KATHOLIEKE UNIVERSITEIT
LEUVEN

PACS Spectrometer flux calibration

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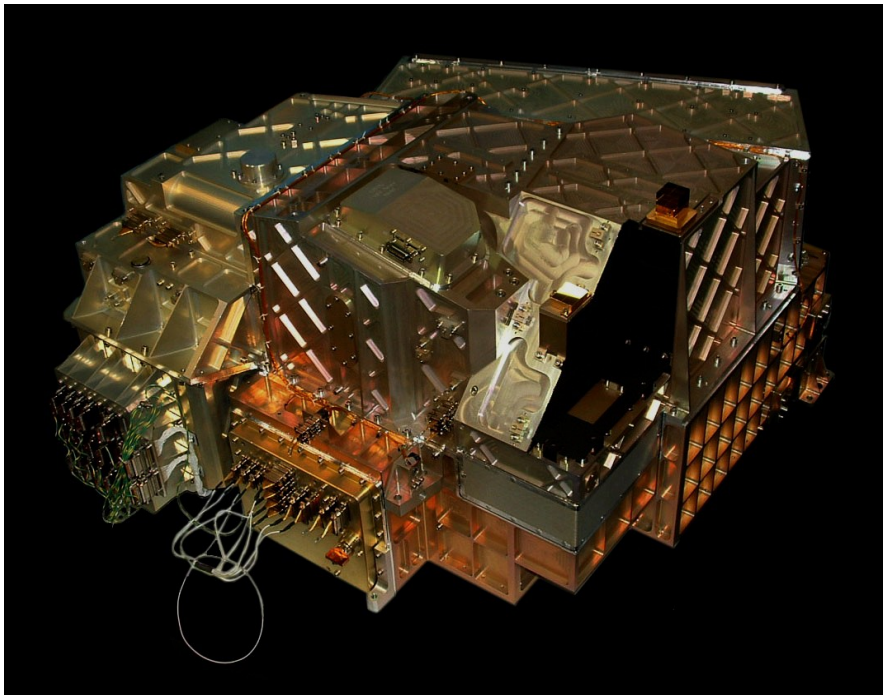
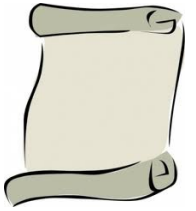
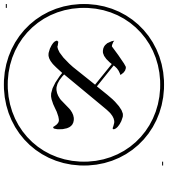


PACS flux calibration concepts



- Nominal response

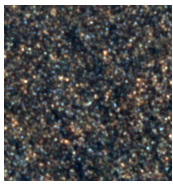


→ Constant Response (abandonned)

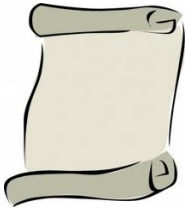
- Calibration Block

→ Tracks response drifts between obs.

- Tel. Background Normalization



→ Also tracks response drifts during the obs.



Calibration Block

- Response from internal calibration block
  - Internal calibration block:
    - differential signal hot/cold load
    - ∀ AORs => allows to track response changes
  - Internal calibration sources calibrated on sky calibrators

    → originally, central spaxel only (hipe 8, cal. set 31)

    → now, central 3x3 spaxels (hipe 10, cal. set 44)

Calibration block scheme

Updates

- Calibration now based on 3x3 spaxels instead of 1
- More robust vs mispointing: σ reproducibility source $\div$ 2
- New versions of calfiles ObservedResponse and CalSourceFlux (calibration set 44)
- No “average” mispointing included anymore

  → better calibration of extended sources (change: ~5%)

  → point sources: new 3x3 calib matches the old one with central-spax only (by constr.)

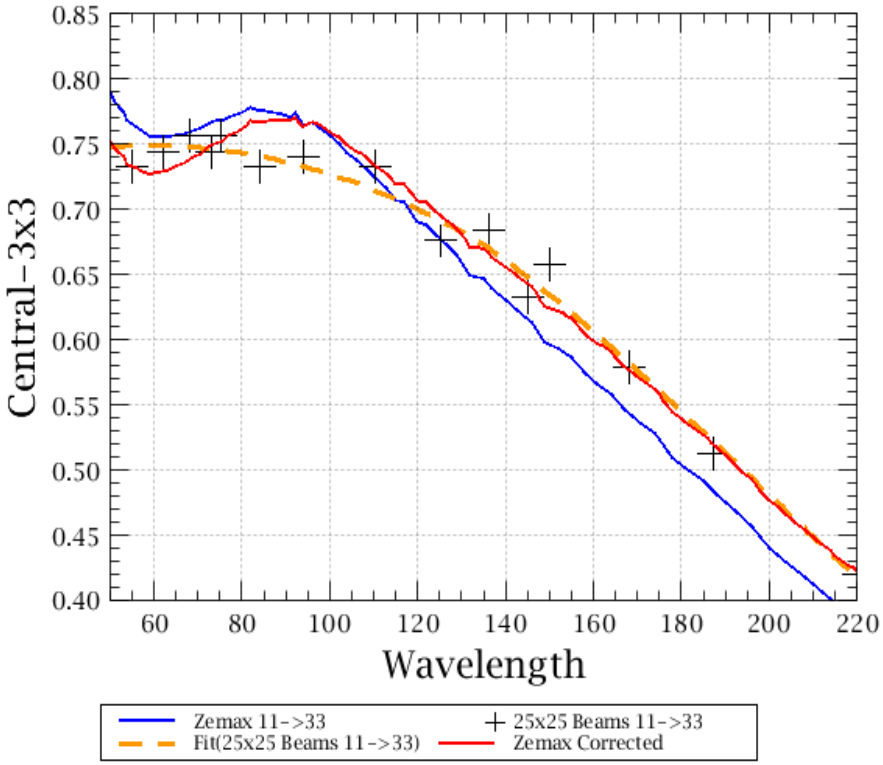
  → lower calibration of point sources' central spaxel

  => calibration of central spaxel spectrum demands extra correction (extractCentralSpectrum)

extractCentralSpectrum

extractCentralSpectrum

- Central / central3x3 calibrated for perfectly pointed point source
  - Based on large spatially oversampled Neptune rasters ('beams')
  - CalTree.spectrometer.pointSourceLoss[“fractionCentral_to_3x3”] (orange curve)
  - Used as reference here



extractCentralSpectrum

extractCentralSpectrum

- Calfile as reference ≡ assume the measured (central / central3x3) reflects the mispointing
- Apply “pointing correction” wrt

$$\text{central} := (\text{central}/3\text{x}3)|_{\text{calfile}} / (\text{central}/3\text{x}3)|_{\text{measured}}$$

