Gaia spectro-photometry absolute calibration

and comparison to classical systems

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CU5-DU13 & CU5-DU14

DU13: provide spectrophotometric standard stars (SPSS)

INAF - Osservatorio Astronomico Bologna: E. Pancino, G. Altavilla, M. Bellazzini, A. Bragaglia, C. Cacciari, G. Cocozza, L. Federici, S. Marinoni, E. Rossetti

University of Barcelona: C Jordi, F. Figueras, J.M. Carrasco et al.

University of Groeningen: S. Trager

DU14: provide integrated photometry and BP/RP calibration model

INAF - Osservatorio Astronomico Bologna: C. Cacciari, P. Montegriffo, S. Ragaini, M. Bellazzini, E. Pancino

Classical spectro-photometry

The aim of spectro-photometric calibration

Place measurements on a standard physical flux scale by removal of the **absorption** by the Earth's atmosphere and **calibration** of the sensitivity of the photometric/spectroscopic equipment at different **wavebands/ wavelengths** *(M. S. Bessell, Ann. Rev. Astron. Astrophys. 2005, Vol. 43, 293)*

The ingredients:

- The data: observed **magnitude** values in various bands or **spectra** (pre-reduced, i.e. flat-field, bias, dark etc. corrected)
- Knowledge of (and correction from) **atmospheric absorption** - not needed for space observations
- Knowledge (and use) of the **instrument response**
- Use of constant brightness **standard stars** - calibrators

Definition of a spectro-photometric system

M.S. Bessell (1999), PASP, 111, 1426; Altavilla et al. (2010), GAIA-C5-TN-OABO-GA-004

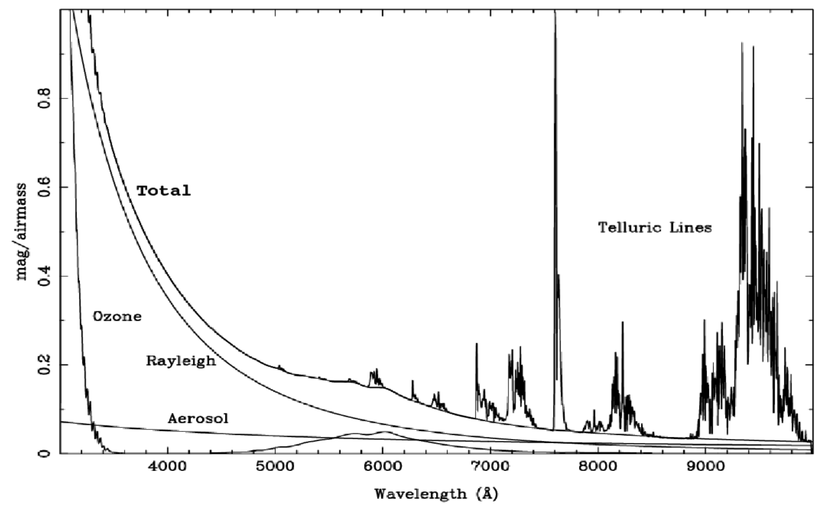
photometry	$m_x = C - 2.5 \log \int f(\lambda)\, T_x(\lambda)\, d\lambda$
spectro-photometry	$s(\lambda) = C\, [\, f(\lambda)\, T(\lambda)\,]$

- **f(λ)**: the stellar SED in [photons s−1 m−2 nm−1]
- **C/C**: zero point defined by a standard star (e.g. unreddened A0V, Vega)
- **T(λ)**: the instrument response function, convolution of
  - area of the telescope primary mirror (entrance pupil area)
  - telescope (mirrors) transmission and optical characteristics
  - camera optics & detector CCD quantum efficiency (QE)
  - filter-coating transmission
  - prism transmission (spectrograph)

Atmospheric absorption

In the optical range, extinction is a combination of:

- **continuous** absorption from Rayleigh scattering of gas molecules - varies with λ^{-4} and linearly with airmass (airmass ≈ *sec Z)*
- **neutral absorption** from dust and aerosols - non-linear variation with airmass
- **telluric** features



Extinction is measured by observing **standard stars at different airmass** (e.g. in the meridian and at high airmass).
Red and blue standard stars are observed to solve for the colour term in the extinction
➔ extinction coefficients, e.g. k_i (mag/airmass) ➔ extinction law as a function of λ

The observed instrumental magnitudes (m_i) are corrected to outside the atmosphere (m_{i0}) by extrapolating to zero airmass ➔ $m_{i0} = m_i - (k_i \times \text{airmass}) - (ki \times \text{airmass} \times \text{colour})$

The observed instrumental spectra are corrected to outside the atmosphere by applying extinction law x appropriate airmass

Atmospheric absorption

In the optical range, extinction is a combination of:

- **continuous** absorption from Rayleigh scattering of gas molecules - varies with λ^{-4} and linearly with airmass (airmass ≈ *sec Z)*
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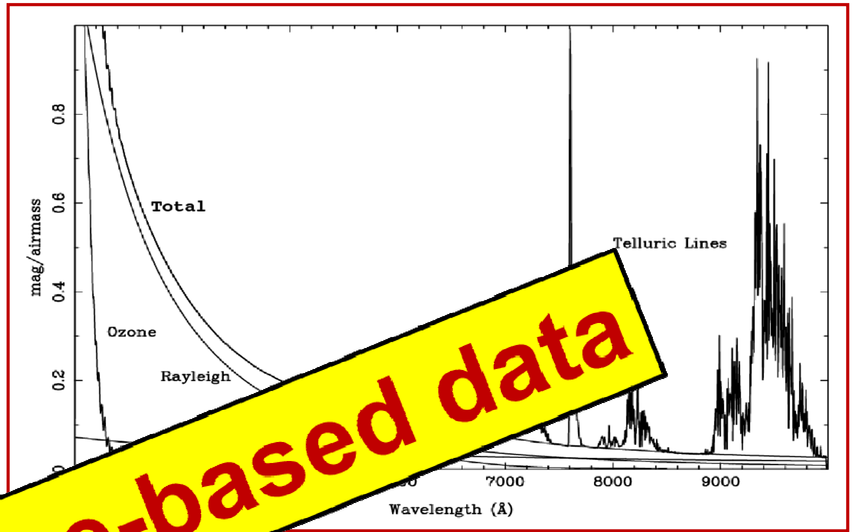
- **telluric** absorption features



