmitted through the object fibre when selected. The object and reference fibres are terminated at the cryostat and are optically coupled into the cryostat to form a pseudo-slit at the entrance of the spectrograph. Starlight from the object fibre is dispersed in the spectrograph and forms the object spectrum side-by-side with a wavelength reference spectrum formed by dispersed arc line light from the reference fibre. Radial velocity is measured by measuring the wavelength shift of the object spectrum relative to the simultaneously exposed wavelength reference spectrum. Figure 1 shows a schematic layout of PRVS.

4.2 FIBER DEPLOYMENT AND ACQUISITION SYSTEM

The Fibre Deployment and Acquisition System is mounted on the ISS close to GCAL. This system re-images the telescope focal plane onto the object fibre and uses a CCD camera (the Fibre Viewer) for object acquisition and slow guiding. It also projects calibration light into the object fibre when required.

The science fold mirror sends the beam to GCAL where a small pickoff mirror sends the f/16 beam to a focal reducing achromatic doublet lens (see Figure 1). This lens re-images the telescope focal plane at f/5.5 onto the object fiber. A focal ratio of f/5.5 is chosen to minimize focal ratio degradation. The fibre is 300 μm in diameter and only uses 1.4″ of the re-imaged field. For median seeing of about 0.6″ at J the light loss (spill-over from the object fibre) is about 2%.

A CaF2 substrate located behind the lens reflects about 1.5% of this beam through a Z-band (0.83-1.00μm) filter and onto a CCD (the Fibre Viewer). The bare substrate reflects enough signal for acquisition and guiding on our faintest RV targets (L2 dwarf 50σ1sec=14.8 at Z, 50% QE) while at the same time minimizing the light loss in the spectrograph path. The brightest stars in the RV survey are early M dwarfs (Z magnitude <5.0) and require additional filtering (Z plus neutral density filter) to avoid saturation in the shortest on-chip integration times of about 0.1 s. This requires a simple filter wheel or slide in front of the CCD camera.

There is a small position offset between the guiding (Z) and observing wavelengths (YJH) due to atmospheric dispersion (about 0.15″ between Z and J at an airmass of 1.5). This is corrected for in software. At an image scale 0.06″/pixel (13μm) a 512x512 CCD format gives a FOV 31″x31″. The lens, substrate, fibre, and CCD are all rigidly mounted and so there is no significant relative flexure (< one CCD pixel/hour). Any flexure in the pickoff mirror acts like a simple guiding error.

When the pickoff mirror is in its retracted position the output of the calibration fibre is re-imaged onto the input of the object fiber at f/5.5. Calibration light (arcs, continuum, continuum plus gas cell absorption) in the object fibre is observed before and after observing the science object.

Several off-the-shelf CCD camera (CCD, dewar, thermoelectric cooler, driver) systems are currently being considered. If space is constrained around GCAL we could build our own system.

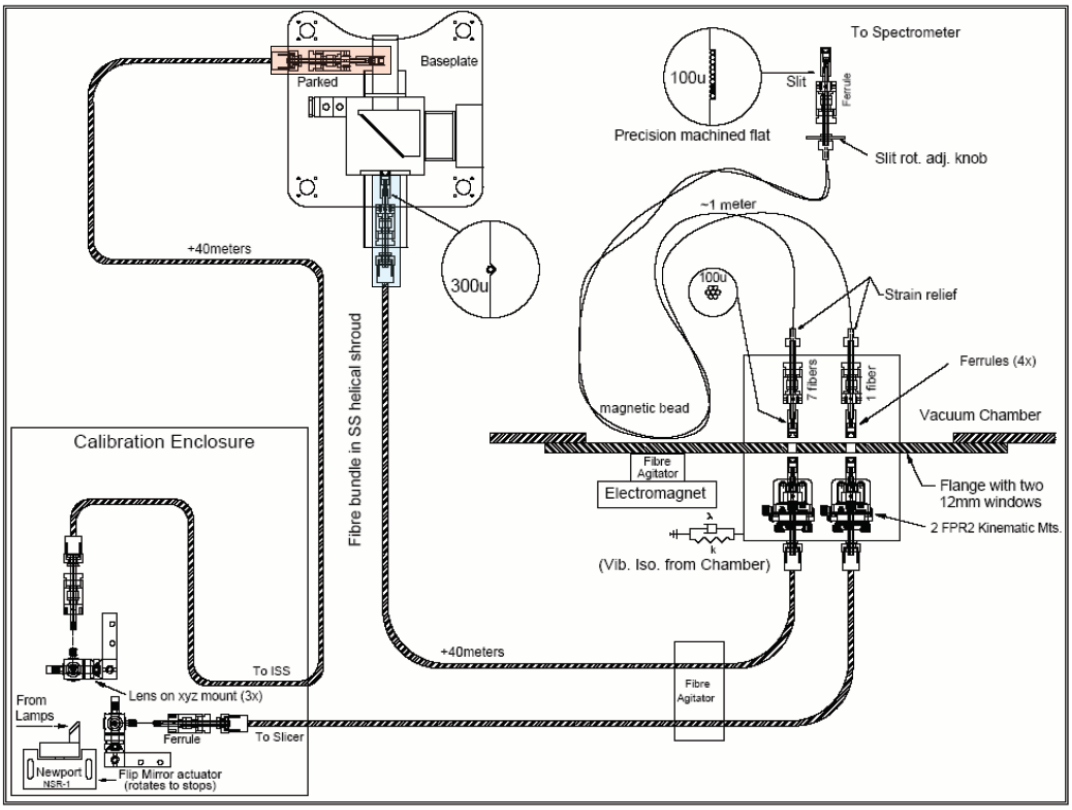

Figure 2 Layout of the Fore-Optics Fibre Assembly

4.3 FORE-OPTICS FIBRE ASSEMBLY

Starlight from the telescope focal plane is re-imaged onto the end of the object fibre at a focal ratio of f/5.5 to minimize focal ratio degradation. The 300 μm diameter object fibre runs from the FDAS through the cable wrap to the cryostat located in the telescope pier laboratory, requiring a fibre length of about 60 m. The 100 μm diameter reference fibre runs from the Calibration Assembly to the cryostat, requiring a length of a few meters. The calibration fibre runs from the Calibration Assembly to the Fibre Deployment and Acquisition Assembly, along the same path as the object fibre. See Figure 2.

The object and reference fibres are terminated at the cryostat and optically coupled into the cryostat by individual collimator and camera lenslets. The reference fibre is re-imaged onto a 100 μm diameter fibre, and the 300 μm diameter object fibre is re-imaged onto a bundle of seven 100 μm diameter fibres that is then is splayed out to form a long pseudo slit at the entrance of the spectrograph (see Figure 3). The reference fibre is added to the top of the pseudo slit. To minimize any scattering of arc light onto the object spectrum at the detector one blank fibre of the same diameter separates the reference and object fibres.

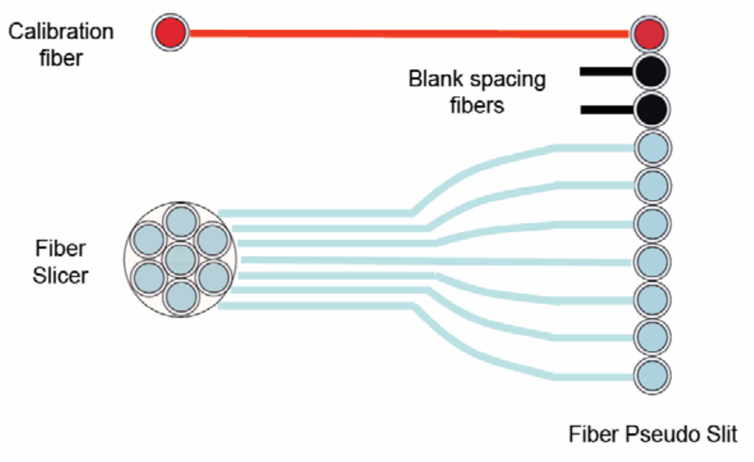

Figure 3 Fibre image slicer and pseudo slit

Immediately outside the entrance to the cryostat the object and reference fibres pass through a mechanical agitator to remove modal noise and to increase spatial scrambling. This device agitates the fibres at a frequency of about 60 Hz and at an amplitude of a few hundred microns. There is about 1 m length of fibre from the image slicer input to the pseudo slit. To remove modal noise this cable is run through magnetic beads that are slightly vibrated through the cryostat vacuum jacket via an electromagnet outside the jacket.