- Line & short range : median correction

  ≡ simple correction to abs. Flux cal for mispointing

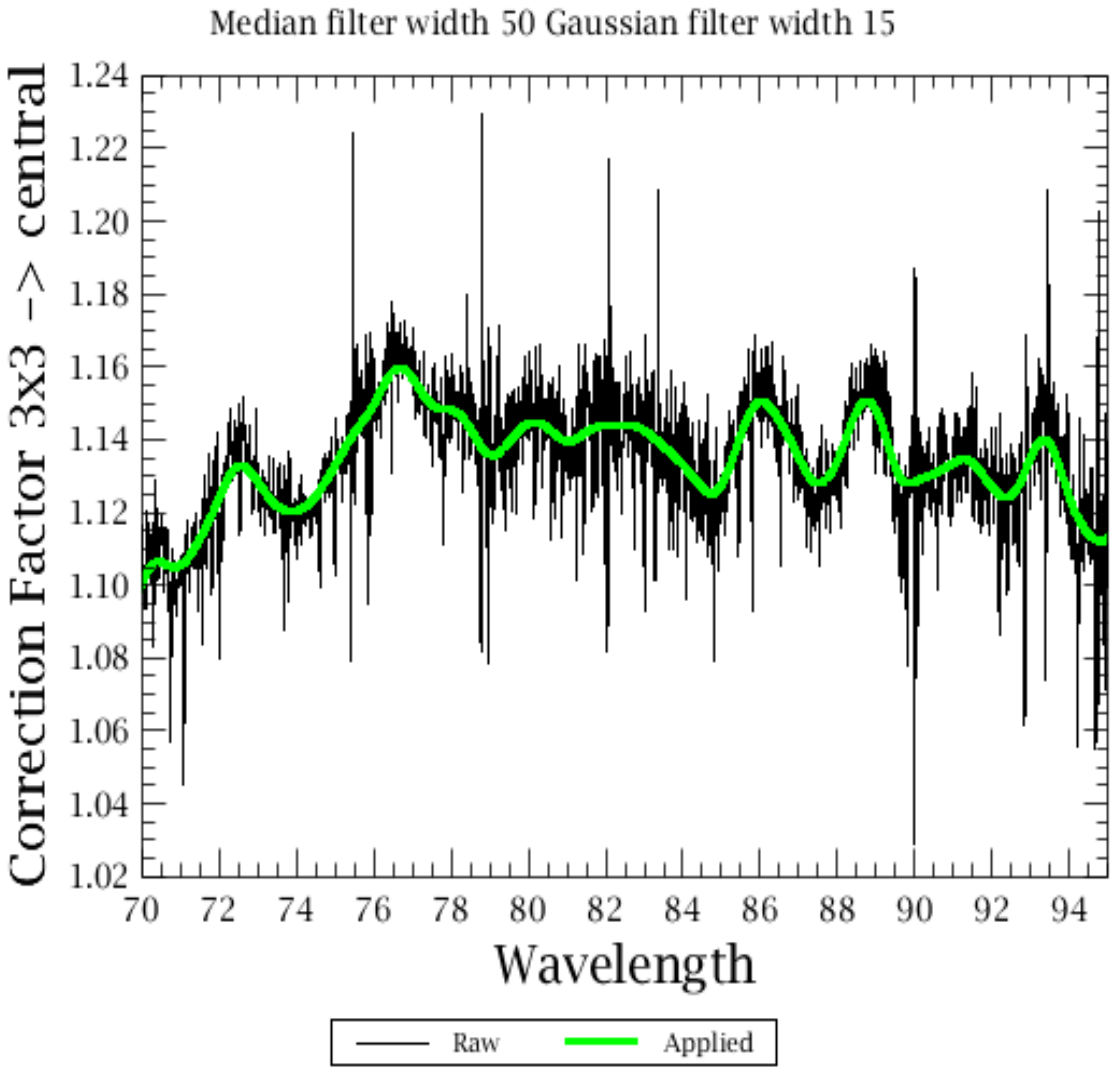
- Range & SED : wavelength dependent

  => also includes a simple correction of the spectral shape

  ≡ to enforcing the spectral shape of 3x3 to the central spaxel

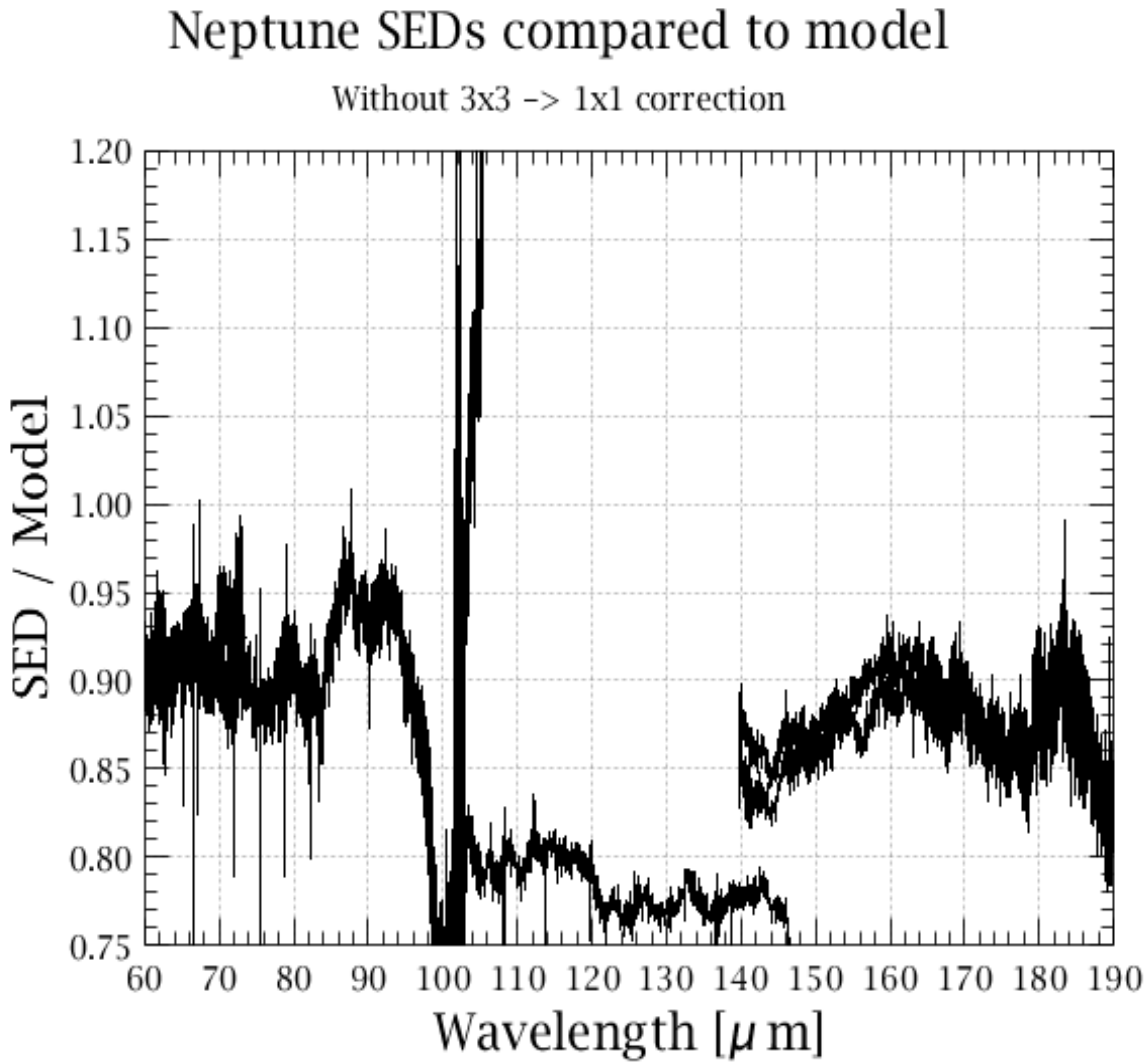
extractCentralSpectrum

extractCentralSpectrum



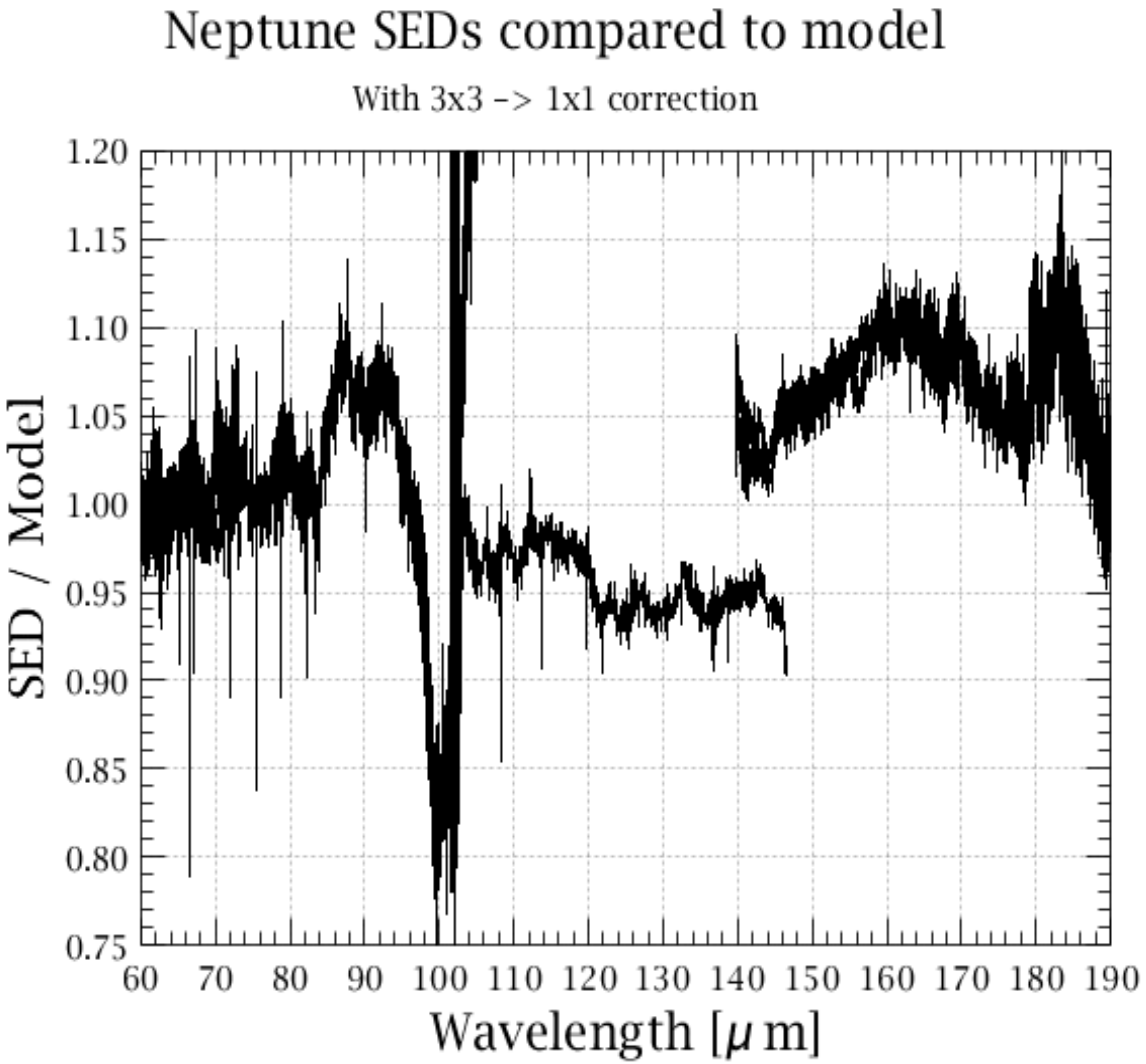
extractCentralSpectrum

extractCentralSpectrum



extractCentralSpectrum

extractCentralSpectrum

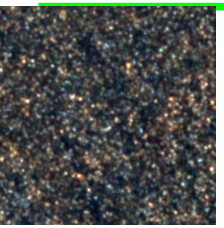


Calibration block scheme

Calfiles

- Calfile ObservedResponse3x3:
  - Average response for central 'meta-spaxel' over all calib.obs.
  - Point Sources: Transfer 3x3 spaxels → full beam
    - point source correction (3x3 → total), calfile pointSourceLoss
  - Extended Sources: Transfer to all spaxels/pixels
    - Flatfield from telescope background (chop OFF)
    - Averaged over all abs. flux cal obs
    - Scale flatfield to mean response central 9 spaxels
  - At key wavelength for each band (60, 75, 150μm)

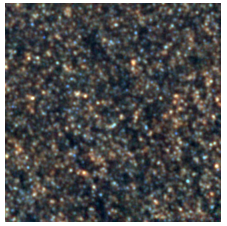
    → Transfer to other wavelengths via RSRF from ILT
- Calfile CalSourceFlux3x3
  - Average differential signal CS1-CS2 over all fluxcal obs
  - At key wavelength for each band



Telescope Background Normalization

- For chopped measurements
  - Telescope visited @every grating position
  - “instantaneous” track of response
- Makes use of the telescope model
- No use of the RSRF
- Source measured in 'telescopes'
- Telescope calibrated on Neptune rasters

Telescope Background Normalisation



- source spectrum [Jy]

  = normalisation pipeline result [Tel.] * Telescope spectrum [Jy]

- Calibration file TelescopeBackground
  - Based on Neptune raster observations / model ESA3
  - Telescope Model scaled for M. temp.