Not needed for space-based data

Extinction is measured by observin[g] ... **different airmass** (e.g. in the meridian and at high airmass).
Red and blue standar[d] ... [us]ed to solve for the color term in the extinction
→ extinction c ... k_i (mag/airmass) → extinction law as a function of λ

The ... instrumental magnitudes (m_i) are corrected to outside the atmosphere (m_{i0}) by extra[p]olating to zero airmass → $m_{i0} = m_i - (k_i$ x airmass) - (ki x airmass x color)

The observed instrumental spectra are corrected to outside the atmosphere by applying extinction law x appropriate airmass

Photometry: instrument response

Oke (1965):
outlined the system of pseudo monochromatic photometry that is the basis of all spectrophotometric calibrations.

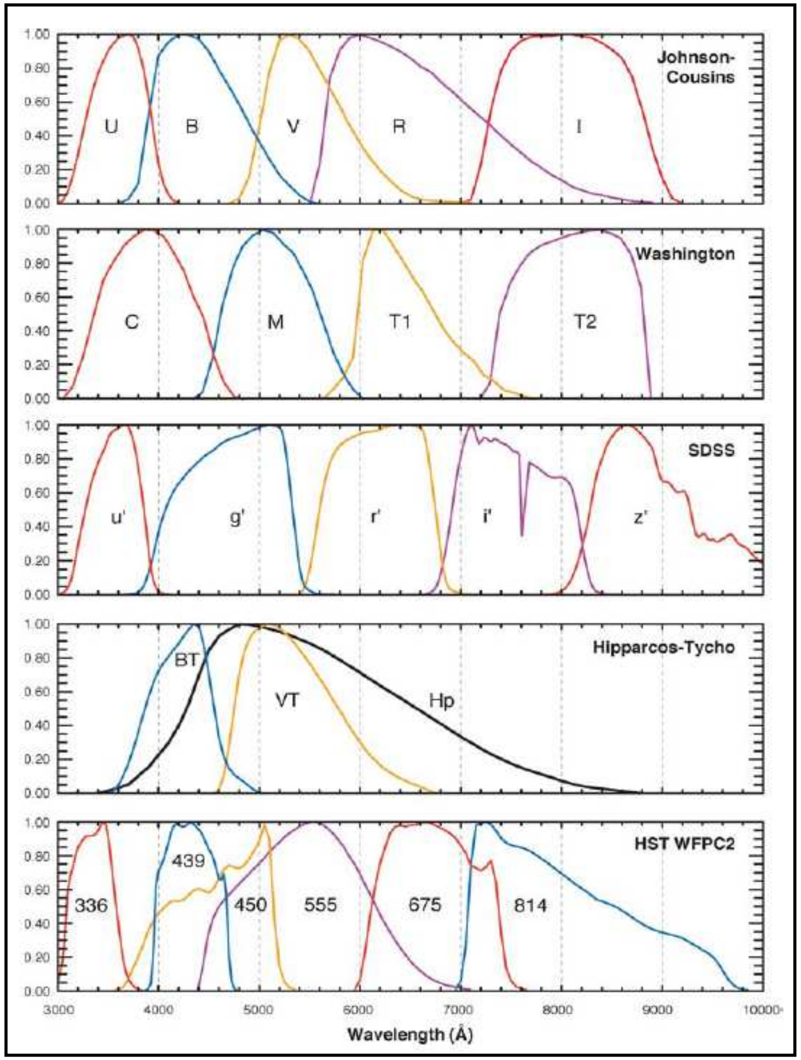
Johnson (1966):
established the UBVRIJHKLMN system of broad-band photometry extending from 300nm to 10μ that forms the basis of all subsequent broad-band systems. Fluxes are normalized to that of Vega.

Strömgren (1966):
devised the intermediate-band uvby system to better measure the temperature, gravity, metallicity and reddening of early-type stars (hotter than the Sun).

Presently, more than 200 photometric systems known

Info on several conventional photometric systems in:
http://stsdas.stsci.edu/documents/SyG_95/

Asiago DB: http://ulisse.pd.astro.it/Astro/ADPS/
Lausanne DB: http://obswww.unige.ch/gcpd/gcpd.html



Schematic passbands of broad-band systems

Photometry calibration

Photometric observations are calibrated through the use of networks of constant brightness standard stars (SS)

To put observations on a standard system: derive the calibration equation = difference between the extinction corrected instrumental values m_{i0} and the standard m value as a function of color:

$$m_{i0} - m = ZP + \alpha(\text{color})$$

α (varying extinction across broad band, difference in filter band wrt standard) should be as small as possible (< ± 0.05);
ZP is the zeropoint constant (includes any neutral extinction residual, aperture correction, etc.)

In principle, only one blue and one red SS are needed to solve for the calibration equation ➔ derive ZP and α ➔ calibrate photometric observations.

In practice, a few more are used for accuracy and reliability:

➔ color range of SS should be large enough to encompass color range of target objects

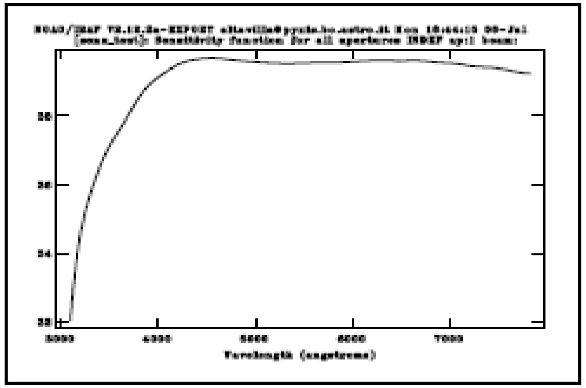
➔ enough SS should be observed during the night to monitor the changing conditions

Each photometric system has produced a list of standard magnitudes and colors measured at specific bandpasses for a set of stars that are well distributed across the sky.

