A Generalized Combinatorial Technique for Linearity Calibrations Applied to Optical Detectors and Spectrographs

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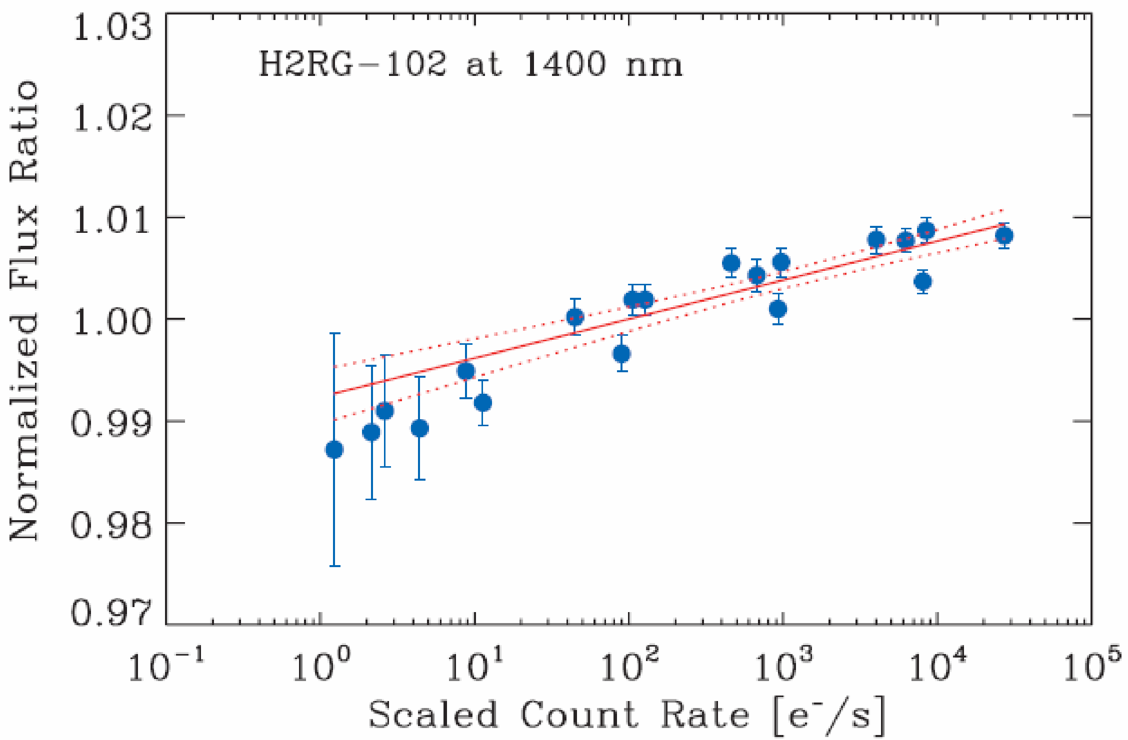
Outline

1. Motivation
2. Basic Concepts
3. Applications
    A. Detector calibrations in the visible and infrared
    B. Spectrograph calibrations
4. New idea for determining integration-time nonlinearities or reciprocities

Nonlinearity issues in Hawaii MCT Arrays



Measurement of Reciprocity Failure in Near-Infrared Detectors

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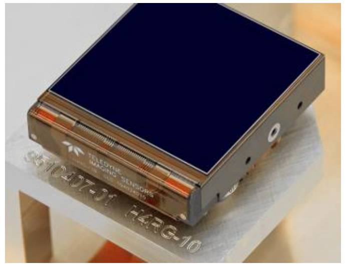
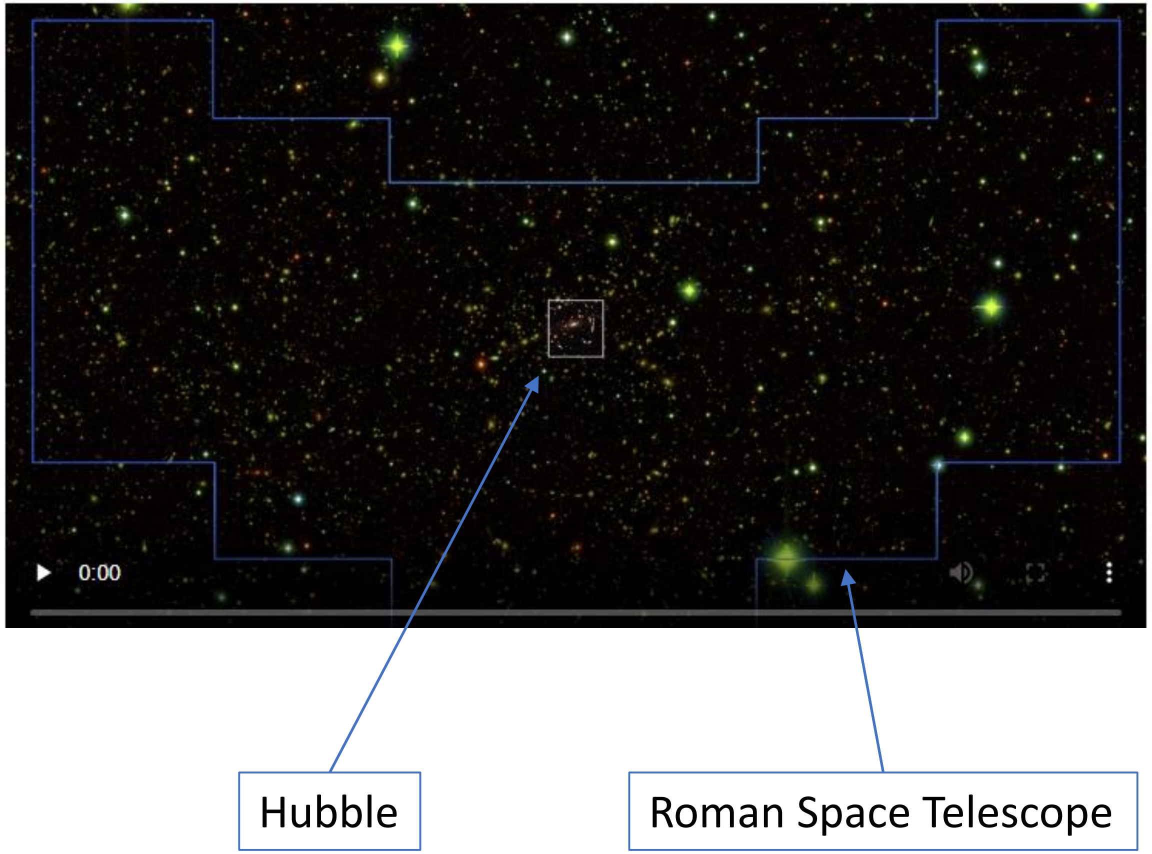




Hubble

Roman Space Telescope

Motivation

Calibrations of instruments are typically performed at one value but instruments are used at many different values by extrapolation from a single, fixed calibration.