  - Update:

    Telescope Model also scaled for ageing (cal. sets 45 & 50)

Flux standards & weights

Fiducial stars	λ_{Key}
αBoo	14
αCet	3
αTau	9
βPeg	3
γDra	3

- Abs. Flux Cal of calibration block scheme
- Comparison of Normalization with C.B.

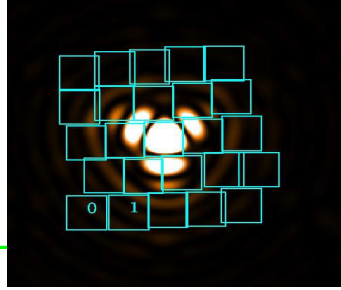
Reproducibility source:

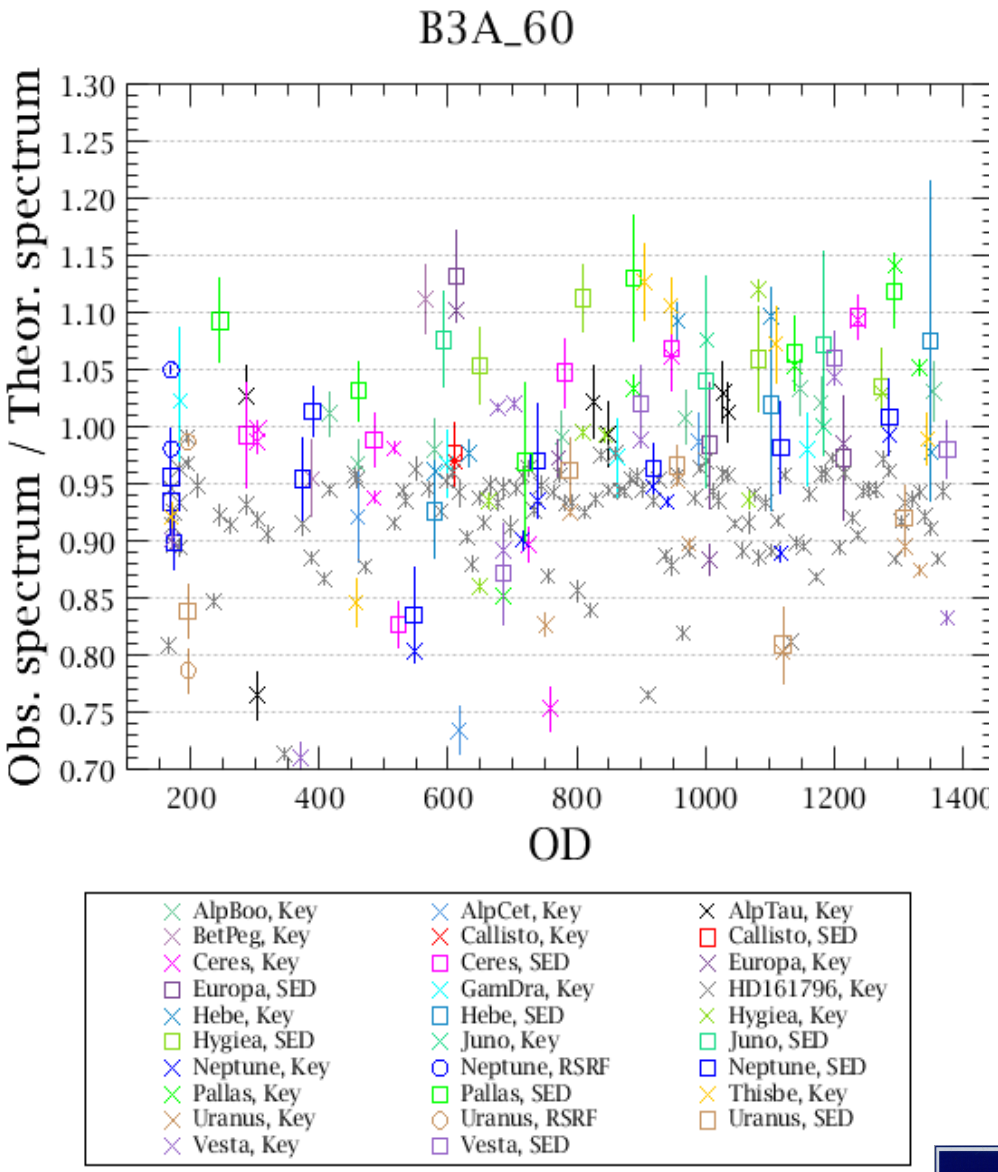
HD161796	116

Solar system	λ_{Key}	SED*
Callisto	1	1
Uranus	12	10
Neptune	10	10
Ceres	12	10
Vesta	7	7
Pallas	6	6
Europa	4	3
Juno	3	3
Hebe	5	3
Hygiea	7	4
Thisbe	5	