4.4 SPECTROGRAPH

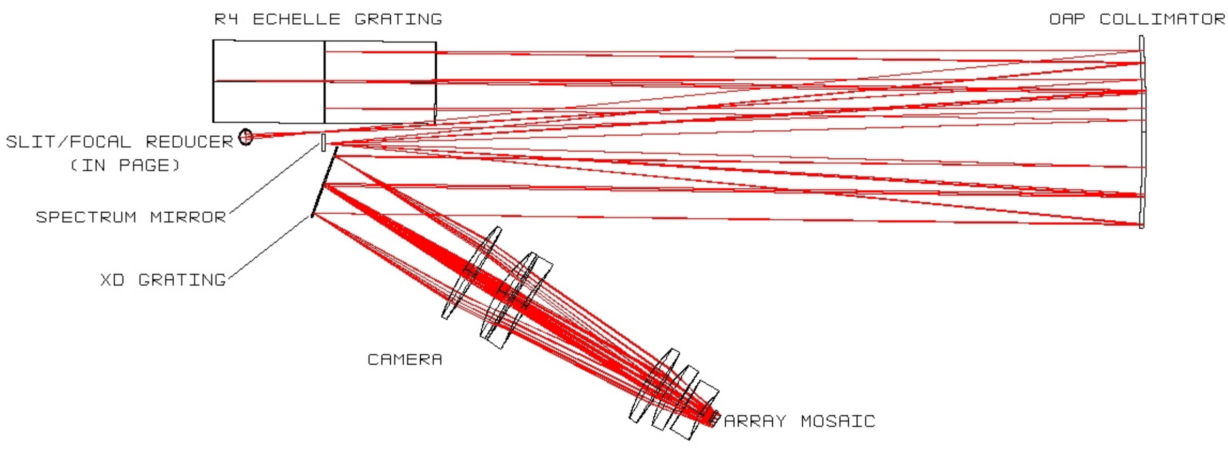

Figure 4. Spectrograph layout

The optical design of the spectrograph is similar to other white pupil spectrographs such as UVES on the VLT, MRS on the HET and, in particular, HARPS on the ESO 3.6m La Silla telescope. The layout of the spectrograph is shown on Figure 4. The f/5.5 beam exiting from the pseudo-slit is reduced to about f/14 by the focal reducer doublet lens. The slower beam is needed to control aberrations in the spectrograph.

A large off-axis parabolic (OAP) mirror then collimates the beam and forms a 140 mm diameter white pupil on the echelle grating. The OAP collimator has a focal length of 2000 mm and a rectangular clear aperture of 500 mm x 446 mm. For thermal stability all the mirrors and gratings are made from Zerodur.

For a resolving power of R=70,000 an R4 31.6 lines/mm echelle grating is required (162 mm x 552 mm). This is the same as used in HARPS, UVES and some other spectrographs. Grating illumination is in pseudo-Littrow mode with an off-plane angle of γ =0.4°. This is optimum for throughput but does introduce a small tilt of about 3° of the re-imaged slit on the detector.

Following dispersion at the grating a second reflection in the OAP forms a dispersed image of the slit on the spectrum mirror (clear aperture 386 mm x 30 mm) that is located next to the echelle. The beam from the spectrum mirror is reflected for a third time in the OAP and forms a second white pupil on the cross-dispersing grating located close to the spectrum mirror. The cross-disperser is a first-order plane grating (100 lines/mm, blaze angle 4°). It is tilted 20° to allow the reflected beam to clear the input beam.

The dispersed beam from the cross disperser is imaged onto the array mosaic by a six-element f/3 refractive camera. All the lenses have spherical surfaces and are made from standard optical glasses with diameters ranging from about 100 mm to 260 mm. An order-sorting filter is the last optical element before the detector. Image quality at the detector is very good with RMS spot diameters < 9 μm (including tolerancing) compared to the re-imaged slit width at the detector of 45 μm (2.5 pixels). Therefore the spectrograph image quality only degrades the resolving power by 2%.

In the baseline design a 1x2 mosaic of H2RG 2048x2048 detectors (18μm pixels) covers most of the YJH spectral range simultaneously at R=70,000 with 2.5 pixel sampling, and with sufficient separation between orders to accommodate the image-sliced slit containing the object and reference fibre.

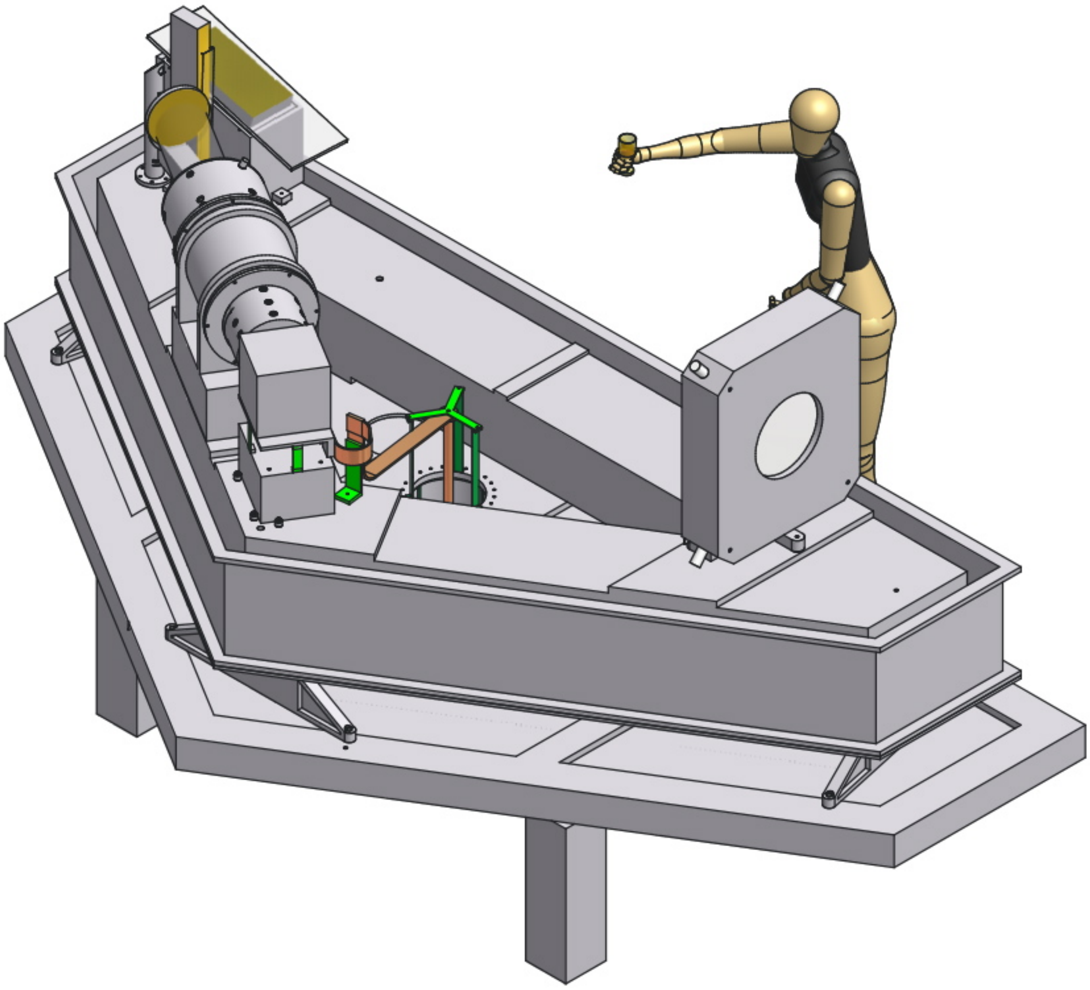

Figure 5. Cryostat optical bench and support structure

4.5 CRYOSTAT

The design consists of a vacuum vessel (~3.3 m x 1.7 m x 1.25 m, volume 2.8 m^3) supported on anti-vibration supports of the type used on optical benches (see Figures 5 and 6). An optical support structure is mounted within the vacuum vessel on an isolating flexure system. The flexure system supports a radiation shield that encloses the optical support structure. It also thermally insulates the optical support structure from the radiation shield. The optical components are mounted within substructure modules, and these in turn are mounted to the optical support structure in a semi-kinematic way. The optical bench and radiation shield are maintained at the operating temperature of 190 K and stabilised to better than 0.05 K by combining a vibration-isolated CTI-1050 closed-cycle cooler with servo controlled resistive heating elements on the optical bench. Liquid Nitrogen plumbing and a dewar is provided to pre-cool the radiation shield and the optical bench. The second stage of the closed-cycle cooler maintains the array mosaic at ~70 K and stabilised to better than 0.01 K. A window/feed-through provides the interface for the fibre coupling. There are also breakout panels for the instrument vacuum services, electrical services and detector signal cabling.