A. Mass Balance (1kg to other masses)
B. AC Resistance Bridges
C. Optical calibrations (can range 10 decades)
    A. Reciprocity (gray level or intensity)
    B. Integration time (or gain)

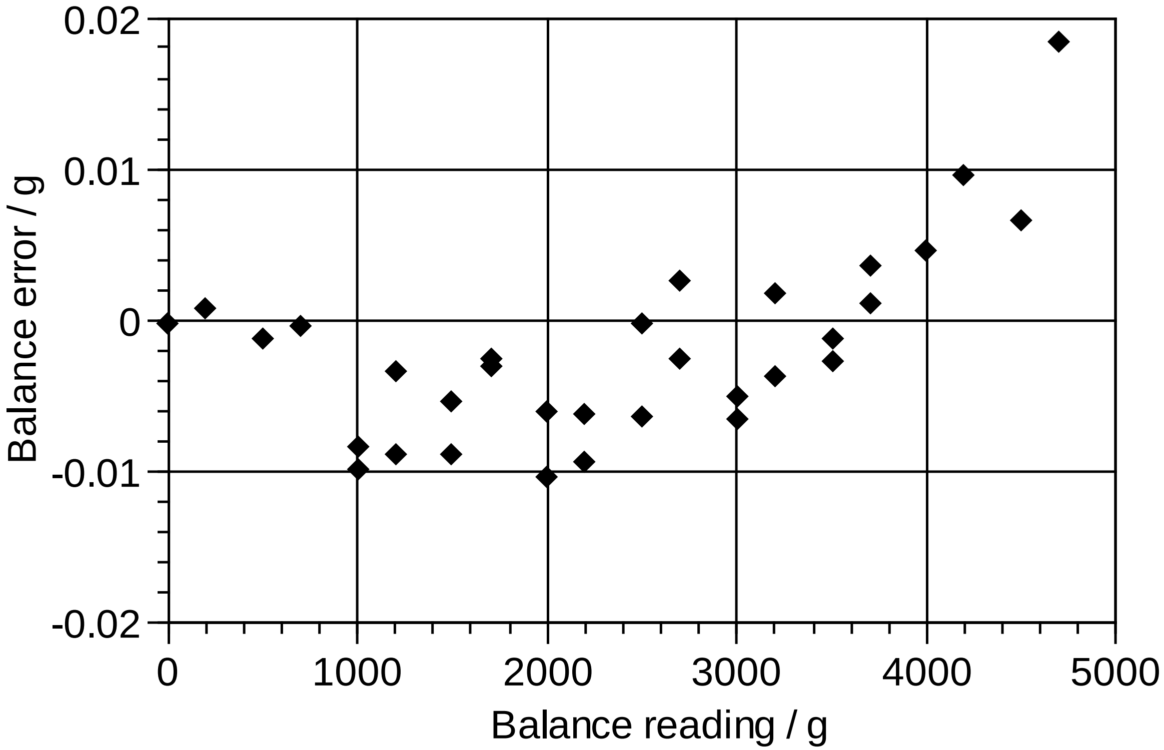
D.R. White, M.T. Clarkson, P. Saunders, and **H.W. Yoon**, "A General Technique for Calibrating Indicating Instruments," *Metrologia* **45**, 199-210 (2008).

Basic Concept: Combinatorial Method

- Use of artifacts which can linearly combined

  Individual masses: 2 kg, 1 kg, 1 kg, 0.5 kg, and 0.2 kg

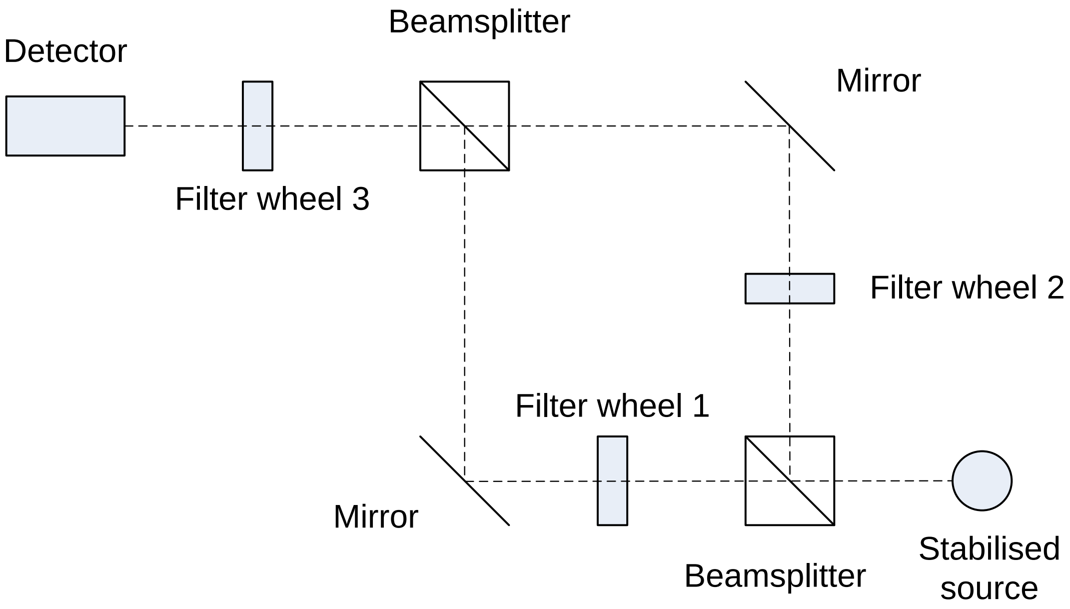
	Increasing sequence					**Gray-code sequence**				
i	$F_{1,i}$	$F_{2,i}$	$F_{3,i}$	$F_{4,i}$	$F_{5,i}$	$F_{1,i}$	$F_{2,i}$	$F_{3,i}$	$F_{4,i}$	$F_{5,i}$
1	0	0	0	0	1	1	0	0	0	0
2	0	0	0	1	0	1	0	0	0	1
3	0	0	0	1	1	1	0	0	1	1
4	0	0	1	0	0	1	0	0	1	0
…										
28	1	1	1	0	0	0	0	1	1	0
29	1	1	1	0	1	0	0	0	1	0
30	1	1	1	1	0	0	0	0	1	1
31	1	1	1	1	1	0	0	0	0	1



Extrinsic and Intrinsic Methods for optical detectors

1. Extrinsic method
   1. Compare to a calibrated detector (detector substitution) (AC-DC method proposed for Roman Space Telescope (WFIRST))
   2. Use 1/r^2 (use drop off in irradiance with distance)
2. Intrinsic method (Flux addition techniques)
   1. $R_1 = S_{1+2}/S_1+S_2$ (mean signal ratio method)
      Nonlinearity correction factor = ΠR_i
   2. Beamconjoiner (combinatorial) method

