The precision radial velocity error budget for the Gemini High-resolution Optical SpecTrograph (GHOST)

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ABSTRACT

The Gemini High-resolution Optical SpecTrograph (GHOST) is a fiber fed spectrograph primarily designed for high efficiency and broad wavelength coverage (363 -1000nm), with an anticipated commissioning early in 2018. The primary scientific goal of the Precision Radial Velocity (PRV) mode will be follow-up of relatively faint (R>12) transiting exoplanet targets, especially from the TESS mission. In the PRV mode, the 1.2 arcsec diameter stellar image will be split 19 ways, combined in a single slit with a simultaneous Th/Xe reference source, dispersed at a resolving power of 80,000 and imaged onto two detectors. The spectrograph will be thermally stabilized in the Gemini pier laboratory, and modal noise will be reduced below other sources through the use of a fiber agitator. Unlike other precision high resolution spectrographs, GHOST will not be pressure controlled (although pressure will be monitored precisely), and there will be no double scrambler or shaped (e.g. octagonal) fibers. Instead, GHOST will have to rely on simultaneous two-color imaging of the slit and the simultaneous Th/Xe fiber to correct for variable fiber illumination and focal-ratio degradation. This configuration presents unique challenges in estimating a PRV error budget.

Keywords: Astronomical Spectroscopy, Precision Radial Velocity, Exoplanets

1. SCIENTIFIC CONTEXT

Since the first direct detection of exoplanets with radial velocity more than 20 years ago, a great number of Precision Radial Velocity (PRV) spectrographs have been constructed at telescopes from 0.7m to 10m diameter throughout the world. The key spectrographs at large (>3 m diameter) telescopes in the Southern Hemisphere are listed in the Table below. Planned instruments (2019 or earlier) are in italics.

GHOST is not primarily a PRV spectrograph, but is designed as a high efficiency spectrograph with a PRV mode. Details are given in Sheinis et al. in these proceedings, and the 2014 GHOST SPIE paper.[6] It is clear in Table 1 that GHOST is attempting to fill the high efficiency, broad wavelength range niche. In this context, it is not expected to be competitive with other instruments for long-term surveys of nearby bright stars, but it is anticipated to be competitive for follow-up of fainter transit targets, especially M dwarfs. This science context is particularly relevant for follow-up of upcoming space missions such as TESS[7]

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Table 1. Southern Hemisphere Large Telescope instruments with PRV mode.

Name	Telescope	Wavelength Range (nm)	Architecture	Efficiency @ Resolution^A
HARPS[1]	ESO 3.6m	378–691	Fiber (double scrambler)	5% @ 115K
UCLES[2]	AAT 3.9m	500–620	Iodine	8% @ 50K
PFS[3]	Magellan 6.5m	500–620	Fiber (double scrambler)	9% @ 50K
SALT-HRS[4]	SALT 10m	500–620	Fiber (double scrambler)	8% @ 70K
ESPRESSO[5]	ESO VLT 8m	380–686	Fiber (double scrambler)	8% @ 120K
VELOCE^B	AAT 3.9m	580–930	Fiber (octagonal)	15% @ 80K
NIRPS	ESO 3.6m	980–1800	Fiber	10% @ 100K
GHOST[6]	Gemini S 8m	363–1000	Fiber (circular)	15% @ 80K