Spectra: instrument response & calibration

The instrument response curve - **C (λ)** - is obtained by comparing the observed spectrum of spectro-photometric standard stars (SPSS) with the corresponding tabulated absolute flux values - SED(λ)

C (λ) = O(λ) / SED(λ)   (DOLoRes LR-B) →



➔ **flux calibration of any given spectrum:**

$$S_{cal} (\lambda) = S_{obs} (\lambda) / C(\lambda)$$

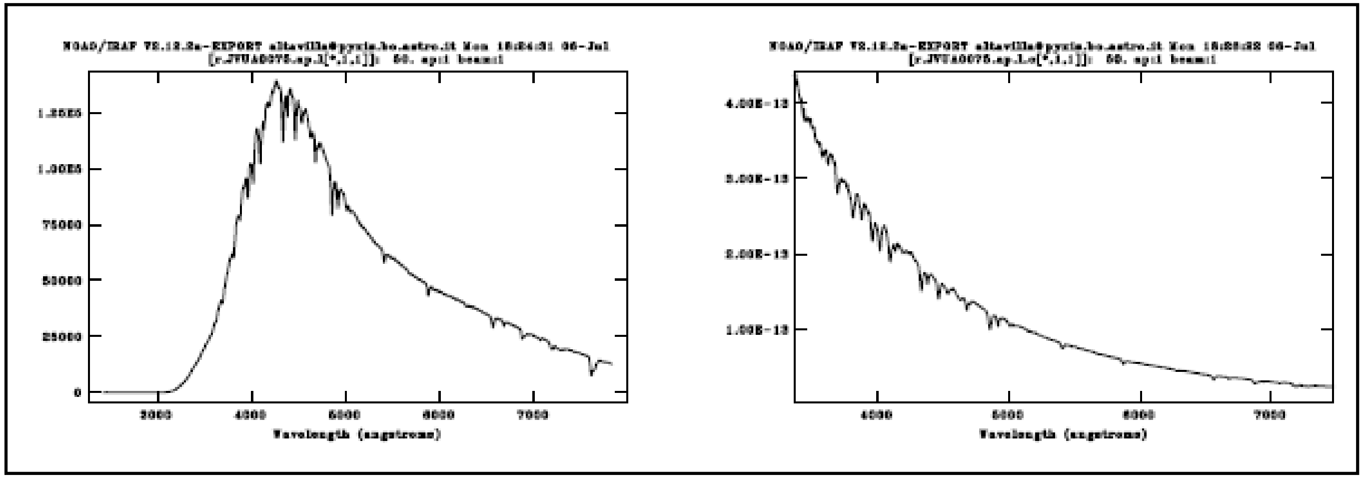
In principle, only one SPSS is needed for spectrophotometric calibration

HZ44 spectrum:

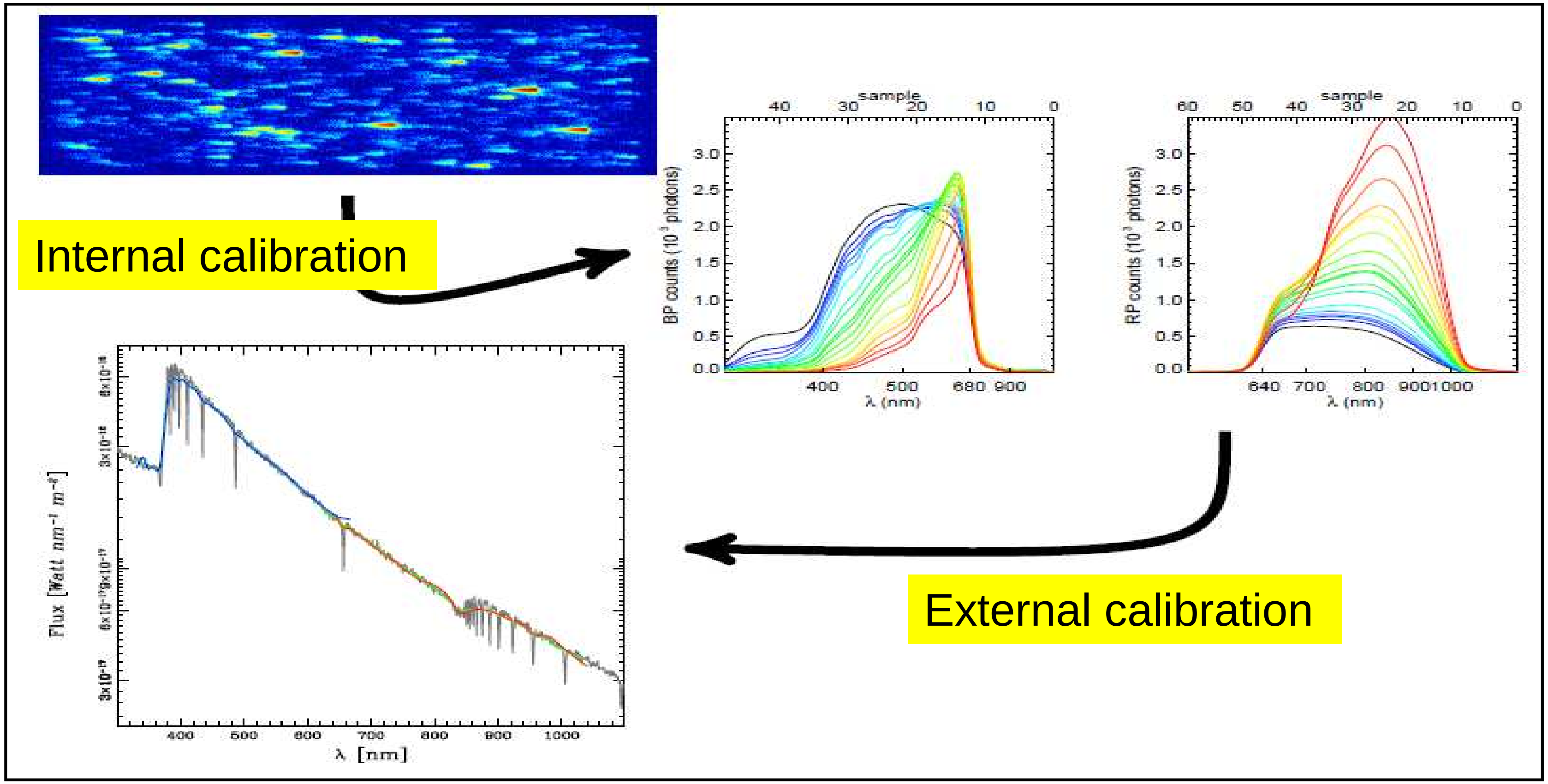
before (left panel)

after (right panel)

absolute flux calibration



Gaia spectro-photometric system



- same principle as for classical spectrophotometry
- much more complicated instrument model