The total mass of the cryostat is 1705 Kg, comprising of the cold structure 863 Kg (optical bench and components 411 Kg, radiation shield 452 Kg), vacuum vessel 747 Kg, legs 45 Kg, and fasteners 50 Kg.

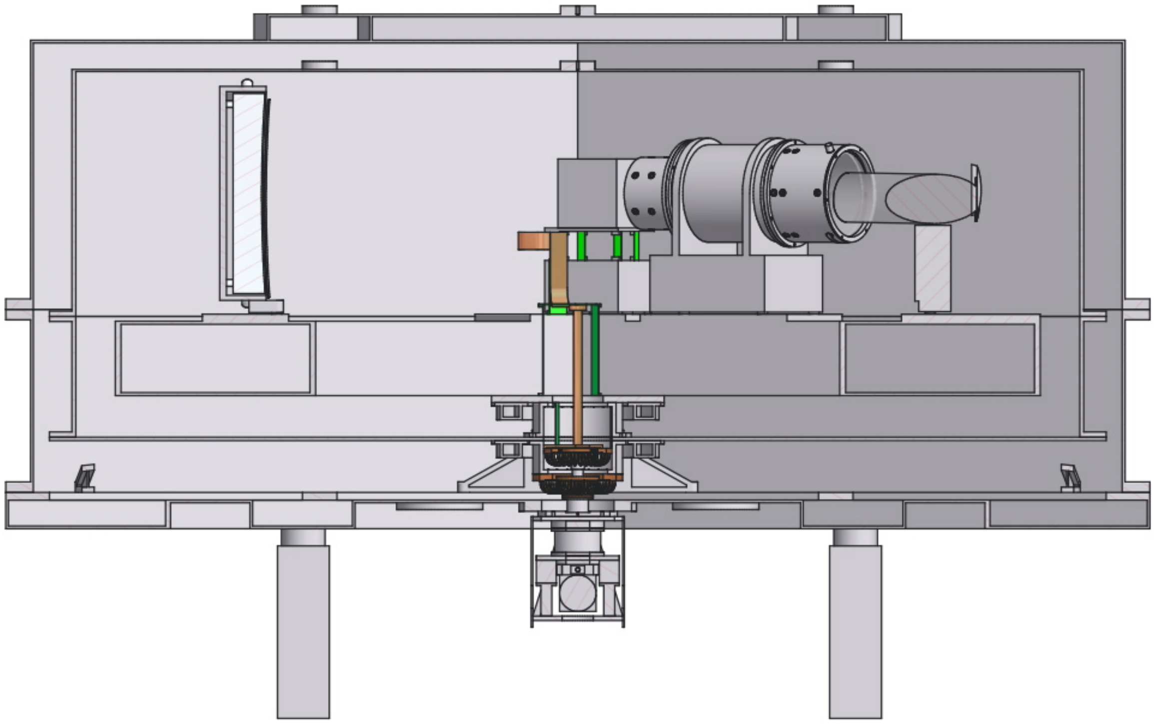

Figure 6. Cryostat cross-section showing the optical bench, radiation shield, vacuum vessel, closed-cycle cooler, and support structure

4.6 CALIBRATION ASSEMBLY

The Calibration Assembly is located next to the cryostat in the pier laboratory. It contains a set of five arc lamps (Krypton Neon, Xenon, and two Thorium-Argon lamps) for standard wavelength calibration, a continuum lamp for flat fielding, and a continuum source with gas cell absorption for additional calibration. The output of the lamps is coupled into fibres and routed either to the calibration fibre or the reference fibre. The arc lamps are optically combined together to provide about 300 bright lines for simultaneous wavelength calibration (to track wavelength shifts) while observing the RV targets. These same arc lamps provide thousands lines for SRF measurement and wavelength solution during daytime calibration. During daytime calibration a series of different integration times can be used for measurements of both bright and faint arc lines. The second Th-Ar lamp is not used during observing but only during daytime calibration to extend its lifetime. It provides a 'gold standard' wavelength reference when the other lamps need to be replaced. The gas cell provides another (limited range) absolute wavelength reference to track any changes in calibration when the arc lamps are replaced. The calibration assembly enclosure is temperature controlled for wavelength stability. The use of the calibration assembly during observing and calibration is described in the two observing scenarios discussed below.

4.7 INSTRUMENT CONTROL

The instrument control sub-system performs top-level configuration and control of other sub-systems. It provides user interfaces and consists of software components that plug in to Gemini software. The sub-system is primarily software but will run on two workstations. One will be located in the telescope dome and will convert the output from the acquisition camera into an offset for the telescope and will control the mechanism that drives the pick-off mirror into the field. The other will be located in the Pier lab and will contain the rest of the instrument control functions. The control software for PRVS is based around Internet appliances; a central instrument sequencer will use existing Applications Programmer Interface's to talk to Galil motion controllers, Lakeshore temperature controllers and Ultracam camera readout systems. We have successfully used these components in previous instruments. The central system uses the Gemini Instrument Applications Programmer Interface for all command and control from higher-level systems, and a remote storage system for data handling.