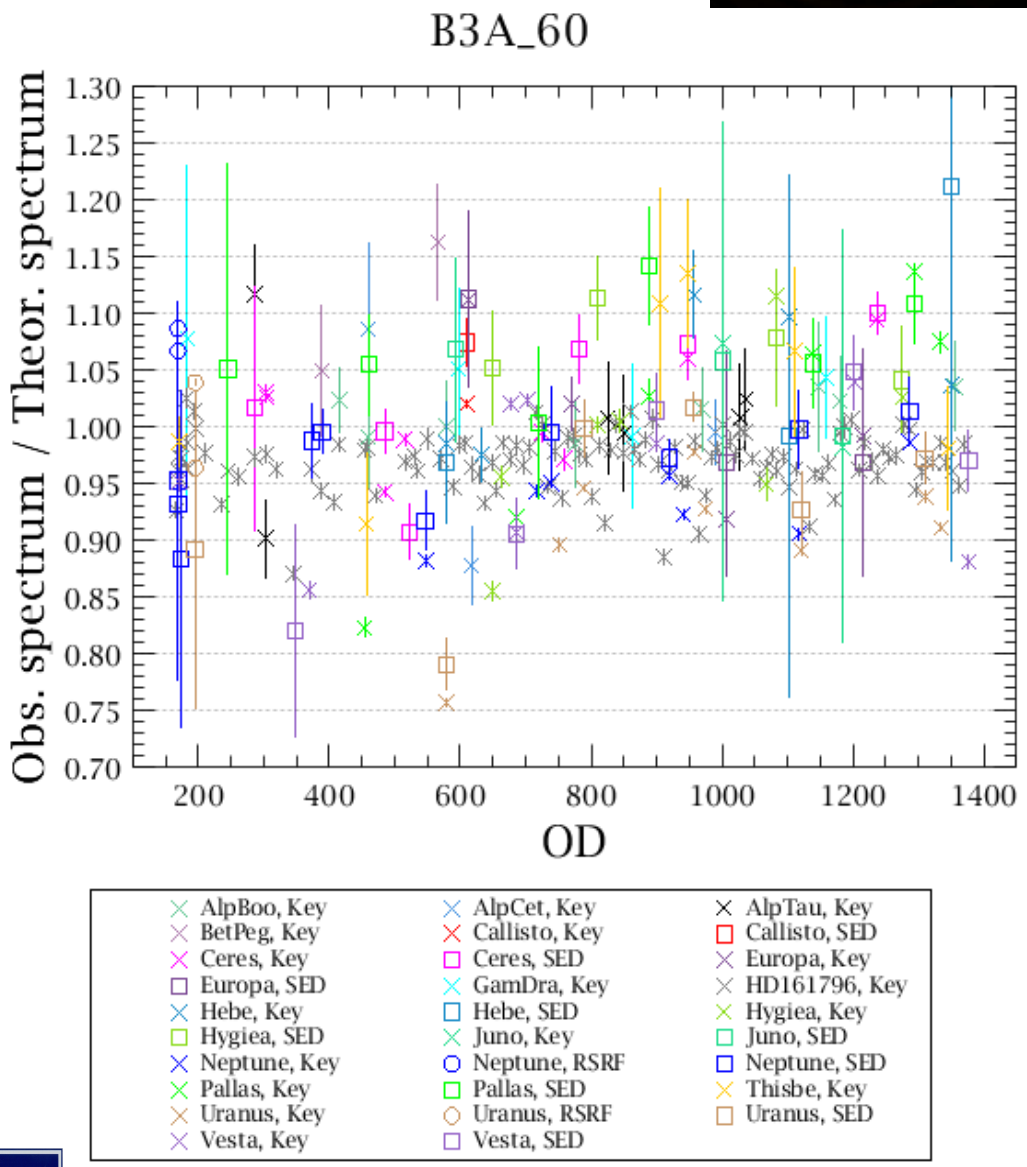
* Chopped & Unchopped

Central ↔ ∫3x3 spaxels



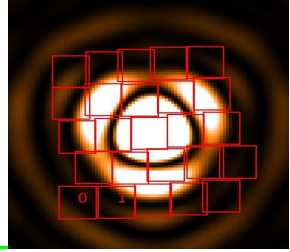


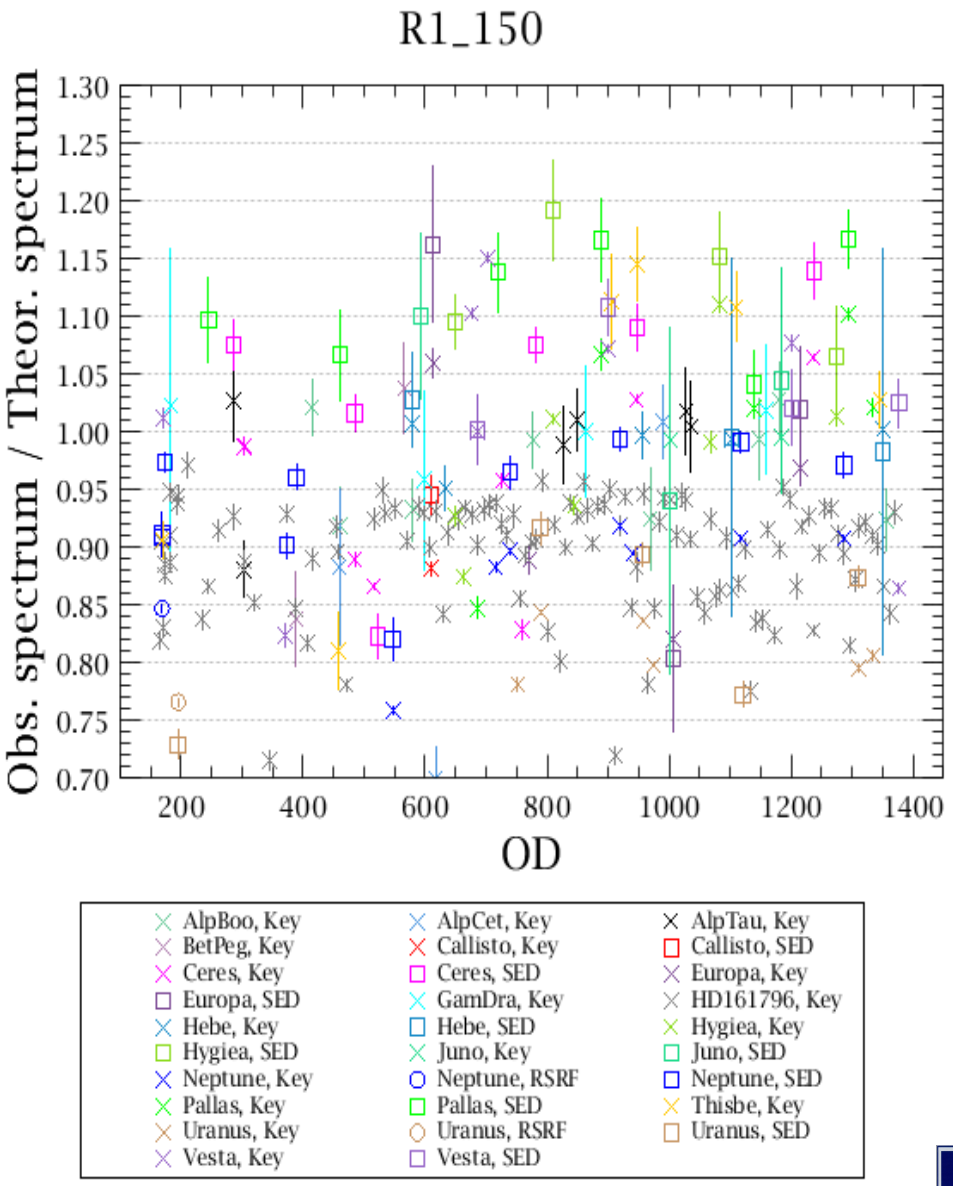
Central Spaxel