Linearity testing of optical detectors using the NIST Beamconjoiner

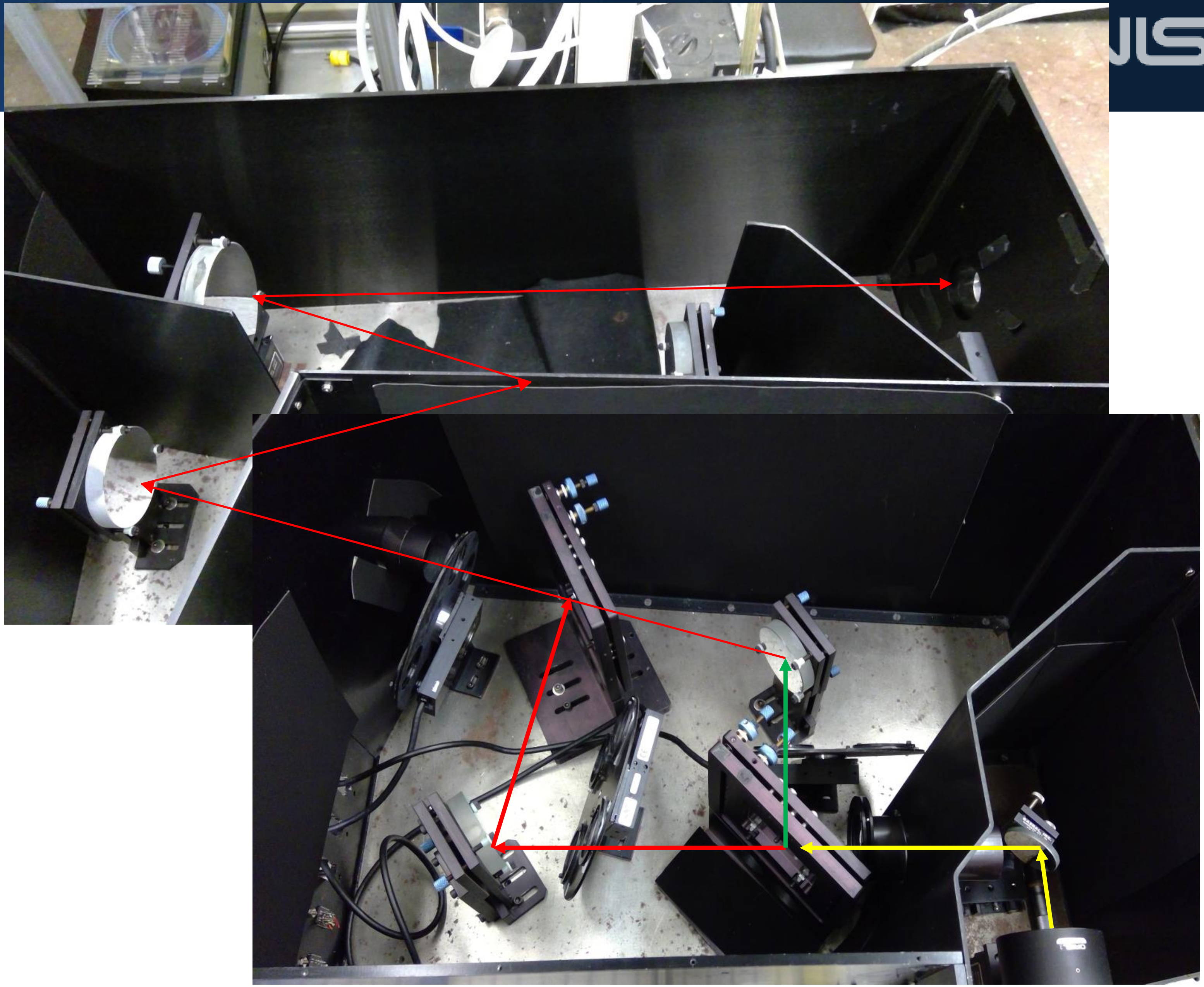


$$\boxed{a_{calc}(i, j, k) = \phi_1(i, k) + \phi_2(j, k)}$$

$$\boxed{s^2 = \frac{1}{80}\sum_i\sum_j\sum_k\left(a_{\mathrm{meas}}(i, j, k) - a_{\mathrm{calc}}(i, j, k)\right)^2}$$

Beamconjoiner

1. Quartz reflective ND filters
2. 3 filter wheels controlled using DC servo motors (for speed)
3. Tungsten-halogen lamp with an MR16 reflector (current-stabilized) **leave on for the duration of measurements**
4. Can use lasers as sources
5. Single run of 150 different measurements takes about 45 min
6. Each run starts with a filter sequence randomization routine



Set up a system of equations

$$\begin{bmatrix} 1 & 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & -1 & -s_{A_1}^{2} & \cdots & -s_{A_1}^{N} \\ 0 & 1 & 0 & \cdots & 0 & 0 & 0 & \cdots & -1 & -s_{A_2}^{2} & \cdots & -s_{A_2}^{N} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 1 & 0 & 0 & \cdots & -1 & -s_{B_1}^{2} & \cdots & -s_{B_1}^{N} \\ 0 & 0 & 0 & \cdots & 0 & 1 & 0 & \cdots & -1 & -s_{B_2}^{2} & \cdots & -s_{B_2}^{2} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & 0 & \cdots & 1 & 0 & 0 & \cdots & -1 & -s_{A_1+B_1}^{2} & \cdots & -s_{A_1+B_1}^{N} \\ 1 & 0 & 0 & \cdots & 0 & 1 & 0 & \cdots & -1 & -s_{A_1+B_2}^{2} & \cdots & -s_{A_1+B_2}^{N} \\ 1 & 0 & 0 & \cdots & 0 & 0 & 1 & \cdots & -1 & -s_{A_1+B_3}^{2} & \cdots & -s_{A_1+B_3}^{N} \\ 0 & 1 & 0 & \cdots & 0 & 1 & 0 & \cdots & -1 & -s_{A_2+B_2}^{2} & \cdots & -s_{A_2+B_2}^{N} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \end{bmatrix} \begin{bmatrix} f_{A_1}^{*} \\ f_{A_2}^{*} \\ \vdots \\ f_{B_1}^{*} \\ f_{B_2}^{*} \\ \vdots \\ f_{A_1}^{*}+f_{B_1}^{*} \\ f_{A_1}^{*}+f_{B_2}^{*} \\ f_{A_1}^{*}+f_{B_3}^{*} \\ f_{A_2}^{*}+f_{B_2}^{*} \\ \vdots \\ r_0^{*} \\ \vdots \\ r_N^{*} \end{bmatrix} = \begin{bmatrix} s_{A_1} \\ s_{A_2} \\ \vdots \\ s_{B_1} \\ s_{B_2} \\ \vdots \\ s_{A_1+B_1} \\ s_{A_1+B_2} \\ s_{A_1+B_3} \\ s_{A_2+B_2} \\ \vdots \end{bmatrix}$$

Signals are measured,
Fluxes are calculated

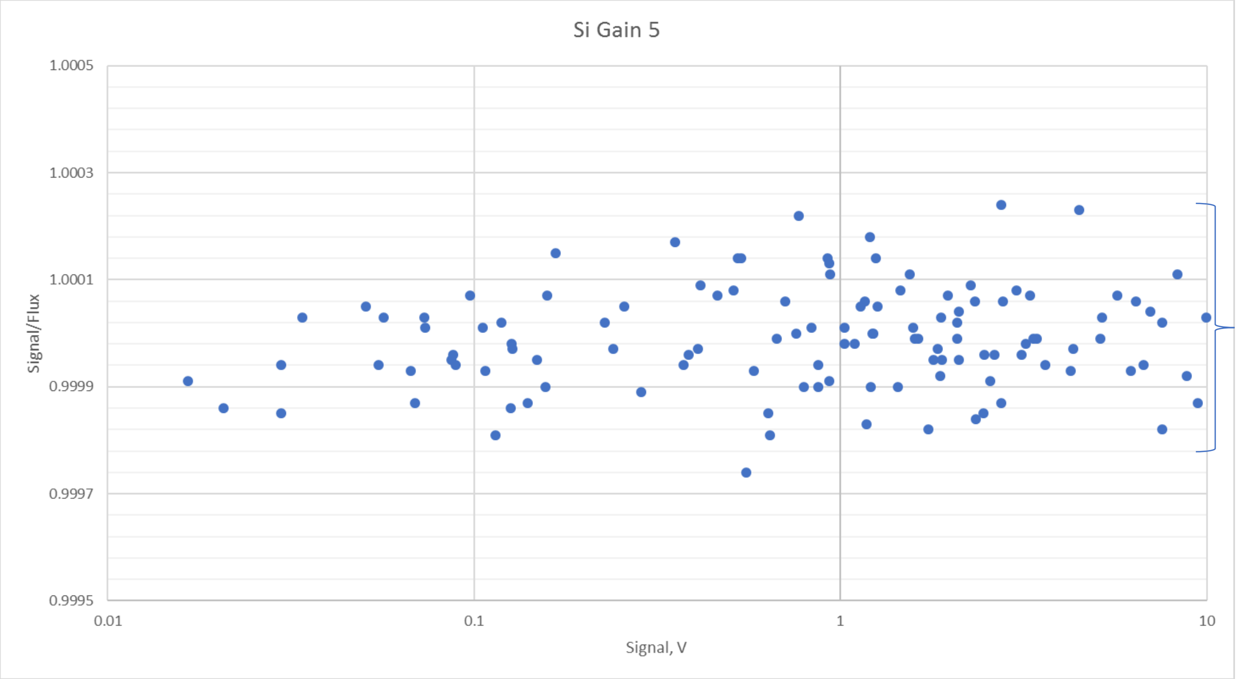
Use UNSLF routine in IMSL Fortran to solve for 40 individual fluxes and 1 or up to 6 unknowns