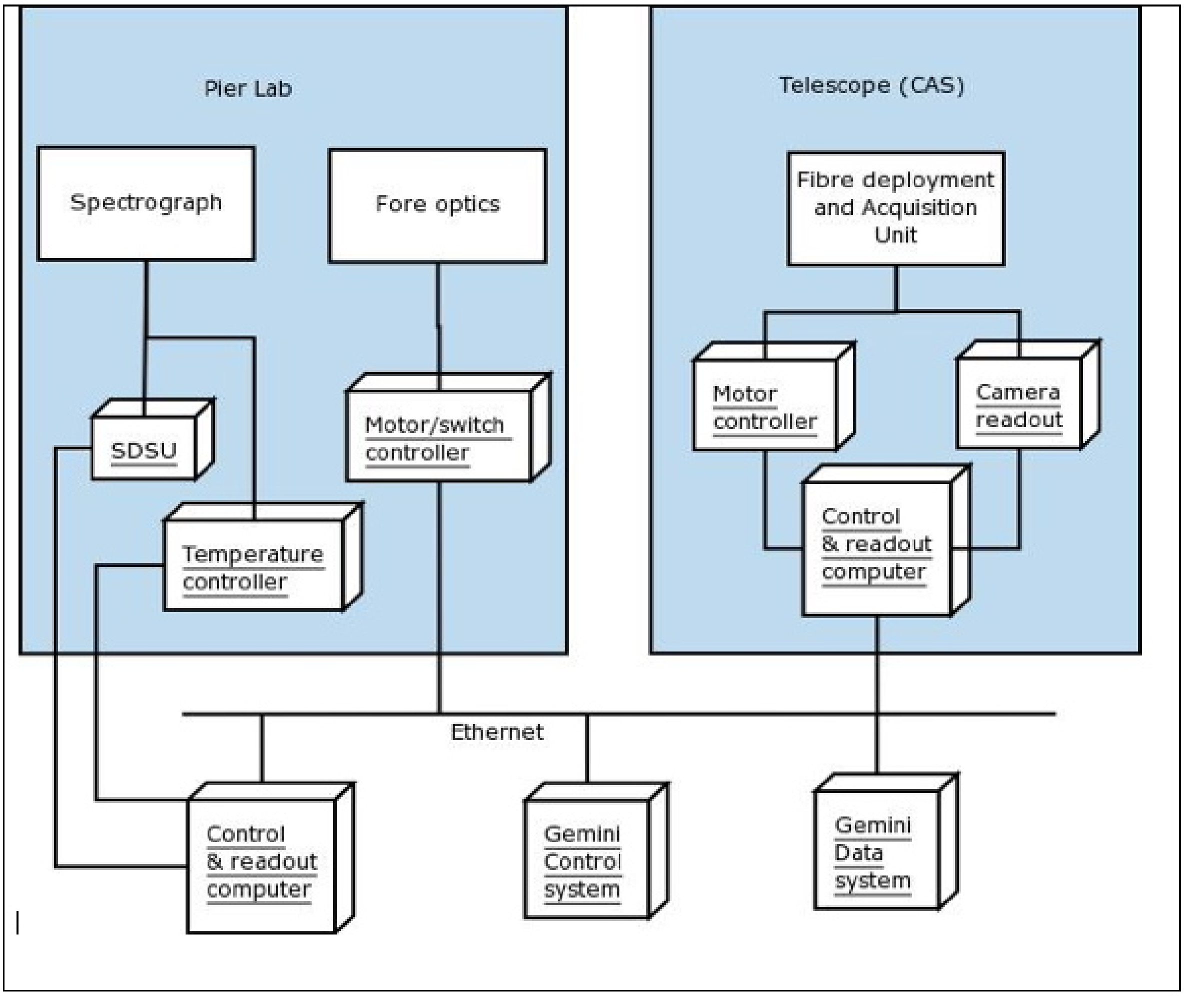

Figure 7. Instrument Control Architecture

4.8 DATA REDUCTION PIPLINE

The Data Reduction pipeline for PRVS will need to reduce multi-order spectral data with emphasis on line extraction and centroiding. In order to maximise the effectiveness of the instrument considerable care must be taken in the preparation and use of calibrations. Optimal extraction routines combined with careful artifact removal will be used to provide data suitable for direct use by radial velocity estimation codes. In addition, quality control checks of short and long-term instrument stability will be provided, along with recipes to pre-process calibration data.

5. OBSERVING WITH PRVS

Observing with PRVS is relatively straightforward since there are only two observing modes and only a few mechanisms. The primary observing mode is Radial Velocity (RV) spectroscopy. RV mode requires exposing simultaneously with arc lines and windowed read outs of the arc lines. The secondary observing mode is High Resolution spectroscopy (HR), which is the same as RV spectroscopy but without the requirement for simultaneous wavelength calibration. For faint objects HR mode is slightly more sensitive than RV mode since the scattered light background from the simultaneously exposed arc lines is removed. With the exception of calibration there is no difference in the setup of PRVS for RV and HR mode.

5.1 OBSERVING MODES SUMMARY

Table 1: Observing Modes

MODE	R	λ/μm	FOV	CALIBRATION
RV spectroscopy	70,000 (2.5 pixel)	Y+J+H	1.4″ fibre	Simultaneous arcs
HR spectroscopy	70,000 (2.5 pixel)	Y+J+H	1.4″ fibre	Sequential arcs

5.2 ACQUISITION AND GUIDING

Fast guiding for windshake is provided by the PWFS and slow guiding for flexure compensation between the PWFS and object fibre is done with the FV CCD. The slow corrections from the FV go via socket communication to the telescope control system. The PWFS also corrects for astigmatism and slow focus changes.

The acquisition and guiding procedure is as follows:

1. Short slew of telescope to target, pointing ± 1-3″ (~1 min)
2. Image with FV and offset to centre of fibre (calibrated in CCD pixel co-ordinates), pointing ±0.1″ (~1 min)
3. Acquire offset star with PWFS. Start fast guiding PWFS (100Hz sampling, ~30Hz correction).
   (~2 min for WFS loop to converge.)
4. Start slow guiding with FV (1Hz sampling, ~0.3Hz correction). Slow guiding can start before the WFS converges.
5. Start spectrograph integration. Typical integration times range from a few minutes to one hour

5.3 OBSERVING MODES DESCRIPTION

5.3.1 RV Mode

Once the target has been positioned on the fibre input and guiding starts very little set up of the instrument is required because of its fixed format and simplicity. The only actions that need to be taken involve calibration sources and readout of the detectors. The only mechanism inside the vacuum jacket is a cold shutter. These actions are described in the Observing Scenarios.

The spectral format on the detectors is fixed. Most of the wavelength range 0.99-1.75μm (YJH) is covered in about 27 orders. Each order contains flux from the star and wavelength fiducial separated by a gap of several pixels. The wavelength fiducial is exposed simultaneously with the star.

At resolving powers of R=70,000 there is effectively no sky background in between the widely separated OH emission lines at YJH. Background comes from dark current and internal scatter from the star, calibration arc lines and OH lines. Therefore a separate sky fibre is not required. The star spectrum is extracted from a dark subtracted and flat-fielded object frame. Depending on the level of the scattered background this may also be measured and subtracted.

5.3.2 HR Mode

This mode is identical to the RV mode except that the science does not require simultaneous exposure of a wavelength fiducial.

5.4 SENSITIVITY

Sensitivity in the two PRVS observing modes is calculated using a model of the sky, telescope, instrument, and detector (for details see the Instrument Design and Analysis document). At resolving powers of ~ R=70,000 at ~1-2μm there is effectively no background from the sky in between the sparse OH emission lines. Most of the background comes from detector dark current and any light scattered inside the instrument. Estimates for the sky brightness due to the moon are also included. The optical bench is cooled to about 190K to keep the instrument thermal background comfortably below the dark current. The model uses a system throughput of 0.10 at Y, J and H and conservative values for the readnoise (10 e RMS with multiple NDRs) and dark current (0.1 e/s).

5.4.1 RV Spectroscopy

Table 2 gives the estimated sensitivity of PRVS in RV mode. Sensitivity is measured away from OH emission lines and telluric features and assumes a flat-fielding accuracy of better than 0.5% per pixel.

Table 2: R=70,000 one-hour 300σ (600 s on chip) continuum sensitivity (Vega magnitudes)

Readnoise (e RMS)	Dark current (e/s)	Y	J	H
10.0	0.10	12.00	11.44	10.91

The only observations required at the science targets are the simultaneous star and arc exposures. Photon rates at the detector for typical survey stars for an estimated instrument throughput of 0.10 are shown in Table 3, where the resolution element is the sum over 2.5 spectral pixels and 17.5 spatial pixels).

Table 3:. Photon rates at the detector

Star	Y mag	J mag	H mag	Photons/s/pixel			Photons/s/R		
				Y	J	H	Y	J	H
M3V	8.7	8.2	7.7	18.4	21.8	21.5	805	954	941
M6V	10.5	9.8	9.2	3.6	5.0	5.4	158	219	236
M9V	12.2	11.2	10.5	0.73	1.4	1.7	32	61	74

The velocity sensitivity has been calculated for range of a M dwarf types and *v* sin *i* (see Science Case document). This modelling indicates that an RMS velocity precision of ~ 1m/s is achievable for a S/N of 300 detection of the continuum, observing in the Y, J and H bands simultaneously (and allowing for about 30% loss of wavelength coverage due to wavelength spill-over at the detectors and masking out of telluric absorptions). Table 4 shows the time to the photon noise limit (assumed to be five times the nominal detector read noise of 10 e RMS), and the time to a S/N of 300 per resolution element, for typical survey stars. It is assumed that flat field noise is insignificant (<0.5%) and that on-chip integration times are long enough to be source photon limited. For the fainter targets an on-chip integration time of about 600 s is required to get photon noise limited. Longer on-chip times are possible but building up the S/N by doing more cycles is preferred so that several frames can be combined to median-out cosmic rays and other noisy pixels.

Table 4: Time to photon limit

Star	Time to photon limit (5σ RN)/s			Time to SNR 300/s/R		
	Y	J	H	Y	J	H
M3V	27	23	23	112	94	96
M6V	139	100	93	570	411	381
M9V	685	357	294	2813	1475	1216

Of equal importance to obtaining good S/N on the star is obtaining good S/N on the arc lines. Modelling indicates that at close to full well capacity (≈ $5x10^4$ e) the measurable RMS velocity precision per line is about 6 m/s. Using Argon, Krypton, Xeon, and Neon arc lamps there about 300 simultaneously useable arc lines in the range 0.99-1.75μm. (Daytime calibration can measure more lines by using a series of different integration times.) This results in an RMS velocity precision limit of 0.3 m/s. Lamp intensities are individually adjusted such that the brightest lines fill the detector well in about 0.1 s. To reach the same S/N on the faintest of these arc lines requires a minimum integration time of 10 s. Although adequate S/N is obtained on the calibration lines in 10 s, the lines must be continuously read out for the duration of the science exposure so that any relative shifts can be tracked and to avoid saturation. Due to the contrast in arc line brightness multiple-sub-array (windowed) readouts are a requirement of the arc line calibration method.