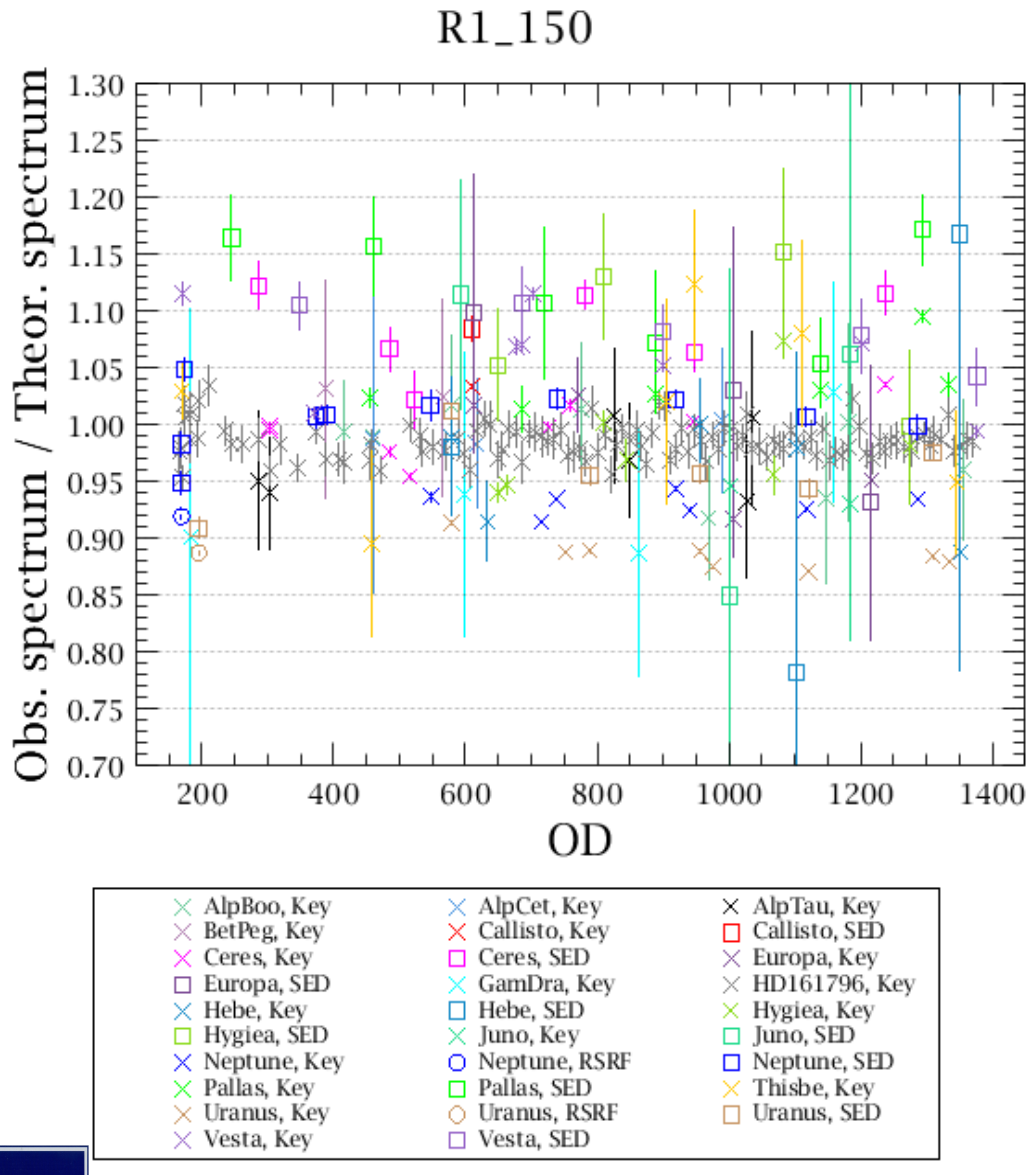
Central 9 Spaxels

Central ↔ ∫3x3 spaxels



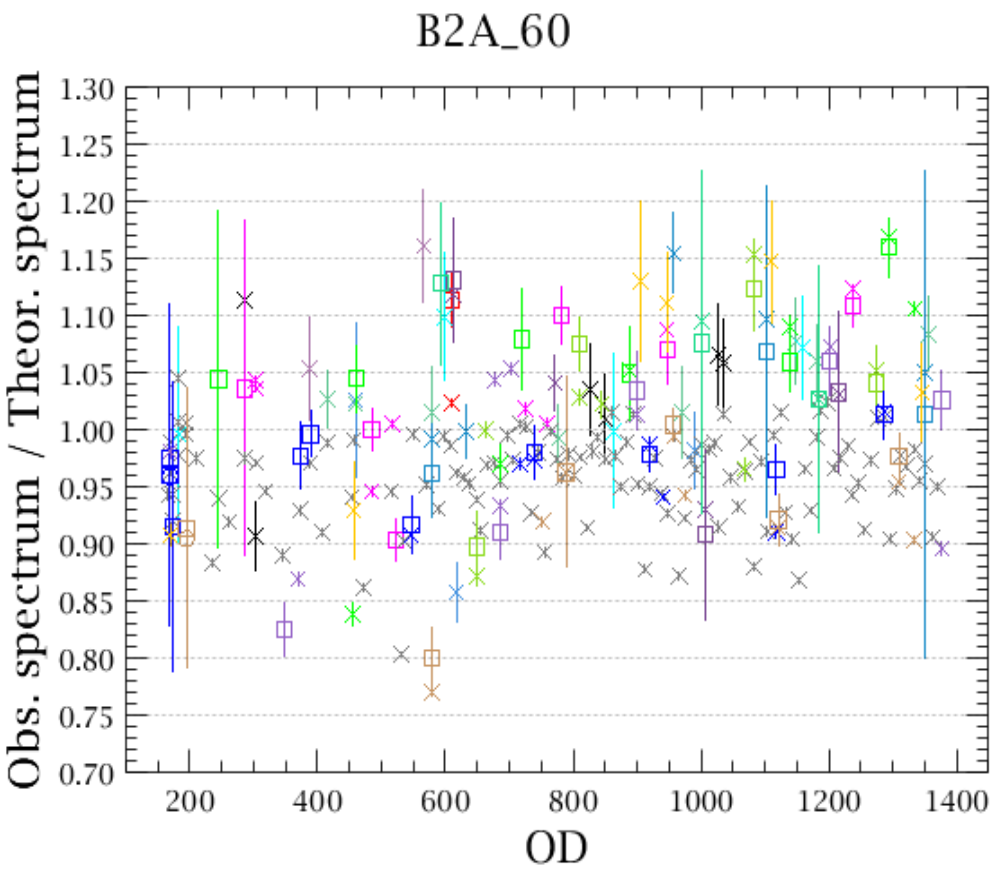


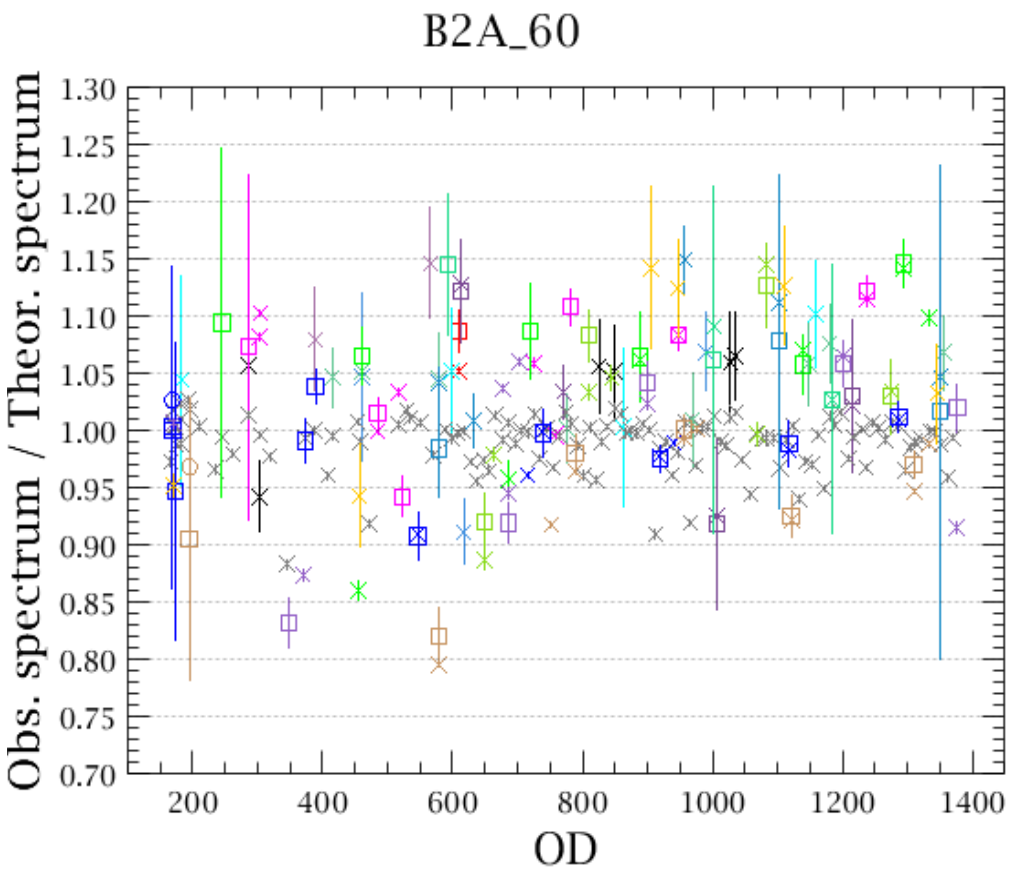
Central Spaxel

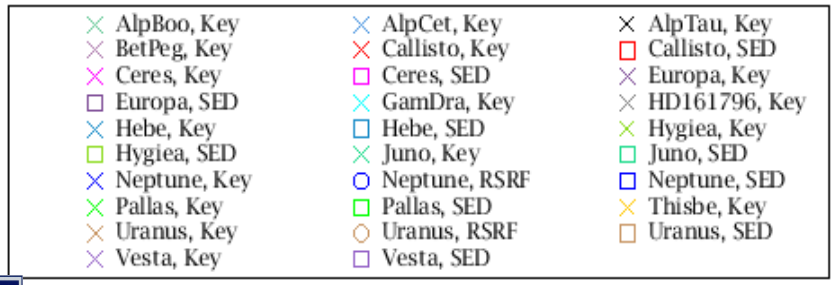