Total of up to 46 unknowns and 120 equations

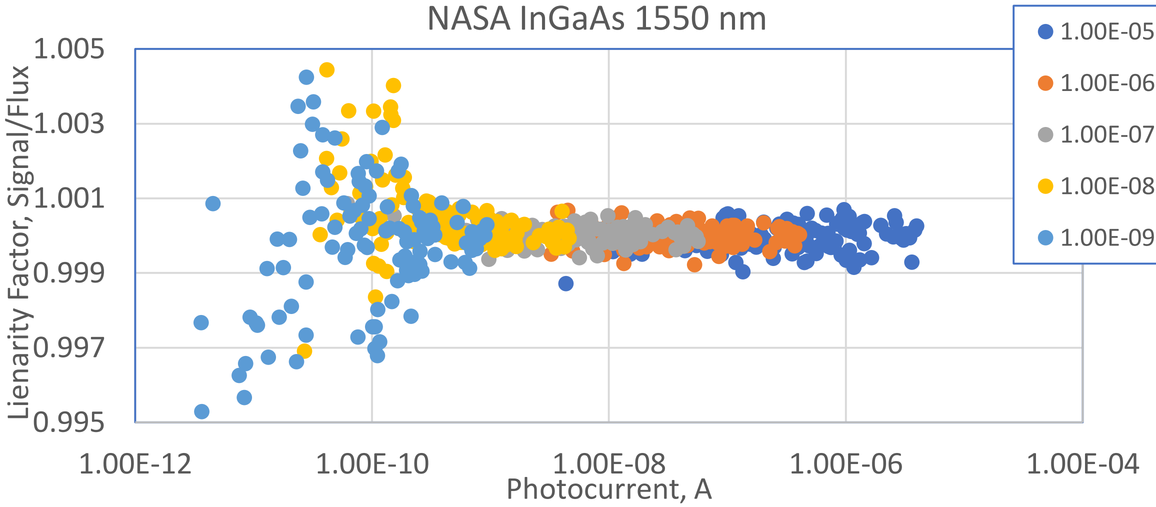
Behrang Hamadani, Andrew Shore, John Roller, Howard Yoon, Mark Campanelli, "Nonlinearity measurements of solar cells with an LED-based combinatorial flux addition method", *Metrologia* **53** 76 (2016)

Linearity measurements of a Si diode

Si trap detector TE stabilized to 29 deg C
1000 nm cut-off filter
100 W QTH lamp

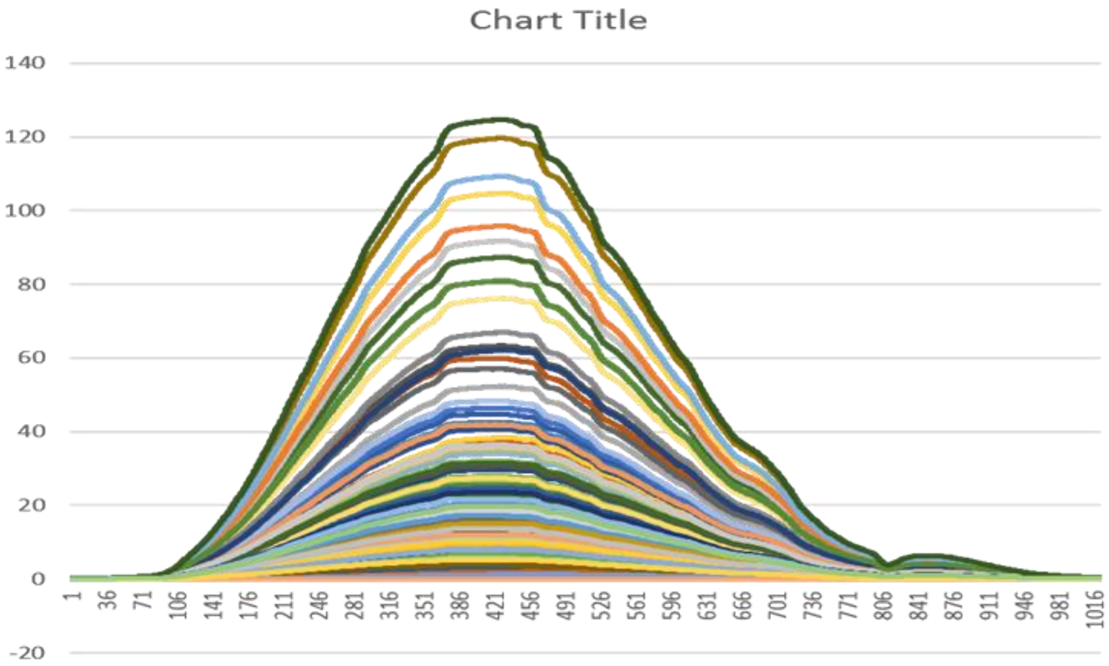


Linearity measured to 0.02 % or 200 ppm (k=2)