A further requirement on array readout is for multiple read sampling to reduce read noise. Multiple read sampling (consecutive reads as the signal integrates) also permits continuous sampling of the stellar signal from which the photon-weighted centre of the integration time can be determined. Knowing the effective time of the RV measurement to better than about 15 s is required since the earth's barycentric velocity typically changes by 1 m/s in 15 s.

5.4.2 HR Spectroscopy

Tables 5 and give the estimated sensitivity of PRVS in HR mode where the majority of science programs are viable with S/N~30 rather than 300. Sensitivity is measured away from OH emission lines and telluric features and assumes a flat-fielding accuracy of better than 0.5% per pixel. In this case the calibration arc lines are not simultaneously exposed and this component of the instrument background is removed, improving the sensitivity. The continuum sensitivity is tabulated in Table 5 and the corresponding line sensitivity is tabulated in Table 6.

Table 5:. R=70,000 one-hour 30σ (600 s on chip) continuum sensitivity (Vega magnitudes)

Readnoise (e RMS)	Dark current (e/s)	Y	J	H
10.0	0.10	14.87	14.32	13.78

Table 6:. R=70,000 one-hour 30σ (600 s on chip) line sensitivity (erg s^{-1} cm^{-2})

Readnoise (e RMS)	Dark current (e/s)	Y	J	H
10.0	0.10	1.34×10^{-16}	1.11×10^{-16}	8.38×10^{-17}

5.4.3 Guiding with the CCD Fibre Viewer

Using the estimated throughput of the telescope plus CCD camera (0.01) the CCD sensitivity on our faintest RV survey targets (L2 dwarf at 6 pc) is 50σ1sec=14.8 at Z (0.83-1.0μm). A S/N of 20 is sufficient to centroid to better than about 0.05″ so this sensitivity meets the requirement for slow guiding on faint targets to track any flexure between the PWFS sensor and the FV. To guide on out brightest targets (Z>1) without saturating in the minimum integration time of ~0.1 sec is done by inserting a neutral density filter with the Z filter.

The use of the FV will significantly improve observing efficiency of the RV M dwarf survey compared to the spiral peak-up process used in bHROS (due to the inaccuracy of the OIWFS mapping).

5.5 CALIBRATION

The PRVS Calibration Assembly provides all calibration sources. Anticipated calibrations include:

- Dark and bias frames
- Spectrograph flat field frames
- Detector flat field (no spectrograph optics) for scattered light modelling
- Frames containing wavelength fiducials (arc lamps and sky telluric spectra)
- Observations of a flat-field source through a gas cell. This is required to validate the long-term wavelength stability of the arc lamps
- Observation of arc lines to measure instrument SRF and wavelength solution
- Observations of telluric standard stars to remove telluric features from science spectra
- Observation of sky to measure location of sky emission lines so that they can be masked out
- Observations of photometric standard stars for flux calibration of spectra. The telluric and photometric standard stars can be the same if suitable
- Radial velocity 'standards'
- Fast rotating A stars: astronomical blackbody sources which maybe used as calibrator references for gas cell work

5.6 DETECTOR CONFIGURATIONS

Anticipated functions include:

5.6.1 Spectrograph Array Mosaic

- Readout modes: single read; Fowler multiple sampling, up-ramp sampling with destructive read out of multiple sub-arrays (~100 5 x 5 pixel boxes once every 0.1 s for up to 1800 s)
- Range of full frame exposure times: minimum exposure limited by the array to ~2 s; typical minimum exposure time ~ 10 s (arc lines), typical maximum exposure time ~ 600 s (photon noise limit on faint star), maximum exposure time ~ 1800 s
- Should be capable of co-adding ~100 integrations within the controller
- Must have the ability to measure dark currents of 0.005e/s

5.6.2 FV CCD Detector

- Readout modes: full array (≥512 x 512 pixels) for acquisition, and one sub-array (~33 x 33 pixels) for guiding
- Range of full frame exposure times: minimum exposure time ~ 0.1 s (to avoid saturation on bright guide star, sub-array), maximum exposure time ~ 300 s for acquisition on faint targets
- Should be capable of co-adding ~100 integrations within the controller
- Must have the ability to measure dark currents of 0.05e/s.

6. HANDLING PRVS DATA

6.1 SOFTWARE REQUIREMENTS

6.1.1 Quick look

The quick look software should be capable of the following operations:

- Display raw data frames as they are read from the array
- Display raw data frames as they are read from the CCD guider
- Each frame should be displayed within TBD seconds

6.1.2 Pipeline data reduction

The pipeline reduction software should be capable of the following operations:

- Support the acquisition mode, including determining target centroids
- Calibration of raw frames
  - Remove bias and dark
  - Flat field
  - Add wavelength scale
  - Running S/N estimate
  - Compute photon-weighted centre of integration time
- Co-addition of object frames as observations progress for real-time assessment of S/N
- Ratio of co-added spectra by telluric standard to remove telluric features in object (HR mode)
- Flux calibrate co-added spectra
- Special requirements for RV data (TBD)

6.2 DATA RATES

The highest data rate is set by the RV mode where it is required to store a non-destructive read of the spectrograph mosaic about every 30 s. This is done so that the photon-weighted midpoint of each RV observation (consisting of many reads up the ramp of the integrating signal) can be determined to better than 30 s to guarantee that errors in the barycentric correction to the Earth's motion be corrected to better than 1 m/s. Assuming an observing efficiency of 80%:

- ~ 800 frames per 8 hour night
- 17 MB per frame (2048x4096x 2Bytes)
- ~ 13 GB per night

Higher data rates might be used for asteroseismology projects where the fast cycle time of infrared arrays is exploited. In this case using the minimum exposure time (2 s) and a cycle time of 6 s would give a data rate of 7.7 GB per hour.

6.3 DATA DISTRIBUTION AND ARCHIVING

PRVS data will be distributed and archived automatically according the standard Gemini procedures through the Gemini Science Archive. Calibration data will also be reduced and archived. Quality control metrics will by produced by the reduction and archived.

7. OBSERVING SCENARIOS

7.1 RV SURVEY OF M DWARFS (M2.5 V TO M9.0 V)

7.1.1 Scientific Background

The Science Case proposes a RV survey of about 500 M dwarfs (~M3V to M9V) to a precision of ~ 1 m/s RMS. The survey requires about 100 nights per year for five years to observe each star for 30 epochs. The goal of the survey is to obtain a census of planets in the range 1-10 $M_{\oplus}$ around M dwarfs, in particular, the survey will be sensitive to Earth mass planets in the habitable zones around late-type M dwarfs inaccessible to optical RV surveys.

7.1.2 Survey Design

Our target list is based on scaling from the 10 pc sample of Todd Henry (privately supplied for this design study). On the timescale of PRVS our target list should be fundamentally improved by the discovery of new nearby M dwarfs and by the better characterisation of known M dwarfs though the multi-band infrared photometry and astrometry from UKIDSS and astrometry from Pan-STARRS. Members of the PRVS science team are closely involved in both of these surveys.

We constructed a mock survey in order to gauge the various factors involved in conducting a high-precision RV survey with PRVS. The input population of ultra-cool dwarfs in the solar neighbourhood was based on Todd Henry’s sample as well as other *Nstars* work by Reid et al. (2004, AJ 128, 463) and Cruz et al. (2003, AJ 126, 2421). The J-band Luminosity Function resulting from this work and used in our mock RV surveys is given in Table 7.