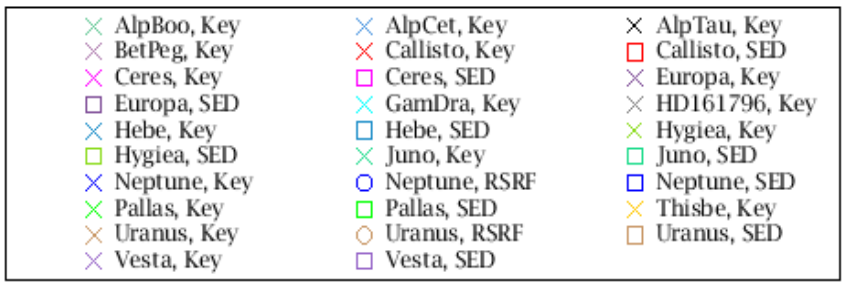
Central 9 Spaxels

Calibration block ↔ Tel. Normalization





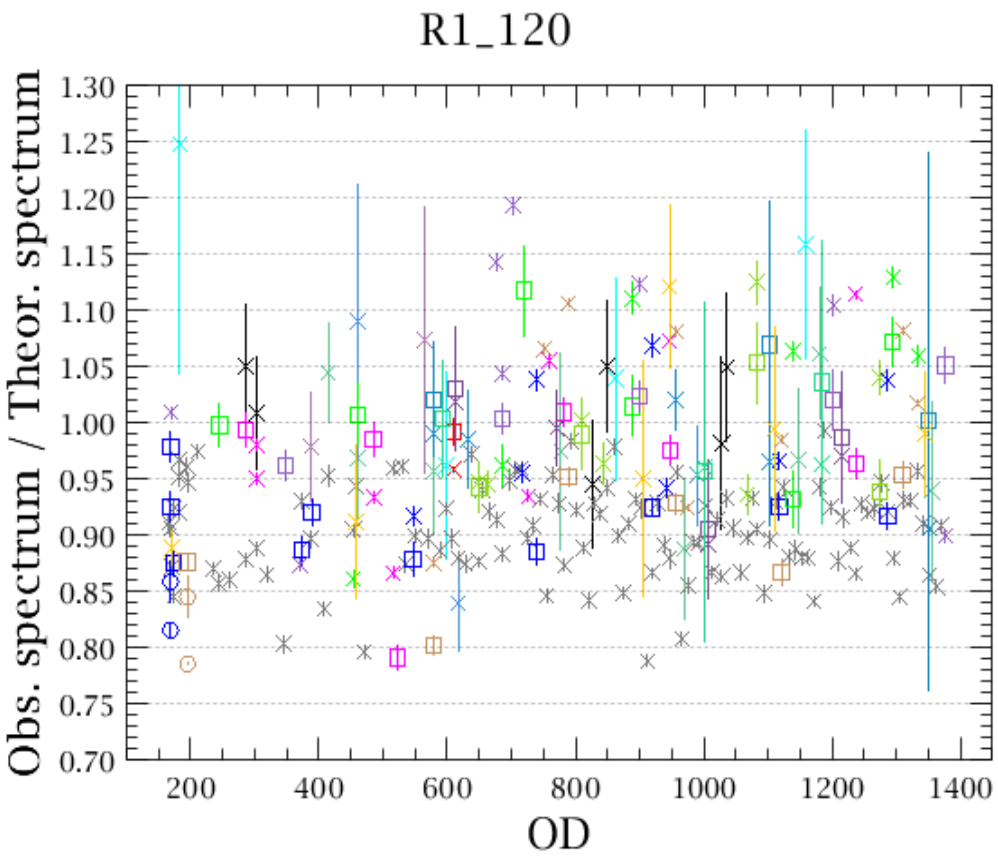


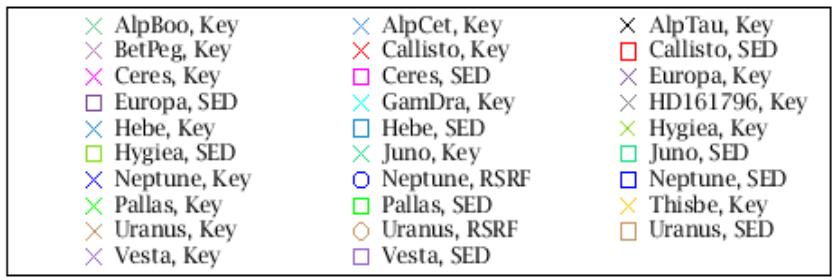