Courtesy A. Brown

Gaia spectro-photometry

Input data: internally calibrated G/G_{BP}/G_{RP} mean magnitudes (flux/mag) & **BP/RP mean spectra** – undergone three basic transformations:

→ epoch data: pre-processed (corrected by internal instrumental effects)

→ corrected to a ***fiducial instrument*** represented by the *nominal* instrument model stored in the PDB

→ averaged to produce mean values on an internally consistent flux scale

To tie the internal flux scale to the absolute flux scale
➔ absolute (external) calibration to derive the true (absolute) instrument model using a set of SPSS

- accuracy requirements: order of mmags (phot) or a few % (spectra)
- depends on accuracy of internal calibrated data & SPSS SEDs
- goal: minimum contribution of calibration model on error budget

$G/G_{BP}/G_{RP}$: external calibration model

Goal: derive true filter bandpass (FB_{true}) using SPSS data. For all SPSS:

$$G_i = [S] \times FB_i^{true} \quad \Rightarrow \quad G_i = [S] \times (FB_i^{PDB} \times FB_i^{corr})$$

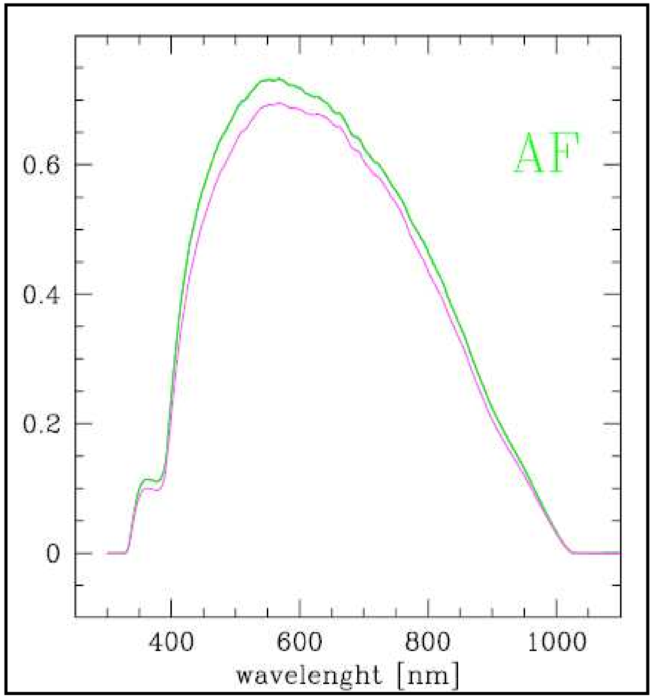
G_i: m-dimen **vector** of observed integrated flux values
(m = number of SPSS ~ 200, *see GAIA-C5-TN-OABO-GA-003*)

[**S**]: **matrix** of n(λ) tabular flux data points (SED) per m SPSS
n(λ) ~ a few 10^3 if SED sampled at high resolution

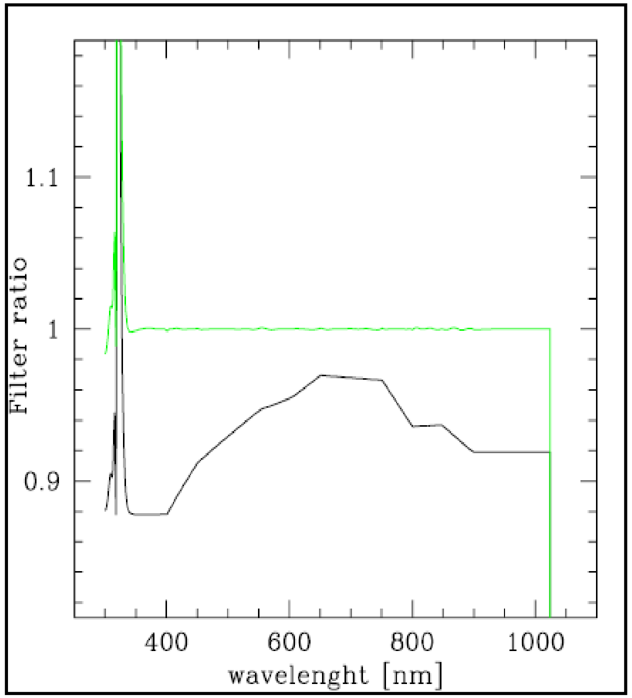
FB_i^{true} : n-dimen **vector** of filter band ***i*** sampled at n(λ) data points

- calibration model needs to decrease dimensionality to n(λ) ≤ m
  force a continuum filter shape → smoothing procedure
- the *nominal* instrument model **FB^{PDB}** sets the basic shape
- the *correction* vector **FB_i^{corr}** defines the residual differences between the predicted (from FB^{PDB}) and the observed SPSS data
- **FB^{true}** is to be determined by least square fit of these residual differences