^{A}Including typical slit losses, at order center

^{B}Veloce Rosso only – upgrades to a 380–980nm range anticipated

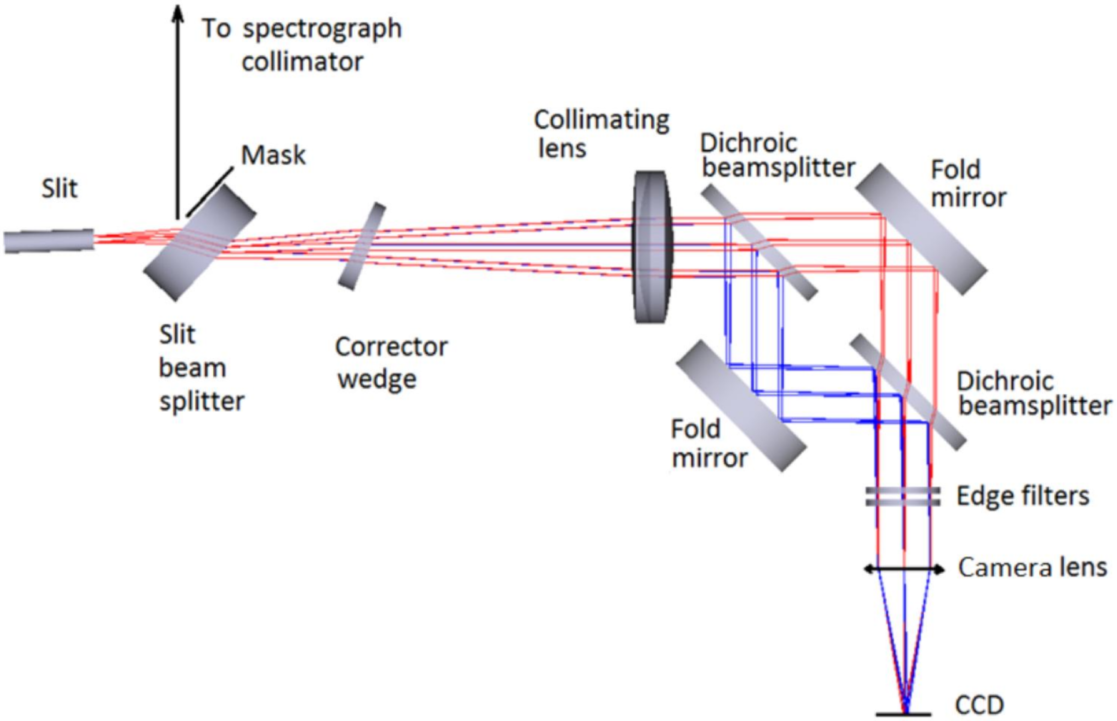

Figure 1. The slit-viewing camera optics for GHOST, which take ∼1% of the light injected into the spectrograph from the fiber and lenslet slit.

2. SLIT VIEWING CAMERA

In high-resolution mode, the GHOST spectrograph is fed by a fiber feed where the stellar image is split in the focal plane, and the telescope pupil is injected onto 19 fiber faces separately. On the fiber cable exit,the fiber faces are imaged via lenslet arrays onto the echelle grating, which is in turn imaged onto the cross-disperser in a white-pupil design. This means that the spectrograph point-spread function, is expected to be largely independent of injection conditions, and stable.

The slit profile on the other hand, is an image of the fiber output far field, which is also dependent on the

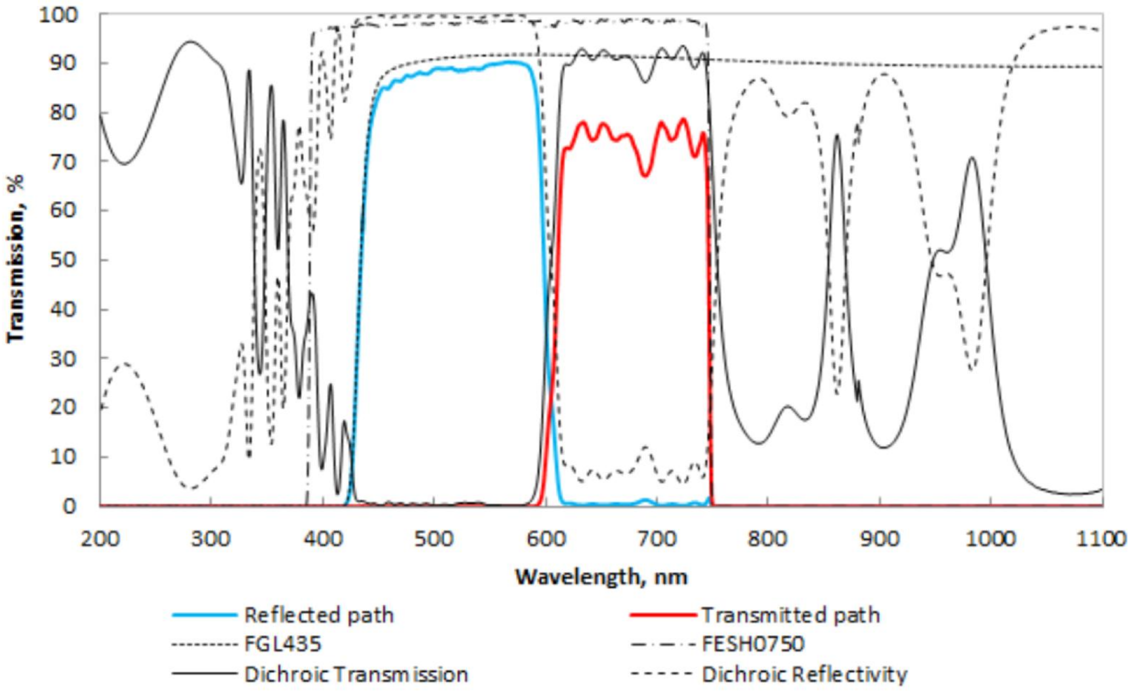

Figure 2. The two filters used to simultaneously image the slit, essential for correcting for slit illumination effects in the error budget.