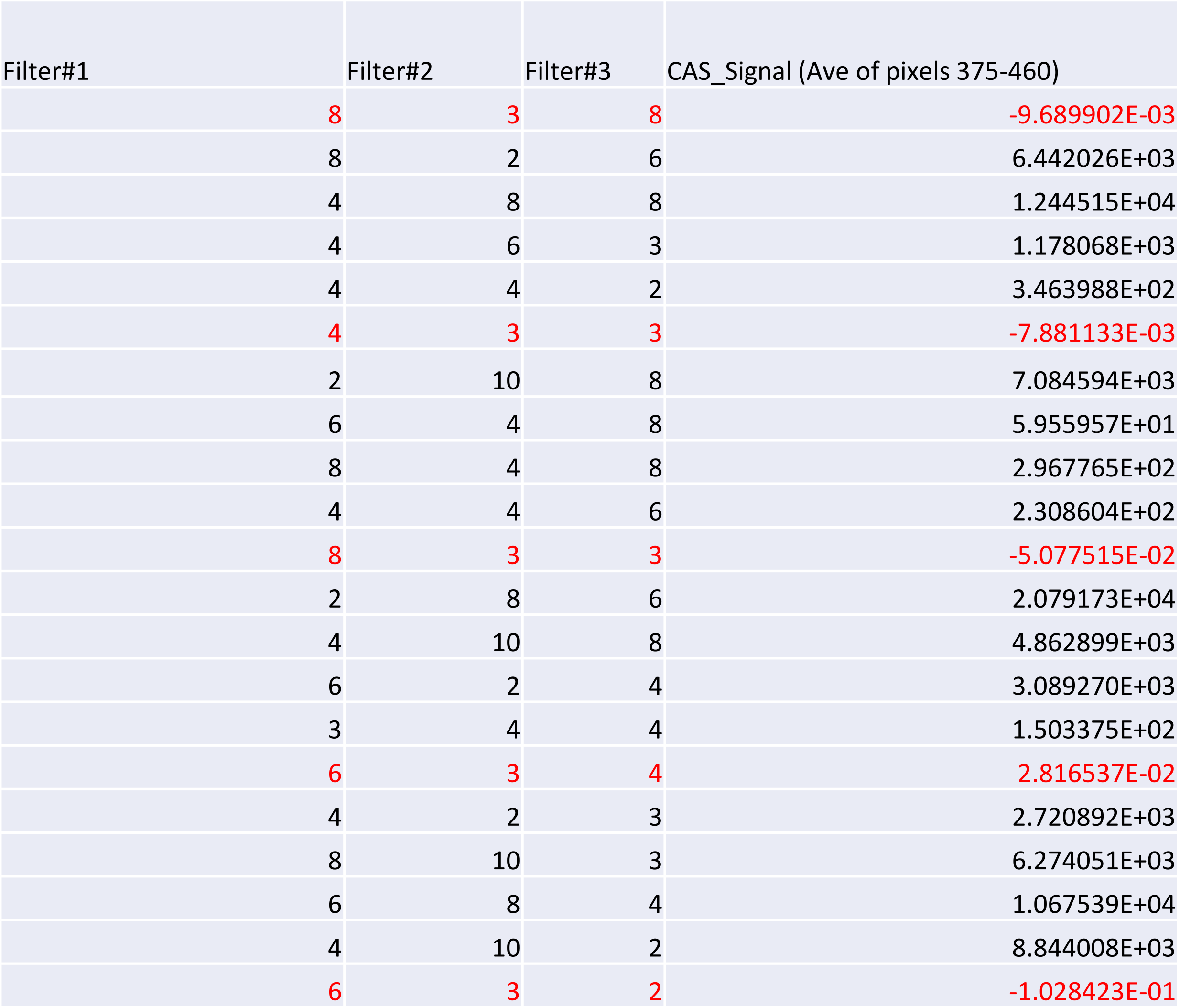


Linearity measurements of spectrographs (factory specs of 0.5 % linearity)

1. Warm up QTH lamp source
2. Move filter combination to the greatest transmittance
3. Adjust integration times to not saturate (stay below 30,000 counts at peak) (15 bit resolution)
4. Fix integration time of spectrograph
5. Run Beamconjoiner spectrograph Labview program
   - Record spectrograph spectrum at each filter combination (140 combinations)
6. Average only middle 375 to 460 pixels for analysis



Part of the beamconjoiner to-be-processed file



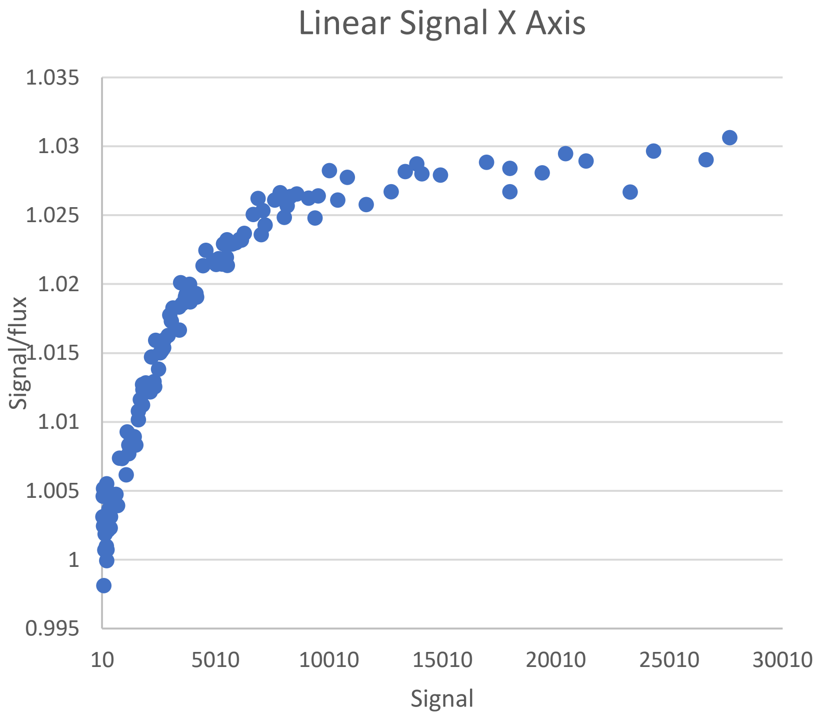
Filter#1	Filter#2	Filter#3	CAS_Signal (Ave of pixels 375-460)
8	3	8	-9.689902E-03
8	2	6	6.442026E+03
4	8	8	1.244515E+04
4	6	3	1.178068E+03
4	4	2	3.463988E+02
4	3	3	-7.881133E-03
2	10	8	7.084594E+03
6	4	8	5.955957E+01
8	4	8	2.967765E+02
4	4	6	2.308604E+02
8	3	3	-5.077515E-02
2	8	6	2.079173E+04
4	10	8	4.862899E+03
6	2	4	3.089270E+03
3	4	4	1.503375E+02
6	3	4	2.816537E-02
4	2	3	2.720892E+03
8	10	3	6.274051E+03
6	8	4	1.067539E+04
4	10	2	8.844008E+03
6	3	2	-1.028423E-01