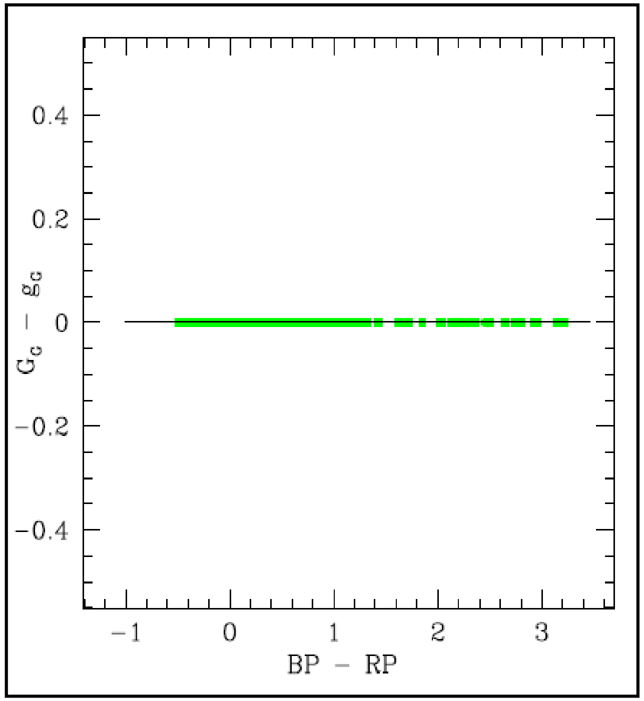
G band calibration: preliminary



G bands: fitted(=true) nominal



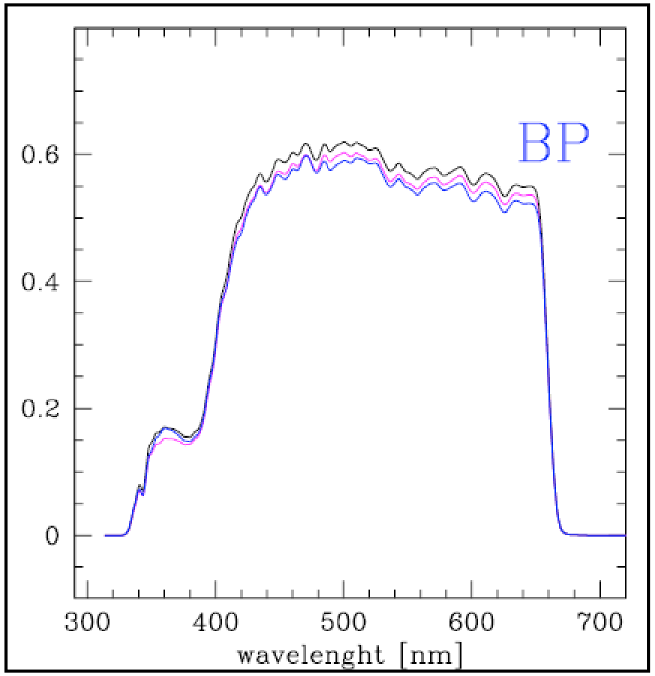
Ratio of **fitted** and **nominal** bands wrt **FB**[true]

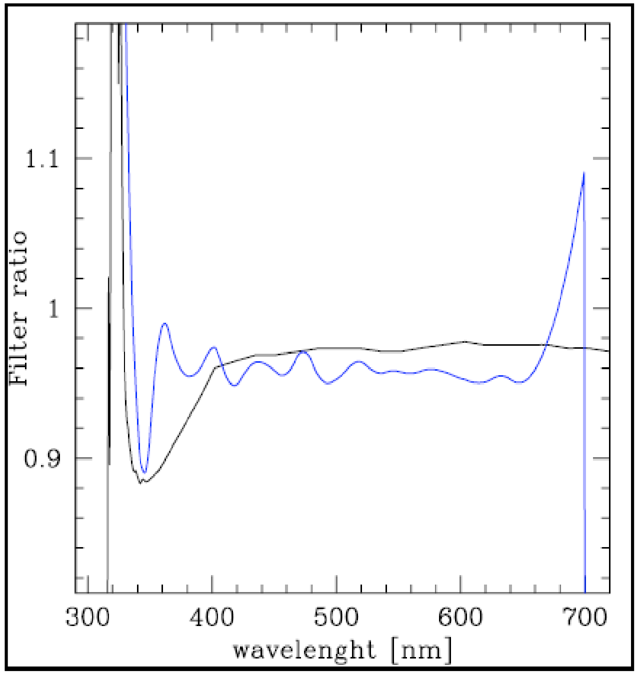


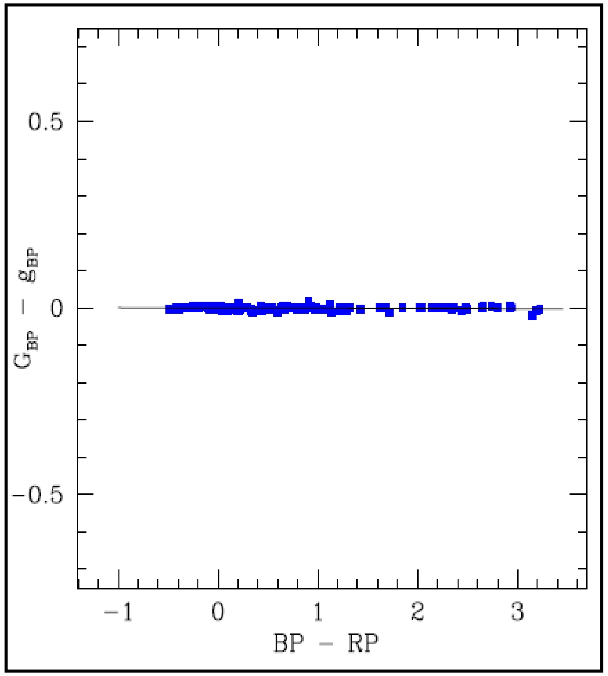
G – g - ZP (mmag): colour equation

Simulations: the purpose is to account for any colour dependence
→ the calibration model should be the **fitted filter band & ** the **zero-point ZP** defined by it, no colour equation → G band is OK

