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The Roman Space Telescope Relative Calibration Sy

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Abstract

One of the Roman Space Telescopes principal science objectives is to measure dark energy's equation-of-state using a strategic combination of imaging and spectroscopic surveys at high galactic latitude. Type Ia Supernovae survey requirements demand 0.3% photometric accuracy and calibration of key systematic effects. One of these is count rate dependent nonlinearity (CRNL) that if uncorrected affects the accuracy of SNe Ia distance measurements. Romans Relative Calibration System (RCS) enables on-orbit measurement and tracking of CRNL, through a direct illumination mode and a simultaneous lamp plus scene mode. We present results on the impact of CRNL calibration on the dark energy figure of merit (FoM), for a specific reduction of RCS capabilities. We examined many combinations of illumination and passbands, finding that only six meet the requirements. No RCS at all results in a factor of 5 degradation in the FoM.

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1. Introduction

The Nancy Grace Roman Space Telescope is a NASA flagship mission described in the 2010 Decadal Survey to be a stage 4 dark energy mission. One of its principal science objectives is to measure the dark energy equation-of-state using a strategic combination of deep and wide imaging and spectroscopic surveys at high galactic latitude with its Wide Field Instrument (WFI, 0.281 deg²). Its data quality and control of systematics should result in a FoM that is 10 times larger than the current value, FoM ~32.6 (Albrecht et al. [2006](#)).

One characteristic of the WFI HgCdTe detectors is count rate nonlinearity (CRNL), where the measured signal level depends on the flux (photons s⁻¹ pixel⁻¹) and the total collected charge—bright sources appear brighter and dim sources, fainter (see Riess [2010](#); Bohlin & Deustua [2019](#)). CRNL may also be wavelength dependent (e.g., Viana et al. [2009](#)). CRNL physics is not well understood, but the current hypothesis ascribes the effect to charge traps (Mosby et al. [2020](#)). To enable temporal and spatial on-orbit measurements of CRNL the Roman Space Telescope will fly a Relative Calibration System. Two methods are planned to determine CRNL:

- 1.

Direct Illumination (DI). Provides light on every pixel of the focal plane array, for each filter, spanning a flux range equivalent to that between a 15th mag star and a 26th mag supernova. With this method, the CRNL is determined by the ratios of any two illumination levels for each filter.

- 2.

Lamp-on/lamp-off (LOLO). Provides a pedestal light level to the image of an astrophysical scene (lamp on) which is then compared to an image of the same scene without the pedestal (lamp off). The measurement uses the simultaneous imaging of many sources of multiple flux levels to determine CRNL.

2. Quantifying the Impact of RCS Describes on the FoM

Observations of Type Ia supernovae (SNe Ia) are used to measure luminosity distances and, from these, infer the expansion history of the universe. The SNe Ia Hubble–Lemaître diagram enables inference of the cosmological relationship between luminosity distance and redshift. In the late 1990s the Supernova Cosmology Project (Perlmutter et al. [1999](#)) and the High-*Z* Team (Riess et al. [1998](#)) showed that this relationship provided evidence for an accelerating expansion rate of the universe, the cause of which is attributed to dark energy.

The 2006 Dark Energy Task Force (DETF) (Albrecht et al. [2006](#)) introduced the dark energy figure of merit, FoM, defined as *the reciprocal of the area of the error ellipse enclosing the 95% confidence limit in the w_0 - w_a plane*, where w_0 is the current value of the

dark energy equation-of-state and w_a represents the time evolution. For reference, in a Λ CDM universe, $w_0 = -1$ and $w_a = 0$. Larger FoM values indicate greater accuracy. If uncorrected for CRNL, the SNe photometry obtained by Roman will be inaccurate, leading to errors in the luminosity distance, and consequently, on the derived cosmological parameters. Hounsell et al. (2018) identify CRNL as the single largest systematic in SNe Ia cosmology. CRNL increases the apparent brightness of the core of the PSF calibration stars relative to the wings, making the apparent PSF sharper than the true PSF. Therefore in the absence of a CRNL correction, the galaxy shapes are under-corrected for the PSF, and the weak lensing signal amplitude will be underestimated. In both cases, if the CRNL is not corrected for it will result in a FoM lower than that specified by the 2010 Decadal Survey, the mission will not achieve one of its prime objectives, reducing it from a stage 4 dark energy mission to a stage 3.

The science requirements flow down such that the accuracy requirement for CRNL correction is 0.3% over 11 mags, comparable to the target brightness range, in each photometric filter: $F062(R)$, $F087(Z)$, $F106(Y)$, $F129(J)$, $F158(H)$, $F184(F)$. There is no requirement on $F146(W)$. The ratio between any two fluxes must be known to 0.14%. In this note we report on a study examining the impact on the SNe FoM if the RCS cannot meet the requirements. Using a Gaussian process, and a fisher-matrix approach (see Astier et al. 2011), we define the uncertainty in the CRNL as:

$$K(\ln \lambda_1; \log_{10} CR_1, \ln \lambda_2; \log_{10} CR_2) = (0.0075 \text{ mag})^2 \times \left[1 + \frac{(\log_{10} CR_1 - \log_{10} CR_2)^2}{2(I^2)} + \frac{(\ln \lambda_1 - \ln \lambda_2)^2}{2(0.5^2)} \right]^{-1} \quad (1)$$

which assumes a weak wavelength dependence on CRNL and no extra margin in the FoM's dependence on CRNL. Results are referenced to the FoM for DI in all photometric filters plus LOLO in $F184$, the initial design reference.