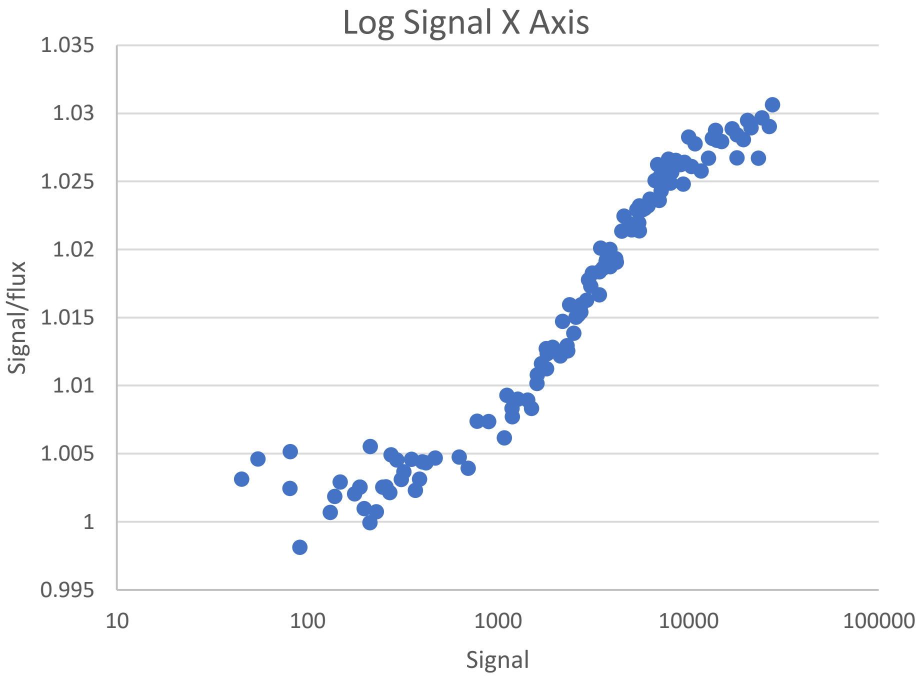
Odd numbers indicate closed positions

Dark measurements are taken at the end of each set of 5 combinations

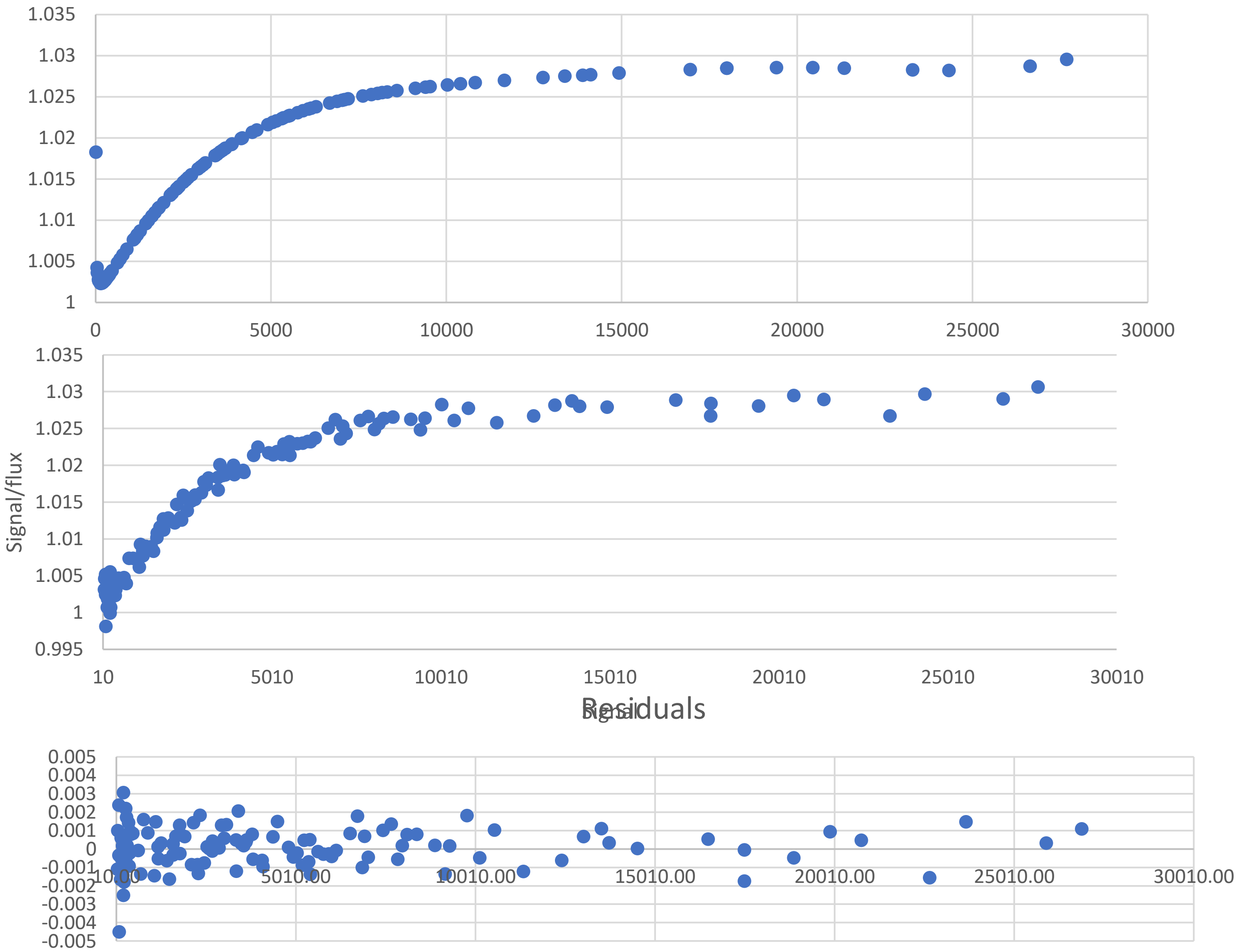
Subsequent runs are performed with a sequence of different filter combinations