BP band calibration: preliminary







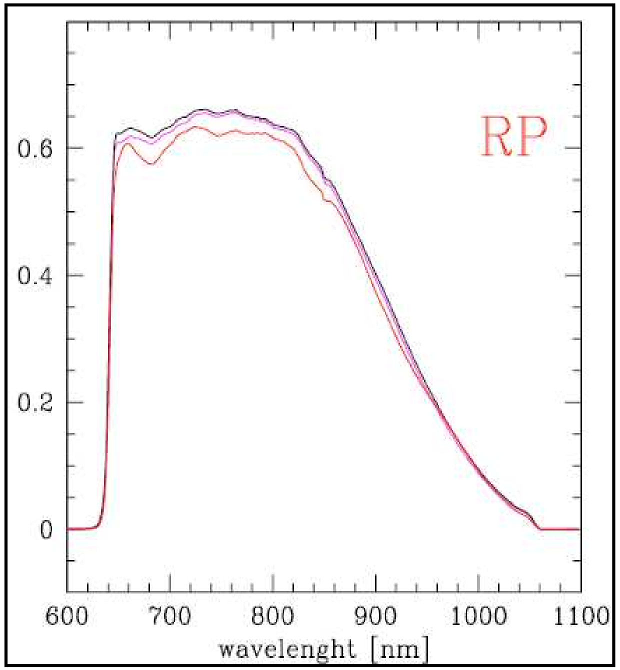
BP bands: fitted nominal true

Ratio of **fitted** and **nominal** bands wrt **FB^{true}**

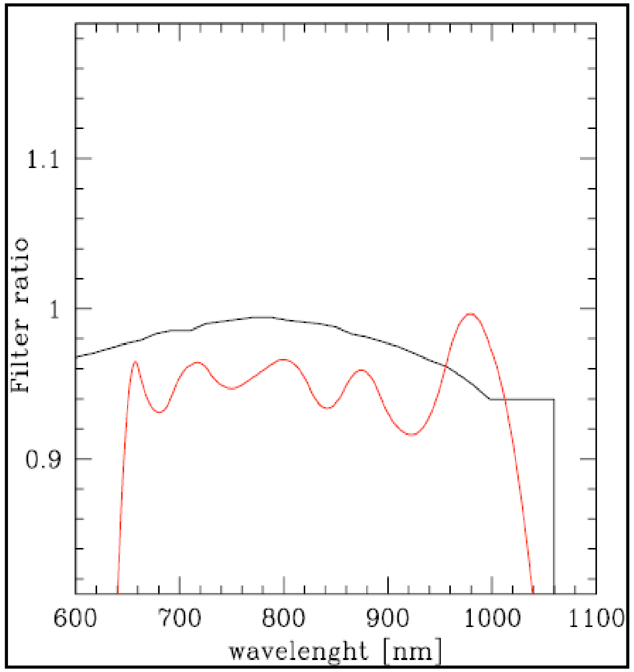
$G_{BP} - g_{BP}$ - ZP (mmag): colour equation

Simulations: flat colour equation, zero-point ~ -4% (flux loss) → BP band is OK

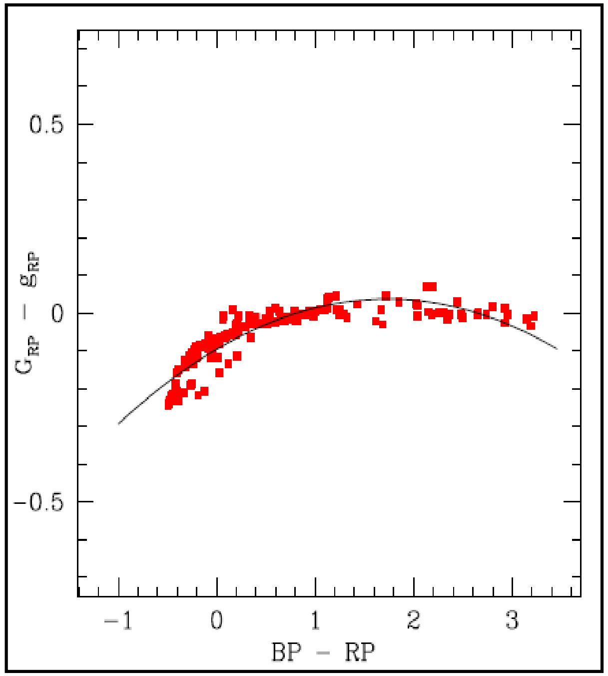
RP band calibration: preliminary



RP bands: fitted nominal true



Ratio of **fitted** and **nominal** bands wrt **FB^{true}**



G_{RP} fitted – g_{RP} obs. - ZP (mmag): colour equation

Simulations: the colour equation is not flat → numerical problems (to be further investigated)

BP/RP spectra: external calibration model

For details see P. Montegriffo: GAIA-C5-TN-OABO-PMN-002, GAIA-C5-TN-OABO-PMN-003, and M09 @ Leiden, 18-20 May 2010

Mean (internally calibrated) spectra can be modeled as:

$$S_{\rm obs}(\kappa) = C \int T(\lambda) L_\lambda(\kappa - \kappa_{\rm p}(\lambda)) S_{\rm true}(\lambda)\, d\lambda$$

discretized as:

$$S_{\rm obs}(\kappa_i) \approx C \sum_j T(\lambda_j) L_{\lambda_j}(\kappa_i - \kappa_{\rm p}(\lambda_j)) S_{\rm true}(\lambda_j)\, \Delta\lambda$$

$T(\lambda_j)$: filter response; **$L_{\lambda j}$**: monochromatic LSF; **k_i**: AL px coordinate; **$k_p(\lambda_j)$**: dispersion function

write as matrix equation:

$$\mathbf{S}_{\rm obs} = \mathbf{D} \times \mathbf{S}_{\rm true}$$

BP/RP spectra: dispersion functions

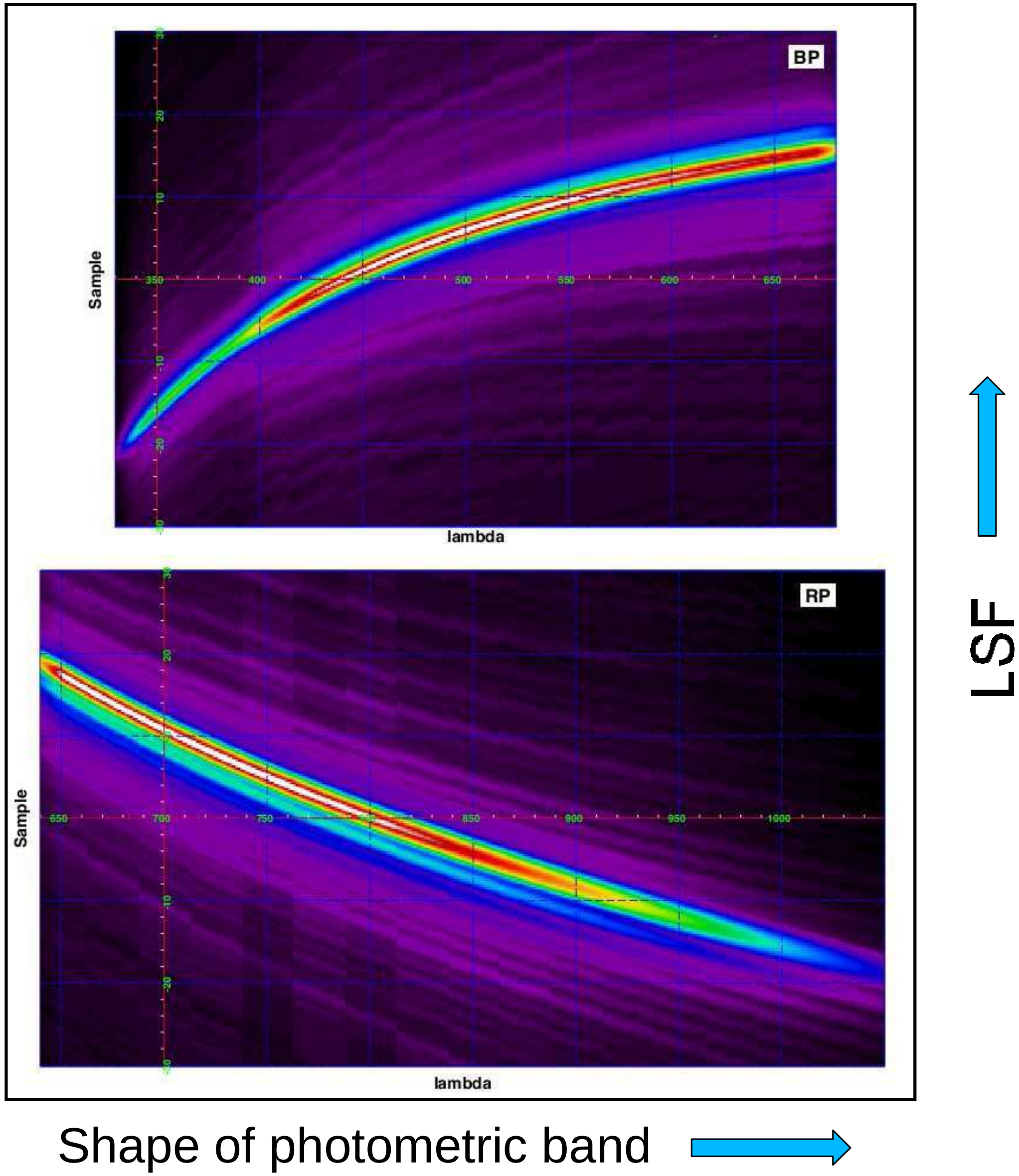
Dispersion matrix **D** for BP (top) and RP (bottom) instruments for **FoV 1 and CCD row no 4**:

- the profile of the columns represents the $LSF_{\lambda j}$ that peaks on the dispersion function at the corresponding wavelength

- the profile of the rows shows the distribution as a function of wavelength of the photons contributing to light in each sample

- the elements defining **D** vary across the focal plane: the absolute calibration refers to the *fiducial* instrument **D**

GAIA-C5-TN-OABO-PMN-002



BP/RP spectra: external calibration model

$$\mathbf{S}_{\rm obs} = \mathbf{D} \times \mathbf{S}_{\rm true}$$

Reduce dimensionality of S_{true} by approximating with a smooth function:

$S_{true} \leftrightarrow S_{smooth}$ → $S_{obs} \approx D_e \times S_{smooth}$

- Coefficients S_{smooth} are known for the SPSS from the approximation model
- Solve for *fiducial* instrument model D_e using the SPSS observations
- Apply D_e^{-1} as the calibration model for the other stars
- Method removes LSF smearing and absorbs residual systematic errors
- Automatically produces wavelength scale to ~ 0.1 of a pixel accuracy (see PMN-004)

BP/RP spectra: hybrid model - preliminary

$$S_{obs} = [D_e] \times S_{smooth}$$

- Express D_e as the product between the nominal dispersion matrix DM and a square matrix **K** (the *kernel*) $\mathbf{D_e = K \times D_n}$

$$\mathbf{S_{obs} = K \times (D_n \times S_{smooth})}$$

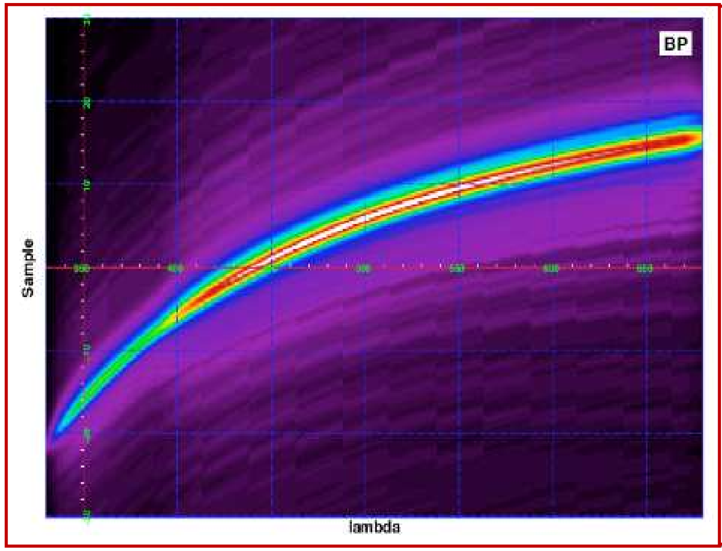
- **K** is fitted with SPSS
- The fitting algorithms:

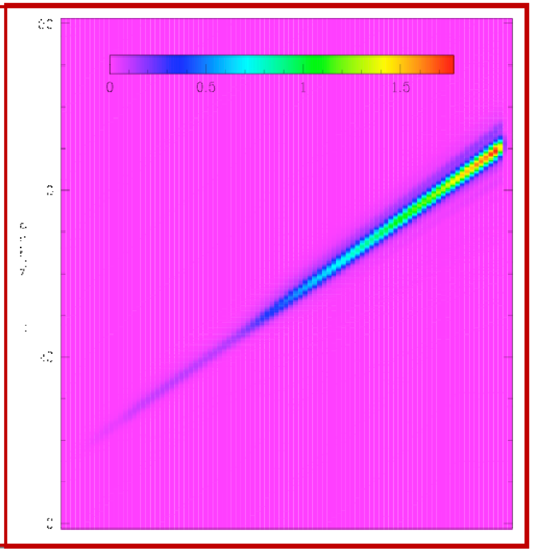
  least squares fit on each row independently

  parametrized fit as in JMC-008:

$$K_{ij} = \sum_{l=0,L} c_{il} \ (i - i_{ref})^l$$

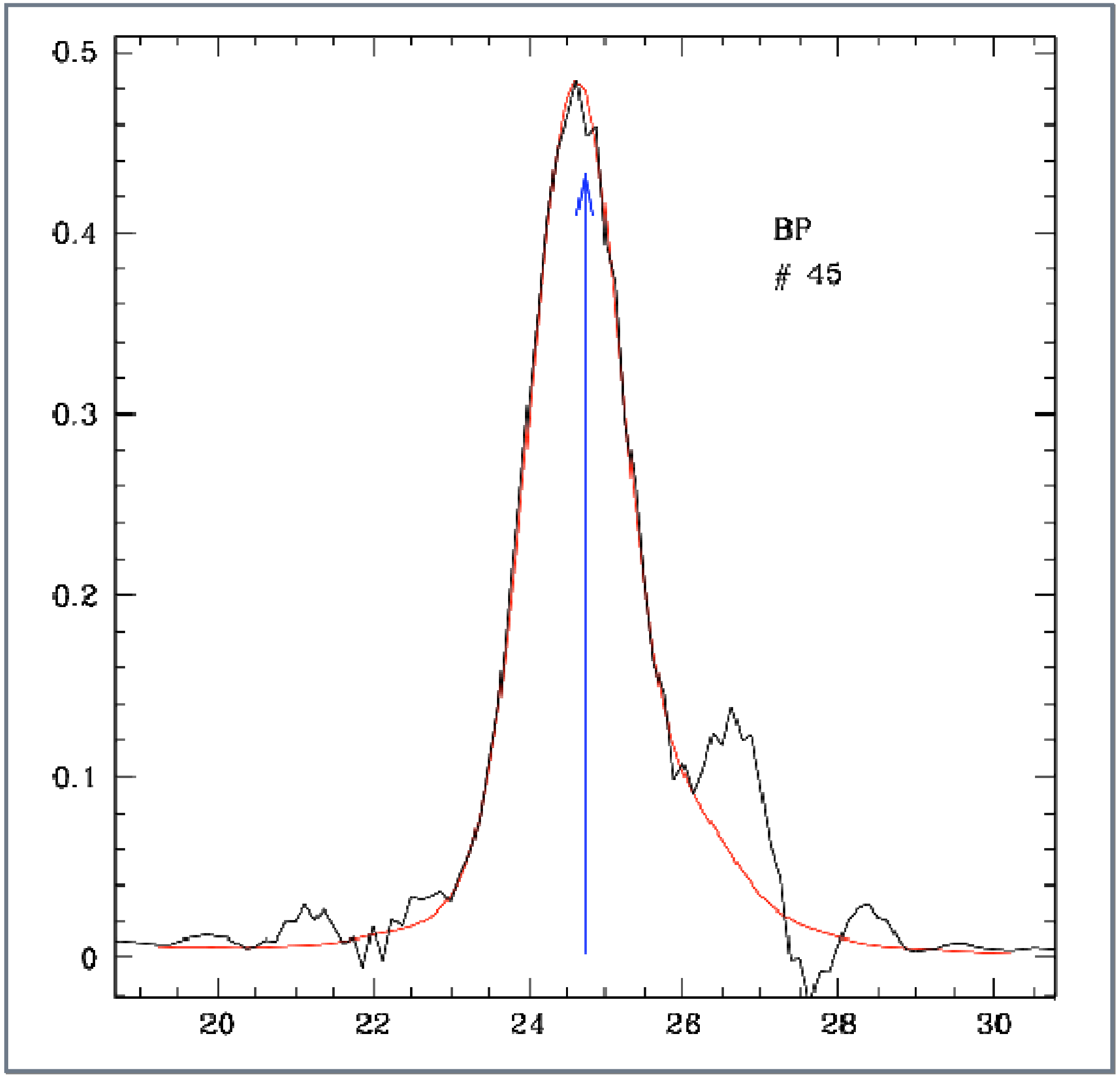
Preliminary results





Cleaner Effective Dispersion Matrix ➔ easier extraction of the Dispersion Curve

Preliminary results



Column # 45 for BP Effective Dispersion Matrix: effective vs. nominal LSF$_{\lambda}$

Spectro-Photometric Standard Stars

DU13 task: provide the grid of SPSS (homogeneous flux scale)
Details in GAIA-C5-TN-OABO-GA-003

- **three pillars** from CALSPEC, V ~ 11.5 to 13.5, **calibrated on Vega**
- **48 primary standards,** V ~ 9 to 14, across the sky
- **~ 200 secondary standards,** V down to ~ 15, preferentially with maximum number of transits
- all spectral types, from bluest (e.g. WDs) to reddest (late types, reddened)

Addition of **SEGUE** stars (TBD): homogeneous flux scale (to be verified), fainter but several thousands → characterisation of entire focal plane ?

Observing campaign:

- more than 200 nights already observed
- spectroscopy complete to ~ 80%
- absolute photometry complete to ~ 22%
- short (long) term variability monitoring nearly completed (ongoing)
- expected completion by 2013