injection conditions. These profiles are expected to have good azimuthal scrambling, but poor radial scrambling. Precision radial velocity is therefore only possible by simultaneously imaging the slit as seen by the spectrograph. A slit viewing camera images this slit in two filters: one at 420-600nm, containing the bulk of radial velocity information for solar-type stars, and one at 600-760nm, containing a large fraction of the radial velocity data for early M-type stars, and relatively few telluric lines.

The data reduction pipeline therefore has to at least take into account the relative shifts measured in the spectrograph between different fiber outputs. It may also have to take into account the slightly different and seeing-dependent widths of the fiber profiles on the slit, to attain the highest possible precision.

3. ERROR BUDGET TERMS

The GHOST PRV error budget was inspired by the error budget of G-CLEF,[8] and is split into a requirements error budget (Figure 3) and goal error budget (Figure 4). The primary difference between the two error budgets is the stability of the spectrograph, which is temperature stabilized in the stable Gemini pier laboratory environment. It is designed with stability in mind, but without specific requirements on point spread function and distortion term stability. For example, modelling of the effects of the maximal allowable ±0.5 K thermal changes on the spectrograph shows a plate-scale change, which is the main kind of distortion taken into account in the 5 m/s distortion velocity uncertainty term. The instrument is modelled to be (but not required) to be much more thermally stable than ±0.5 K, and it is also not too complex to remove the effects of a simple plate-scale change in software (although this is not baseline). The key terms are:

- *Slit Profile Measurement Errors*: Errors in measuring the slit profile with the slit viewing camera, due to slit viewing camera aberrations. This system subsamples the individual lenslets with double the sampling of the spectrograph, so it is a small term.
- *Pixel Stability*: Primarily due to thermal changes, the Th/Xe calibration source and stellar spectrum will seasonally move up to 0.3 pixels from the nominal position. As in any non-diffraction limited spectrograph,

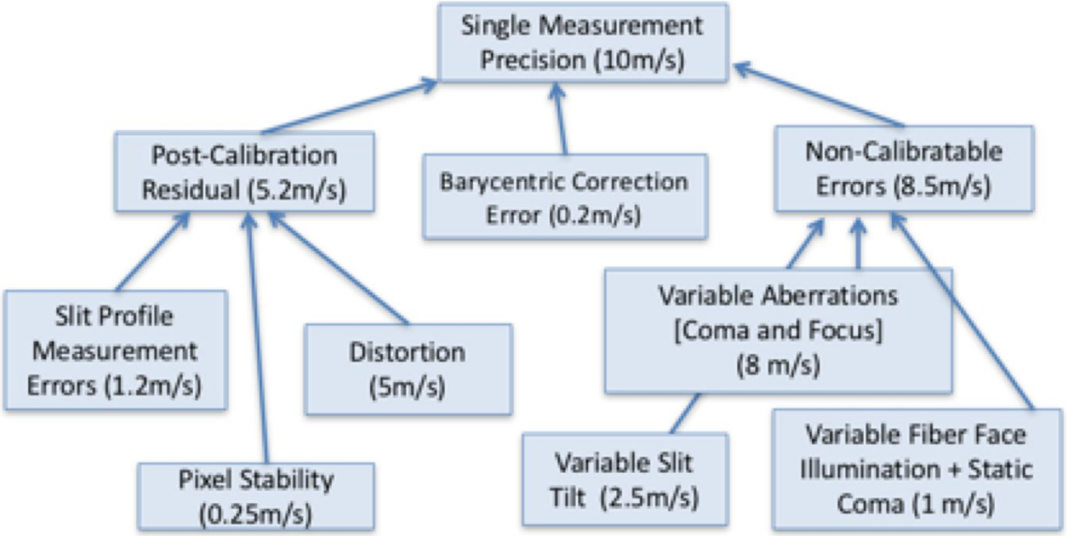

Figure 3. Error budget terms for meeting the instrument requirement of 10m/s. These individual terms are derived from subsystem requirements.