Beamcon_20190712_007 UV CAS

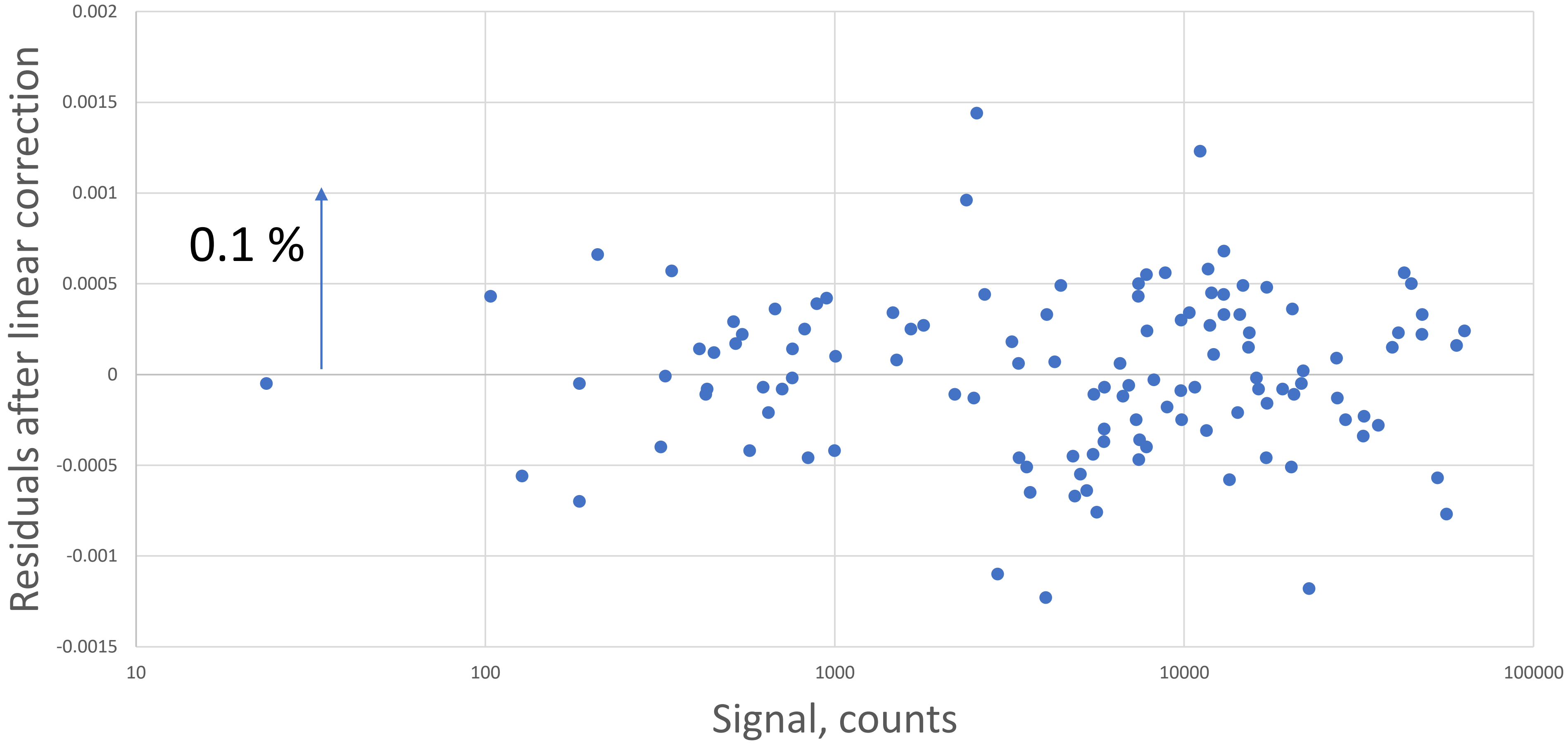




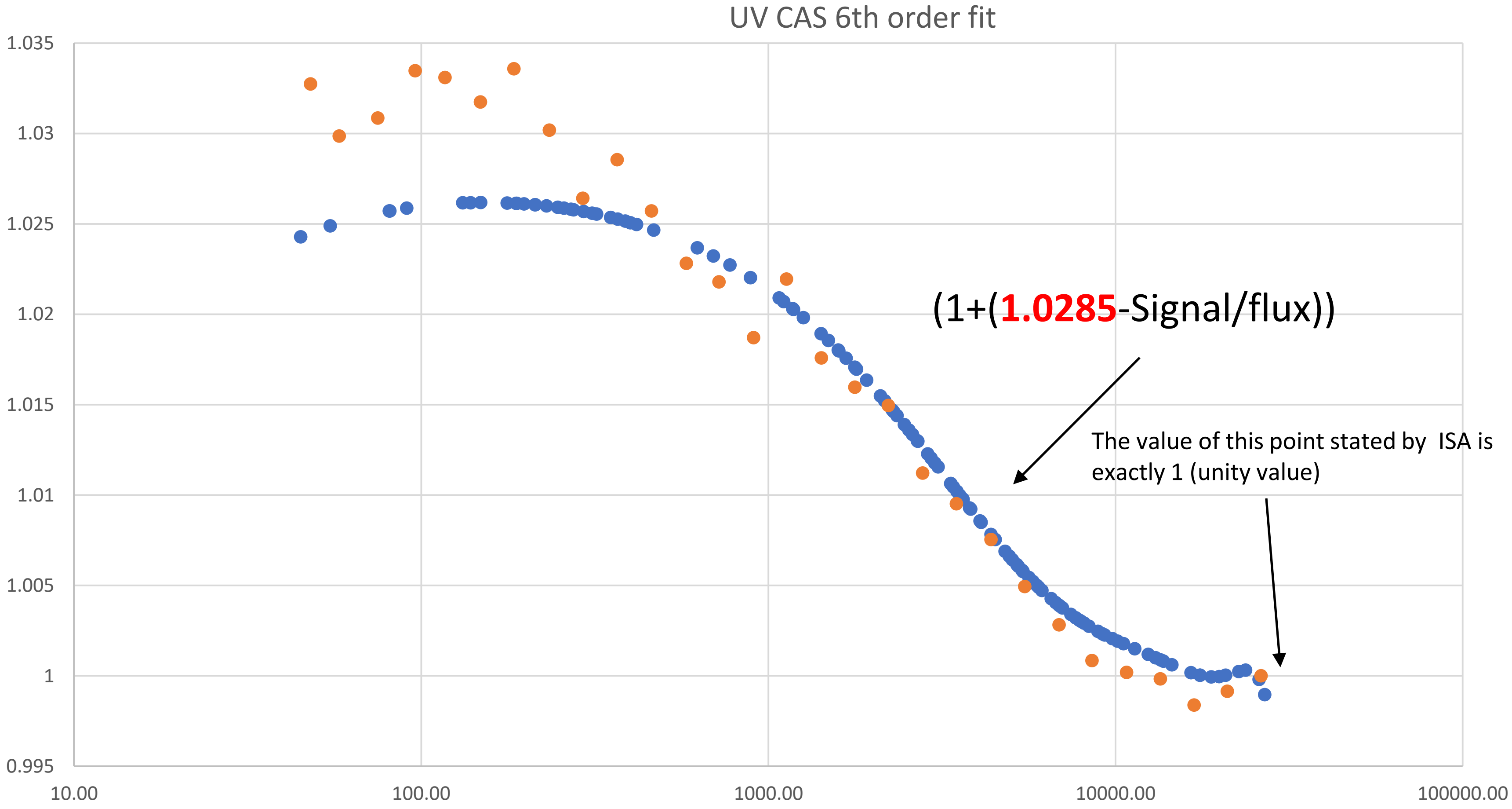
Fitted nonlinearity using 6th order polynomial (residuals of 0.05% (*k*=1))



Nonlinearity correction of spectrographs to 0.1 %



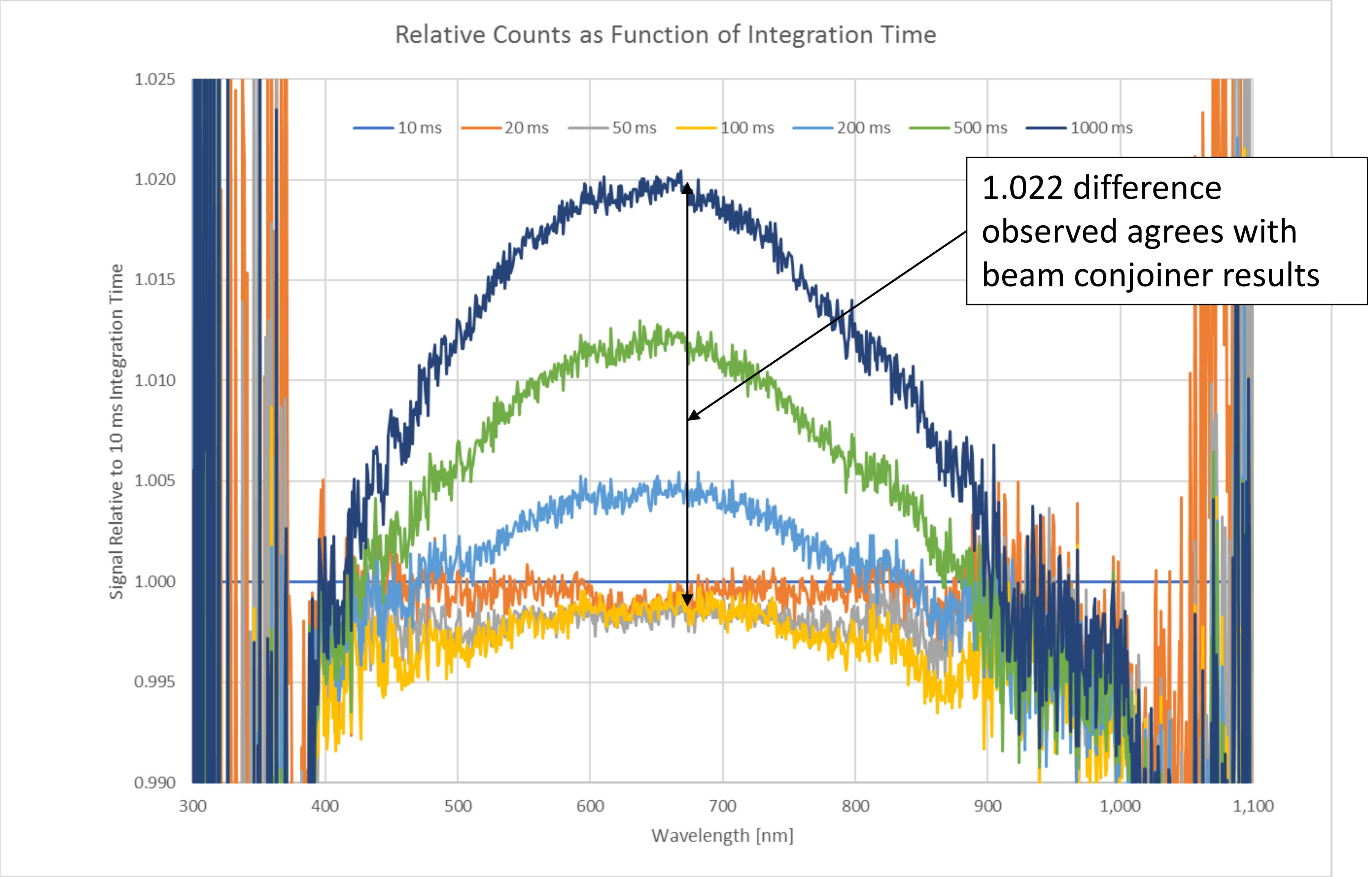
Comparison to manufacturer's values (by flipping and scaling to 1 at highest signals)



(1+(**1.0285**-Signal/flux))

The value of this point stated by ISA is exactly 1 (unity value)

Air LUSI Cal CAS (tested using constant source changing integration times or reciprocity)