Table 7: J-band Luminosity Function

M(J)	ϕ	f_{good}	M*	~ Sp T
5.25	3.4	1.0	0.64	M0
6.25	4.9	1.0	0.55	
6.75	4.7	1.0	0.46	M1
7.25	6.1	1.0	0.37	
7.75	6.3	1.0	0.30	M3
8.25	5.3	1.0	0.24	
8.75	5.4	0.75	0.19	M4
9.25	5.3	0.75	0.15	
9.75	4.3	0.5	0.12	M5
10.25	2.7	0.5	0.10	
10.75	1.79	0.5	0.090	M7
11.25	1.12	0.5	0.081	M8
11.75	0.97	0.1	0.076	L0
12.25	0.60	0.1	0.074	L1
12.75	0.34	0.1	0.073	L3
13.25	0.30	0.1	0.073	L4

M(J) is the J-band magnitude, ϕ is the space density in units 10^{-3} stars/pc^3, $\mathbf{f_{good}}$ is an ad hoc parameter which represents the fraction of stars useable for an RV survey (inactive and *v* sin *i* < 10 km/s). **M*** is the mass in units of the sun based on a 5 Gyr Baraffe model (which is a good fit to the published dynamical data of Delfosse et al. 2004 (ASP Conference Series 166, 318). **Sp T** is the approximate spectral type.

The mock survey described here is meant to be representative, not definitive. Our quantitative evaluation reveals several key results:

- As expected for a survey spanning a factor of ~100 in absolute infrared magnitude, it is easy to observe many of early-/mid-M types at little cost in telescope time. The required amount of observing time for these bright targets is driven by the fixed overhead, not by the integration time, and hence there is a strong premium on minimising the observing overheads (e.g. target acquisition).
- Observing the coolest objects is very costly in observing time, not only because these objects are getting fainter but also because the LF is turning down, i.e. there is a lower space density of these ultra-cool objects.
- Observing at Y, J and H-band is sufficient. Observing at K does not add much; although the coolest dwarfs are quite red, they also are relatively rare and faint.

The survey is optimized to cover as many mid to late M dwarfs (M5 V to M9 V) as reasonable. These lower mass stars require a velocity precision of ≈ 2 m/s to detect terrestrial mass planets in the habitable zone. Surveys of early M stars can cover more stars but require a velocity precision of ≤ ~ 1 m/s .

For viable surveys we consider that we need to survey ~ 500 stars over 30 epochs over about five years to be comparable with optical surveys (see the Science Case). The important parameters include instrument sensitivity, the S/N per target observation to reach a desired RV precision, the number of observing nights per year, the fraction of stars of suitable stars, and observing efficiency and observation overhead for acquisition. Our analysis based on the Bouchy et al. (AA 374, 733, 2001) formulation indicates that a S/N of 300 is required to each a velocity precision of ~ 1 m/s. As an independent check Alex Wolszczan used his RV code to extract radial velocities from simulated PRVS spectra and this method also finds that a S/N of 300 is required for a RV precision ~ 1 m/s. Based on measurements of activity in M stars 30% of the stars in each luminosity bin are rejected. Although our modelling shows that *v* sin *i* > 10 km/s is not in itself a significant hindrance to measuring precise radial velocities (see the modelling presented in the Science Case) the mock survey is shown for all remaining stars and for stars with *v* sin *i* < 10 km/s to assess the effect on the surveys where velocity jitter in fast rotators is a factor. This effect is quantified in the $\mathbf{f_{good}}$ parameter in the J-band Luminosity Function (see Table 7) and comes from *v* sin *i* measurements of M and L stars. Mock surveys are computed for 50 and 100 nights per year for five years.

Table 8: Mock M Dwarf RV Surveys

S/N:	**300**			
Nights/year :	**100**		**50**	
***V* sin *i* / km/s:**	**All**	**<10**	**all**	**< 10**
~ Sp. Type	**Number of Stars**			
M2.5 V	77	90	35	41
M3.0 V	77	90	35	41
M4.0 V	77	90	35	41
M5.0 V	77	90	35	41
M6.0 V	77	58	35	41
M6.5 V	35	17	35	17
M8.0 V	10	5	10	5
M9.0 V	3	1	3	1
L1.0	1	0	1	0
L2.0	0	0	0	0
Total	434	441	198	253

Table 8 shows the results of several simulations of the M Dwarf RV Survey. These simulations indicate that 50 nights per year is marginal (only about 200 stars) for a good survey and that 100 nights per year is better (over 400 stars). These results are preliminary and much more work needs to be done to design an optimised survey.

As an example, the output of the simulation for 100 nights/year, S/N=300, *v* sin *i* < 10 km/s (red in Table 8), is given below:

---

(1) Magnitude-limited sample:

fraction of sky observable = 0.66
fraction of non-active stars = 0.7
accounting for fraction of good stars in each LF bin: YES

minimum S/N = 300
max integration per object = 4800.0 sec
limiting mags {Y,J,H} = 12.30, 11.75, 11.20

N*(max) = # of stars observable to specified sensitivity limit
d(max) = maximum distance (pc) the spectral type can be observed

---

~SpT	fgood	M(Y)	d(max)	N*(max)	M(J)	d(max)	N*(max)	M(H)	d(max)	N*(max)
2.5	1.00	8.2	68.9	3986	7.8	68.0	3832	7.2	67.7	3776
3.0	1.00	8.8	53.7	1590	8.2	54.0	1616	7.7	53.3	1552
4.0	0.75	9.3	41.1	545	8.8	42.9	619	8.2	42.0	580
5.0	0.75	9.9	31.5	240	9.2	34.1	304	8.7	33.4	287
6.0	0.50	10.5	24.1	58	9.8	27.1	83	9.2	26.8	81
6.5	0.50	11.0	18.8	17	10.2	21.5	26	9.6	21.5	26
8.0	0.50	11.7	14.1	5	10.8	17.1	9	10.1	17.7	10
9.0	0.50	12.2	10.8	1	11.2	13.6	3	10.5	14.5	3
10.0	0.10	12.8	8.3	0	11.8	10.8	0	10.9	11.9	0
11.5	0.10	13.4	6.2	0	12.2	8.6	0	11.3	9.9	0

---

(2) Simulated survey

fraction of sky observable = 0.66
fraction of non-active stars = 0.7
accounting for fraction of good stars in each LF bin: YES

minimum S/N = 300
max integration per object = 4800.0 sec
limiting mags {Y,J,H} = 12.30, 11.75, 11.20

observing efficiency = 80.0%
fixed overhead per star = 180.0 sec
min integration per star = 60.0 sec
# of epochs needed per star = 30
max # of targets per LF bin = 90.0
max # of bright targets per LF bin = 90.0
hours of observing per night = 8.0
survey duration = 5.0 yrs

N* = # of stars observed in sample
<dist = max distance (pc) of targets for each LF bin
Tmax = max integration time of targets for each LF bin
Nts/yr = # of telescope nights per year needed

*** Y-band ***

~SpT	M(Y)	fgood	Mstar	d(max)	N*(max)	N*	<dist	Tmax	Nts/yr
2.5	8.2	1.00	0.30	68.9	3986	90	19.5	30.6	4.8
3.0	8.8	1.00	0.24	53.7	1590	90	20.6	104.3	4.8
4.0	9.3	0.75	0.19	41.1	545	90	22.6	434.9	9.5
5.0	9.9	0.75	0.15	31.5	240	90	22.7	1298.0	21.6
6.0	10.5	0.50	0.12	24.1	58	58	24.1	4800.0	45.7
6.5	11.0	0.50	0.10	18.8	17	17	18.8	4800.0	13.4
8.0	11.7	0.50	0.09	14.1	5	5	14.1	4800.0	3.9
9.0	12.2	0.50	0.08	10.8	1	1	10.8	4800.0	0.8
10.0	12.8	0.10	0.08	8.3	0	0	0.0	0.0	0.0
11.5	13.4	0.10	0.07	6.2	0	0	0.0	0.0	0.0

Total number of targets = 441.0

Telescope nights per year = 104.53

*** J-band ***

~SpT	M(J)	fgood	Mstar	d(max)	N*(max)	N*	<dist	Tmax	Nts/yr
2.5	7.8	1.00	0.30	68.0	3832	90	19.5	32.3	4.8
3.0	8.2	1.00	0.24	54.0	1616	90	20.6	102.1	4.8
4.0	8.8	0.75	0.19	42.9	619	90	22.6	367.0	8.5
5.0	9.2	0.75	0.15	34.1	304	90	22.7	947.1	16.7
6.0	9.8	0.50	0.12	27.1	83	83	27.1	4800.0	65.4
6.5	10.2	0.50	0.10	21.5	26	26	21.5	4800.0	20.5
8.0	10.8	0.50	0.09	17.1	9	9	17.1	4800.0	7.1
9.0	11.2	0.50	0.08	13.6	3	3	13.6	4800.0	2.4
10.0	11.8	0.10	0.08	10.8	0	0	0.0	0.0	0.0
11.5	12.2	0.10	0.07	8.6	0	0	0.0	0.0	0.0