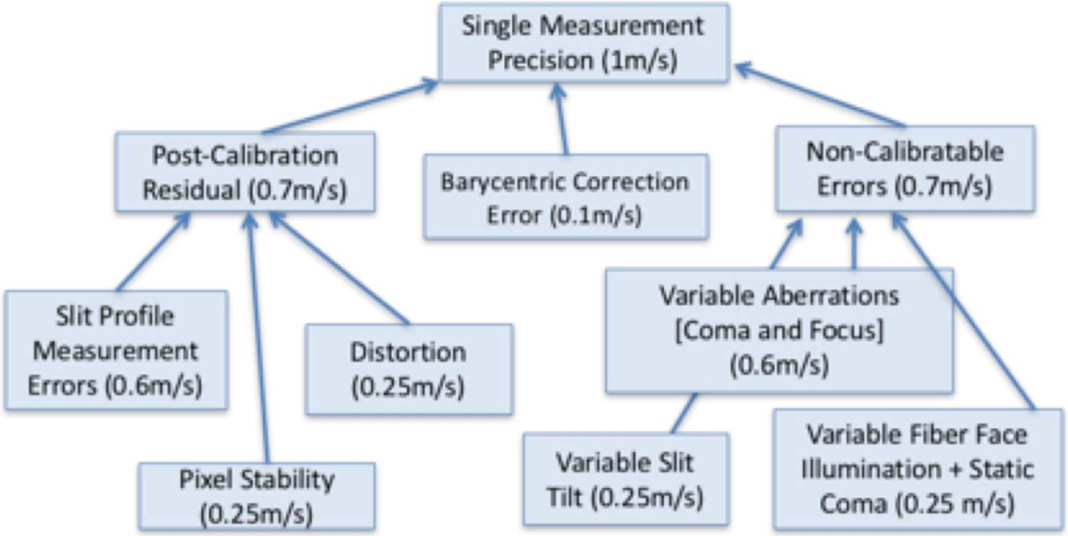

Figure 4. Error budget terms for meeting the instrument goal of 1m/s. These terms are derived from best guesses of subsystem error terms, and do not include photon-noise (i.e. this budget is for the bright limit).

the point-spread function is not formally Nyquist sampled, which induces a pixel-phase error on the position measurement of each Th/Xe line. This term is small and uncorrelated between Th/Xe lines, producing 0.25 m/s overall.

- *Distortion* (Variable): The Th/Xe lines do not sample exactly the same spectral region as the stellar spectra, so variable distortion has the effect of causing imperfect measurements of stellar spectral shifts by the Th/Xe lines. Worst-case (0.5C) thermal changes may cause a 0.1 pix gradient in alignment across each order, imperfectly measured by the Th/Xe. In computing this error term, there is no assumed software that solves for distortion terms: the Th/Xe is simply assumed to measure a simple shift in pixels for each order.
- *Barycentric Correction*: An imperfect observing epoch, due to e.g. seeing changes during an observation and subsequent variable slit losses, causes an error in the barycentric correction. The slit viewing camera measures the observing epoch directly by taking many short (∼10 s) exposures during the long spectrograph exposure, so this is small term.
- *Variable slit tilt* between the slit viewing camera and the spectrograph causes a velocity error, as the Th/Xe lines are on one side of the pseudo-slit. This has been modelled mechanically, and the small term reflects the symmetry in the mechanical design, where thermal changes do not cause a first-order slit tilt.
- *Variable aberrations* in the spectrograph shift high spatial frequencies by a different amount than mid spatial frequencies. The spectral shift measured is a combination of shifts at all spatial frequencies, and the greater content of high spatial frequencies in the Th/Xe lines with respect to the stellar spectra causes a radial velocity error. This term is ameliorated by careful camera element alignment which eliminates large common-mode coma terms, and spectrograph thermal stability that is likely to significantly exceed requiremnets.
- *Static aberrations* in the spectrograph (especially coma) combined with *variable fiber face illumination* (and hence variable spectrograph pupil illumination). This is a small term because the pupil is evenly illuminated by design.

4. FUTURE WORK

A simulator and data reduction pipeline is currently under development for GHOST. The next step in examining the error budget will be to put all known terms into the simulator, and determine the radial velocity errors from the pipeline outputs. In the first instance, spectra will be extracted to a single one-dimensional spectrum per object, using a 2-dimensional weighting function derived from the slit viewing camera. If this proves to be a limiting factor in achieving the goal radial velocity precision, then the precision radial velocity science team aims to work with Gemini to upgrade the pipeline to include a 2-dimensional forward modelling radial velocity mode.

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