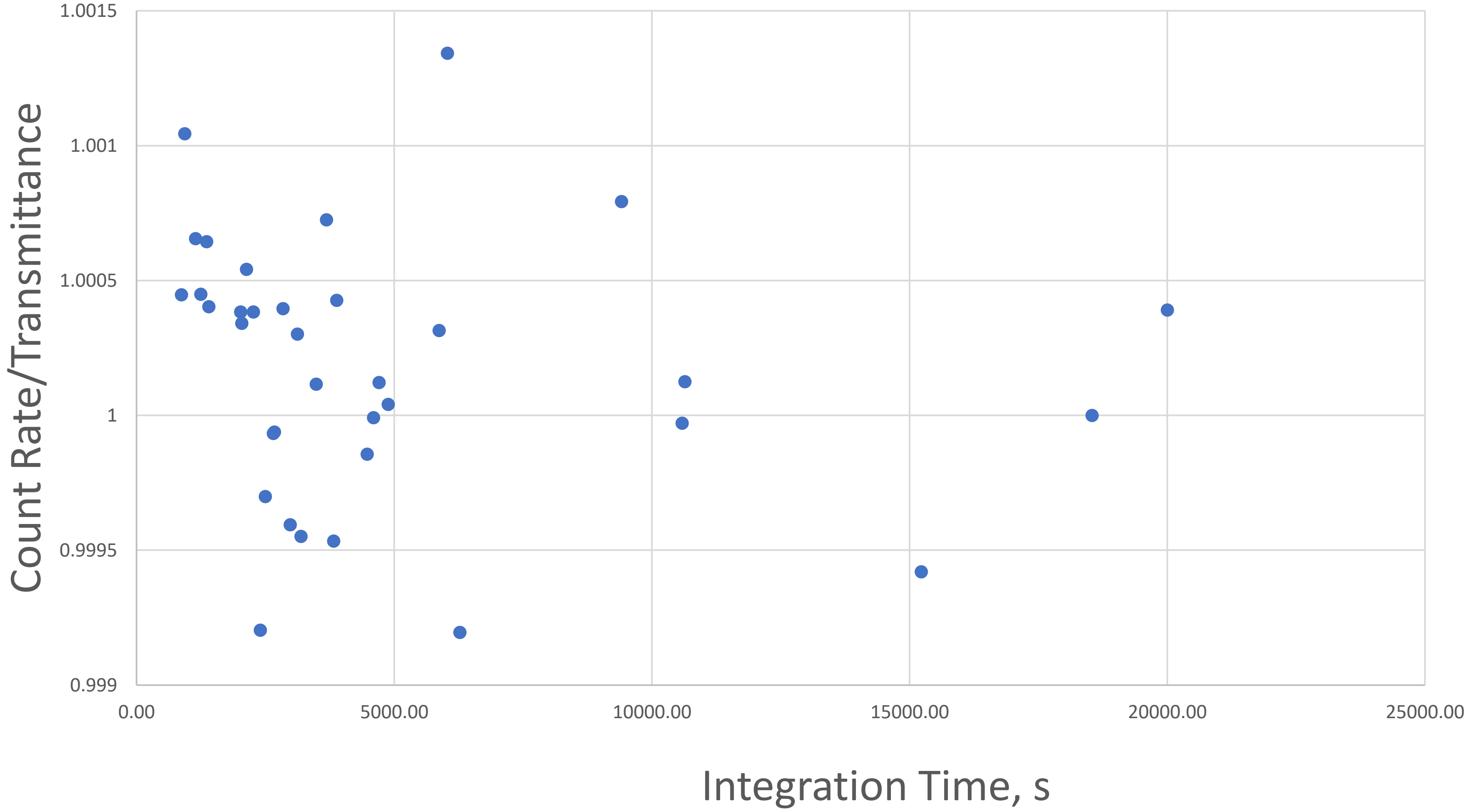


1.022 difference observed agrees with beam conjoiner results

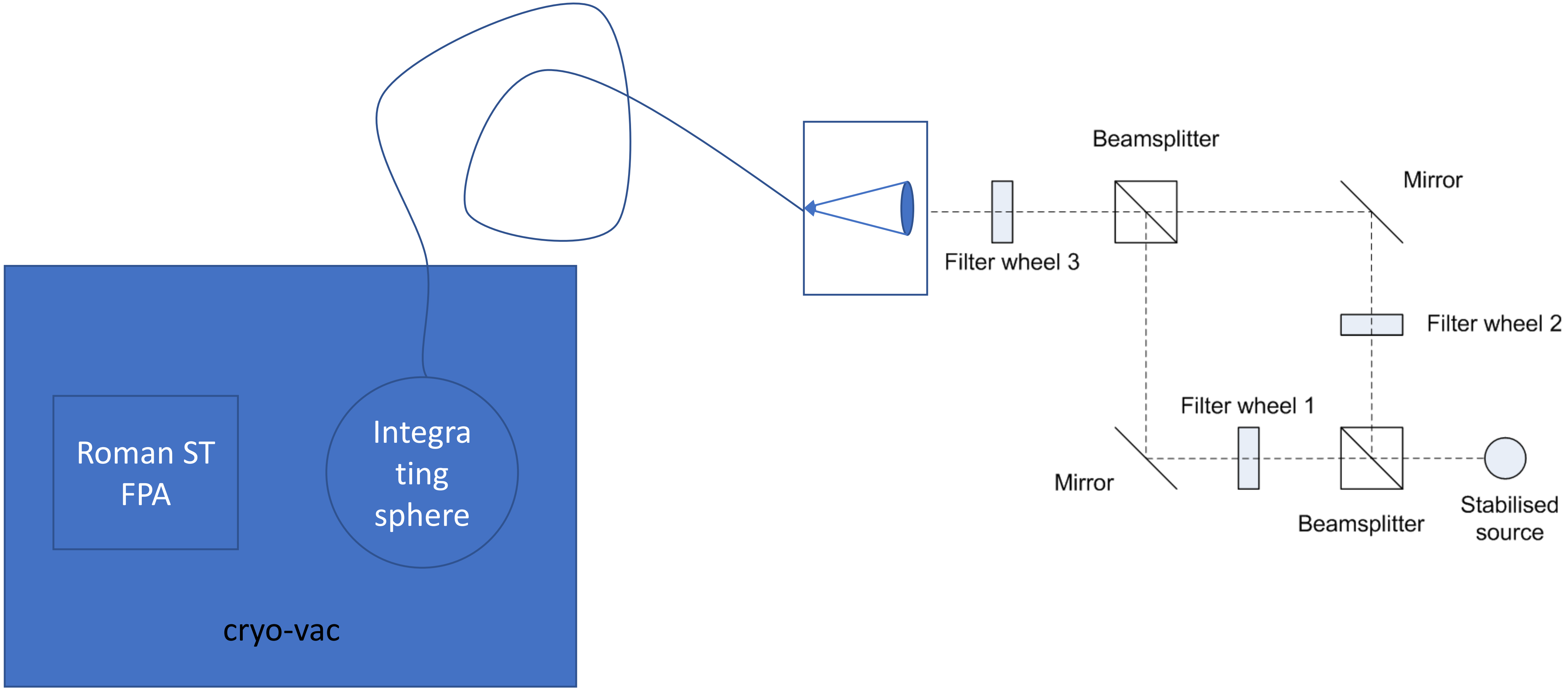
Now examine reciprocity

1. Apply gray-level linearity corrections to the spectrograph
2. Determine relative transmittances of the filter combination
    1. Obtain transmittance ratios normalized to the highest transmittance
3. **Note: at this point, 120 neutral density filter transmittances are known !**
4. Perform another set of measurements with changing integration times with intensities set close to 30,000 or some level
5. Plot count rate/normalized transmittance ratios as a function of integration times
6. Measure the dispersion or the shape of the plot

Reciprocity



Use of a low-OH fiber input to cryo-vac chamber



Conclusion

1. Flux addition method can be used to determine gray-level linearities to 200 ppm
2. Linearities of both single element detectors and spectrographs can be characterized in the visible and infrared wavelengths
3. Reciprocities can also be measured using this technique