Total number of targets = 481.0

Telescope nights per year = 130.109

*** H-band ***

~SpT	M(H)	fgood	Mstar	d(max)	N*(max)	N*	<dist	Tmax	Nts/yr
2.5	7.2	1.00	0.30	67.7	3776	90	19.5	32.9	4.8
3.0	7.7	1.00	0.24	53.3	1552	90	20.6	107.7	4.9
4.0	8.2	0.75	0.19	42.0	580	90	22.6	400.2	9.0
5.0	8.7	0.75	0.15	33.4	287	90	22.7	1022.6	17.8
6.0	9.2	0.50	0.12	26.8	81	81	26.8	4800.0	63.8
6.5	9.6	0.50	0.10	21.5	26	26	21.5	4800.0	20.5
8.0	10.1	0.50	0.09	17.7	10	10	17.7	4800.0	7.9
9.0	10.5	0.50	0.08	14.5	3	3	14.5	4800.0	2.4
10.0	10.9	0.10	0.08	11.9	0	0	0.0	0.0	0.0
11.5	11.3	0.10	0.07	9.9	0	0	0.0	0.0	0.0

Total number of targets = 480.0

Telescope nights per year = 130.931

7.1.3 Required Observations

Observations will be taken in the RV mode of PRVS. This mode acquires simultaneous star and arc line spectra across the wavelength range 0.99 -1.75µm at a resolving power of R=70,000. Guiding on the science targets with the FV simplifies acquisition and significantly improves the observing efficiency of the survey.

To reach the required velocity precision a S/N of 300 is needed. For a typical M3V star (Y magnitude 8.7) a typical suitable time would be 30 s x 1 co-adds x 6 cycles for a total integration time of 160 s. The requirement for 6 separate frames (cycles) is to median out cosmic rays. For the fainter stars in the survey exposure times are set by the star. For a typical M9V star (Y magnitude 12.2) a suitable integration time is 600 s x 6 cycles for a total integration time of 3600 s. The on-chip integration time of 600 s is required to get photon noise limited. Longer on-chip times are possible but building up the S/N by doing more cycles is preferred so that several frames can be combined to median-out cosmic rays and noisy pixels.

To track long-term wavelength shifts between the object and calibration fibres, the same calibration arc lines are projected into the object fibre as well as the reference fibre before and after observing Two different types of flat field will be taken. The first is an internal lamp illumination of the science arrays, bypassing the gratings. The purpose of this flat field is for a pixel-pixel (spatial) gain map that will be used to fit and subtract scattered light. The second is a spectral flat field exposure through the fibres. Dark frames are also taken. For accurate measurement of the instrument SRF and wavelength solution arc line are made.

7.1.4 Planning the Observation

Targets will be drawn from the RV target list to minimise telluric absorption but also with consideration for their priority. The priority weighting will be based on a number of factors including (1) number of RV points obtained, (2) the sampling interval with respect to previously obtained epochs, (3) usefulness of current epoch in constraining periodicities (where there are few points) and orbital parameters (where an orbital solution has been determined), (4) whether the object already has planetary signal (further observations should be made to search for other signals), (5) the importance of the RV signal relative to the aims of the survey (determination of a precise orbit for spectroscopic binary), (6) evidence for activity, (7) data reduction difficulties and (8) acquisition problems

7.1.5 Long-term Calibration (Daytime)

To measure RV precisions of ~ 1 m/s the instrument SRF needs to be measured as accurately as possible. Similarly the wavelength solution also needs to be measured as accurately as possible. By observing a second Ar-Th arc lamp, and separately, a continuum lamp through a gas cell, the absolute wavelength calibration of the arc lamps can be monitored. This step is required to allow for replacing burnt out lamps. Based on experience with HARPS the expectation is that given the designed high stability of the instrument these calibrations need only be made once every several months or whenever the instrument is adjusted (e.g. lamp replacement or servicing). Data taken during lab testing and commissioning will determine the frequency of long-term calibration. In principle SRF and wavelength calibration could be conducted every day.

- SRF measurement and wavelength calibration
  - Turn on the arc lamps. Wait till they stabilize (about 30 min TBC)
  - Move array blank-off out
  - Move to illuminate both the object fibre and the reference fibre with [Kr+Ne+Xe+Th-Ar] arc lamps
  - Set exposure time and configure science arrays for multiple sub-array read out
  - Record an arc frame and display on the Quick Look
  - Repeat for many different exposure times to get S/N > 1000 (TBC) on ~ 1000 arc lines
  - Move to illuminate both the object fibre and the reference fibre with second Th-Ar arc lamp
  - Set exposure time and configure science arrays for multiple sub-array read out
  - Record an arc frame and display on the Quick Look
  - Repeat for many different exposure times to get S/N > 1000 (TBC) on ~ 1000 arc lines
  - Turn off the [Kr+Ne+Xe+Th-Ar] arc lamps

- Absolute wavelength calibration
  - Move to illuminate both the object fibre and the reference fibre with the second Th-Ar arc lamp
  - Set exposure time and configure science arrays for multiple sub-array read out
  - Record an arc frame and display on the Quick Look
  - Repeat for many different exposure times to get S/N > 1000 (TBC) on ~ 1000 arc lines
  - Turn off the second Th-Ar arc lamp
  - Turn on continuum lamp viewed through gas cell
  - Set exposure time and configure science arrays for normal full frame read out
  - Record a gas cell frame and display on the Quick Look
  - Turn off continuum lamp
  - Move array blank-off in

7.1.6 Start of Night Calibration and Setup

Flat, dark and arc line exposures are acquired just before and after observing science targets. There are two types of flat field exposures, one to flat field the science exposures and another to help with scattered light subtraction using an (un-dispersed) internal flat-field lamp.

Any movement of the object fibre relative to the calibration fibre is tracked by illuminating the object fibre and calibration fibre with the arc lamps immediately before and after observing science targets. If required, this can be measured several times per night in order to track and fit any shift.

- Configure instrument for calibration
  - Move array blank-off out
  - Fibre Deployment pick-off mirror retracted
  - Turn on [Kr+Ne+Xe+Th-Ar] arc lamps. Wait till they stabilize (about 30 min TBC)

- Spectral flat-field frames
  - Turn on flat-field lamp
  - Move to illuminate both the object fibre and the reference fibre with flat-field lamp
  - Set exposure time and configure science arrays for normal full frame read out
  - Record a flat-field frame and display on the Quick Look
  - Turn off flat-field lamp

- Spatial flat-field frames
  - Turn on internal flat-field lamp
  - Set exposure time and configure science arrays for normal full frame read out
  - Record an internal flat-field frame and display on the Quick Look
  - Turn off internal flat-field lamp

- Dark frames
  - Move array blank-off in
  - Set exposure time and array read out mode identically to the science exposure
  - Record a dark frame and display on the Quick Look.
  - Repeat as needed for flat-field, arc and other calibration frames

- Arc lamp calibration
  - Move array blank-off out
  - Move to illuminate both the object fibre and the reference fibre with arc lamps
  - Set exposure time and configure science arrays for multiple sub-array read out
  - Record an arc frame and display on the Quick Look
  - Move array blank-off in

7.1.7 Setup Prior to the Observation

- Configure instrument for observing
  - Move array blank-off out
  - Move to illuminate the object fibre with light from the telescope (Fibre Deployment pick-off mirror deployed)
  - Move to illuminate the reference fibre with arc lamps

- Acquisition and Guiding Setup
  - Slew telescope to science target
  - Set CCD FV neutral density filter in or out depending on brightness of target
  - Acquire science target with fibre viewer (31x31″ FOV, 0.06″/pix,). Take an image and display on Quick Look. Offset telescope to move target into centre of fibre
  - Acquire offset guide star with PWFS and start PWFS guiding
  - Start guiding with the fibre viewer, keeping object in centre of fibre. Send corrections to telescope tracking via socket (slow) connection. Use 2x2″ (33x33 pixel) sub-array box centred on fibre

7.1.8 Science Observation Sequence

With the fibre viewer guiding and the instrument correctly configured, science integrations can start.