Multiple DI and LOLO filter combinations were examined for the case where the RCS maximum light level is reduced by $\sim 90\%$ in $F062$, $F129$, $F168$ and $F184$, and by 20% in $F087$, $F106$ compared to the baseline maximum of $30,000 \text{ photons s}^{-1} \text{ pixel}^{-1}$.

Figure 1 shows that six combinations of DI and LOLO keep the FoM within 10% of the baseline:

- 1.
DI only in all filters,
- 2.
LOLO only in all filters,
- 3.
LOLO in W and F ; DI in R, Z, Y, J, H, F

- 4.
- 5.
- 6.

LOLO in W and F ; DI in R, Z, J

LOLO in R, Z, Y, J, H, F ; DI in R, Z, J

LOLO in F ; DI in R, Z, Y, J, H, F

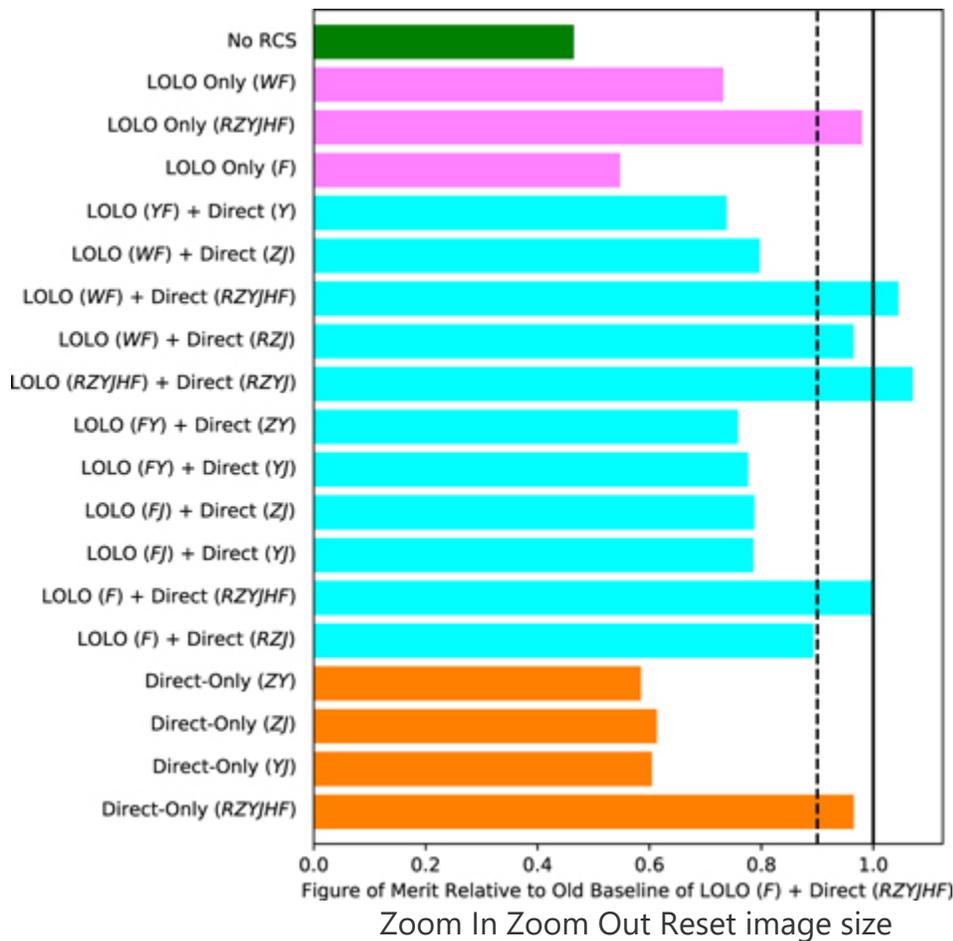


Figure 1. Figures of Merit using a simple fisher-matrix code (e.g., Astier et al. [2011](#)) for a range of RCS scenarios. The dashed vertical line represents a 10% margin on the baseline FoM. We consider direct-illumination only, LOLO-only, and both. When using LOLO with the $W146$ filter, we assume we can also use the LEDs for the $Z087$, $Y106$, $J129$, $H158$, and $F184$ filters. LOLO in $W146$ is seen to be less effective than direct-illumination at these wavelengths, as it does not extend to as low count rates as DI).

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We also investigated the increased risk of other failures:

- 1.
Without the RCS, the baseline dark energy FoM falls by over 50%, a factor of five more than the margin allowed in the Science Requirements.
- 2.
DI in only 2 filters puts nearly a 40% hit on the FoM.
- 3.
LOLO in only two bandpass (*W* and *F184*) has a 20% hit on the FoM.
- 4.
A failure of LOLO can be mitigated with DI in all bandpass.
- 5.
LOLO in all filters can mitigate a full DI mode failure.

This analyses required a few simplifying assumptions and ignored other known issues. These must be understood in order to properly interpret the results presented above. We assumed that DI and LOLO can achieve the same precision, and when the two methods are combined the uncertainties are reduced by $\sqrt{2}$. This is true at high level, but not in the details. For example, LOLO is not as good as DI at determining spatial variation in CRNL or CRNL at low count rates. LOLO needs an assumed functional form, that DI can, in principle, provide.

We recommend using multiple methods to determine and cross-check this vital calibration measurement. A hidden systematic would be difficult to tease out from just one method e.g., distinguishing between CRNL and classical count dependent non-linearity.

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