- Set the exposure time (e.g. 30 s x 1 coadds x 6 cycles for typical M3V star, 600 s x 1 coadd x 6 cycles for typical M9V star, see Table 3) and read out mode (multiple sub-array and full array multiple sampling).
- Record science exposures and display on Quick Look
- Stop guiding and slew to next target
- Take a sky exposure sometime during the night suitable for identifying OH emission lines. This frame will be used to identify OH emission lines so that they can be masked out during the reduction process

7.1.9 End of Night Calibration and Shutdown

Any movement of the object fibre relative to the calibration fibre during the night is tracked by illuminating the object fibre and calibration fibre with the arc lamps immediately after observing science targets. If required, this can be measured several times per night in order to track and fit any shift.

Flat, dark and arc line exposures are acquired just after observing science targets.

- Arc lamp calibration
  - [Kr+Ne+Xe+Th-Ar] arc lamps still on
  - Move to illuminate both the object fibre and the calibration fibre with arc lamps
  - Set exposure time and configure science arrays for multiple sub-array read out
  - Record an arc frame and display on the Quick Look
  - Turn off the arc lamps

- Spectral flat-field frames
  - Turn on instrument flat-field lamp.
  - Move to illuminate both the object fibre and the calibration fibre
  - Set exposure time and configure science arrays for normal full frame read out
  - Record a flat-field frame and display on the Quick Look
  - Turn off instrument flat-field lamp.

- Spatial flat-field frames
  - Turn on internal flat-field lamp
  - Set exposure time and configure science arrays for normal full frame read out
  - Record an internal flat-field frame and display on the Quick Look
  - Turn off internal flat-field lamp

- Dark frames
  - Move array blank off in
  - Set exposure time and array read out mode identically to the science exposure
  - Record a dark frame and display on the Quick Look.
  - Repeat as needed for flat-field, arc and other calibration frames
  - Move array blank off out

- Safe instrument
  - Turn off all lamps
  - Move array blank in
  - Retract Fibre Deployment pick-off mirror

7.2 GAMMA RAY BURSTS

7.2.1 Scientific Background

The extreme brightness of Gamma Ray Bursts (GRBs) makes them excellent probes of star formation, reionization of the intergalactic medium, and metal enrichment in the early Universe (see Science Case document). At redshifts z > 6, line blanketing in the Lyman alpha forest essentially removes nearly all the light below the red-shifted Lyman alpha position. Very small amounts of light still penetrate at z = 6.5 and can be analyzed using the separation between their positions (the "dark gap" statistics) to analyze the structure and neutral fraction of the intergalactic medium (e.g. Songaila & Cowie, AJ 123, 2183, 2002). However, nearly all of the information at these redshifts must come from metal lines longward of Lyman alpha. At z > 6.5 lines of Si II, Si IV, C IV, Ni II, Al III and Zn II are shifted into the 0.99-1.75 μm range of PRVS. At z > 7 the Lyman alpha emission line from the host galaxy could also be detected.

Interesting work can be done at R~5,000, but R≥30,000 is needed resolve the major velocity components and for studying the multiple velocity components within the host galaxy (Fiore et al. ApJ 624, 853, 2005), allowing a detailed abundance analysis. The high resolving power of PRVS is also useful to minimize telluric contamination.

7.2.2 Required Observations

The most distant burst detected to date is GRB 050904 (Haislip et al. Nature 440, 181, 2006; Kawai et al. Nature 440, 184, 2006) which had a magnitude of J~16.5 after one hour. To reach this magnitude with PRVS requires an integration time of about four hours for a useful S/N of 30 and with the resolving power binned by a factor of two to R=35,000. However, it is considered that even a S/N~10 at R≥30,000 could deliver unique science on z>6 GRBs. Acquisition times faster than one hour are entirely feasible (see below) in which case the afterglow is brighter and easier to observe.

At these high resolving powers the highest background in between the OH emission lines is from the dark current (scattering from the OH lines is estimated to be less than the dark current). The OH emission lines themselves can be masked out with little loss in wavelength range (a few percent). Consequently, there is no need for a separate sky exposure, only dark exposures, which are stable enough to be done at the beginning or end of the night.

A telluric standard star needs to be observed at the same air mass as the science target. Telluric features in the science target spectrum are removed by dividing by the telluric standard star spectrum.

Given the ultra-stable nature of PRVS the wavelength solution for the GRB spectra can be taken from the long-term (probably months) RV calibration measurements and so arc line observations are not required in HR mode.

To identify the GRB an exposure can be made with the FV CCD (FOV 31″x31″). A 5 s integration gives a detection of S/N=50 at a Z-band (0.83-1.00μm) magnitude of about 16.5

7.2.3 Planning the Observation

GRBs are still relatively rare events, although with Swift they are detected at a rate of ~2 per week GRBs at high redshift are much rarer with z>6 probably occurring only 1 or 2 times per year (although this rate is still highly uncertain, and may be higher). Swift is likely to run until at least 2010 and so may overlap with PRVS operations. The scenario post Swift is much more uncertain with bursts being provided primarily via GLAST, and possibly via other proposed GRB missions such as EXIST (http://exist.gsfc.nasa.gov/). Thus we might expect that PRVS could provide exciting science for a number of moderate redshift bursts (z~3-4) and may observe a handful of z>6 bursts per year.

Given the random nature of GRB events PRVS has an advantage when rapid rescheduling of the telescope for Targets of Opportunity (ToO) is required since the Fibre Deployment and Acquisition System is permanently fixed on the ISS and so PRVS is always ‘on’ the telescope. Consequently any GRB can be acquired within minutes (TBC) of notification. All calibration is done following the ToO observation.

7.2.4 Setup Prior to the Observation

- Suspend scheduled observing on notification of GRB event
    - Safe scheduled instrument

- Configure PRVS for observing (assuming it is already powered up)
    - Move array blank-off out
    - Select GCAL path with science fold mirror
    - Move to illuminate the object fibre with light from the telescope (Fibre Deployment pick-off mirror deployed)

- Acquisition and Guiding Setup
    - Slew telescope to science target
    - Set CCD FV neutral density filter to out
    - Acquire science target with fibre viewer (31x31″ FOV, 0.06″/pix,). Take an image and display on Quick Look. (SWIFT positions are good to 2.5″ within 10 s of it acquiring the target.) Offset telescope to move target into centre of fibre
    - Acquire offset guide star with PWFS and start PWFS guiding
    - Start guiding with the fibre viewer, keeping object in centre of fibre. Send corrections to telescope tracking via socket (slow) connection. Use 2x2″ (33x33 pixel) sub-array box centred on fibre

7.2.5 Science Observation Sequence

With the fibre viewer guiding and the instrument correctly configured, science integrations can start.

- o Set the exposure time (e.g. 1800 s x 1 coadds x 8 cycles for J=16.5) and set read out mode (full array multiple sampling).
- o Record science exposures and display on Quick Look
- o Stop guiding
- o Slew to telluric standard star (match air mass of science target) and start guiding (as above)
- o Set exposure time and set read out mode (multiple read sampling)
- o Record telluric standard star exposure and display in Quick Look
- o Stop guiding

7.2.6 Post Science Observation

- Safe PRVS
  - o Move array blank in
  - o Retract Fibre Deployment pick-off mirror

- Restart scheduled observing
  - o Setup scheduled instrument
  - o Select science path with science fold mirror
  - o Resume scheduled observing

7.2.7 End of Night Calibration and Shutdown

Flat field and dark exposures are acquired after observing science targets.

- Dark frames
  - o Move array blank off in
  - o Set exposure time and array read out mode identically to the science exposure
  - o Record a dark frame and display on the Quick Look.
  - o Repeat as needed for flat-field and any other calibration frames
  - o Move array blank off out

- Spectral flat-field frames
  - o Turn on instrument flat-field lamp.
  - o Move to illuminate both the object fibre
  - o Set exposure time and configure science arrays for normal full frame read out
  - o Record a flat-field frame and display on the Quick Look
  - o Turn off instrument flat-field lamp

- Safe instrument
  - o Turn off all lamps
  - o Move array blank in
  - o Retract Fibre Deployment pick-off mirror