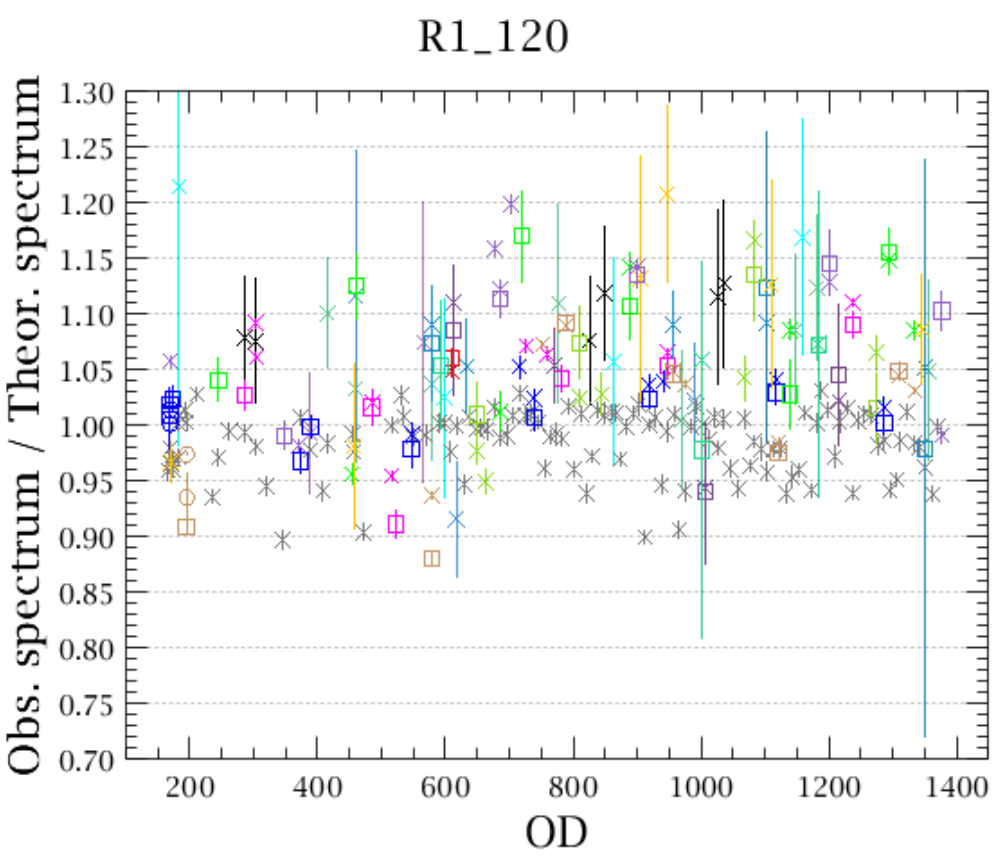
Cal. Block

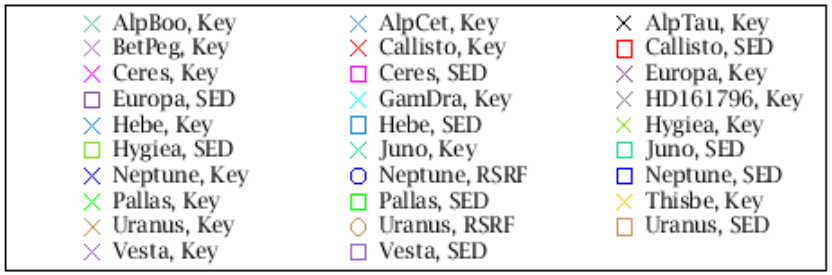
Tel. Background

Calibration block ↔ Tel. Normalization





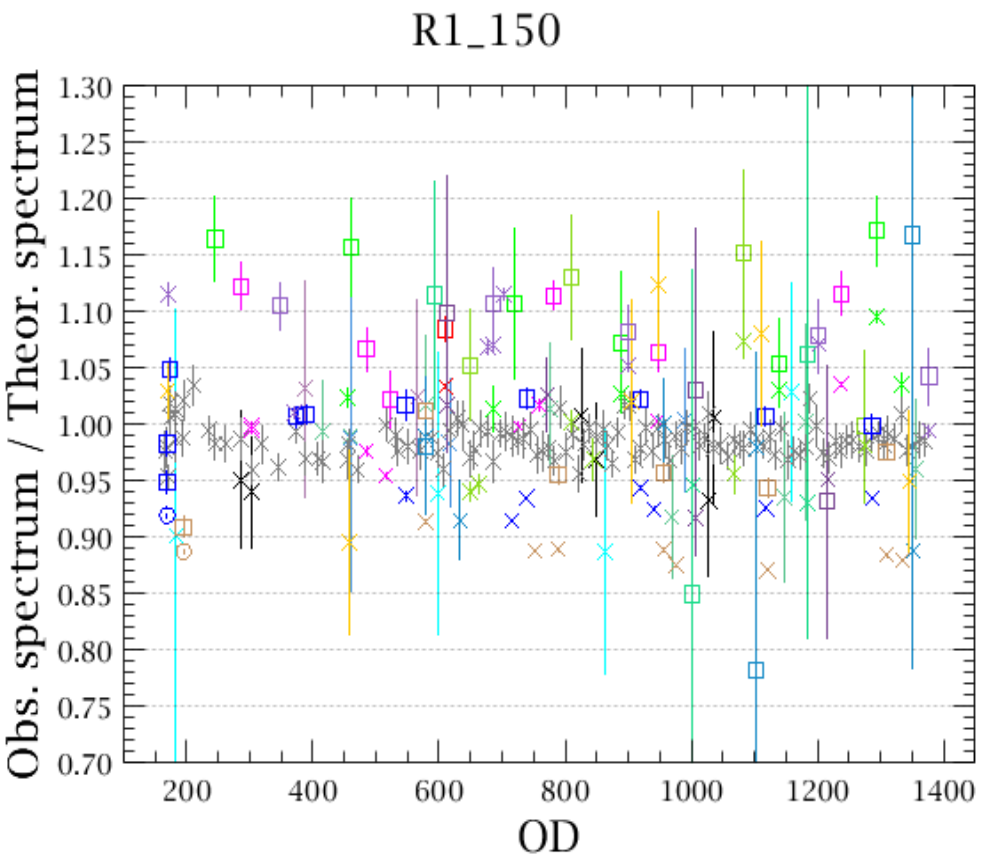


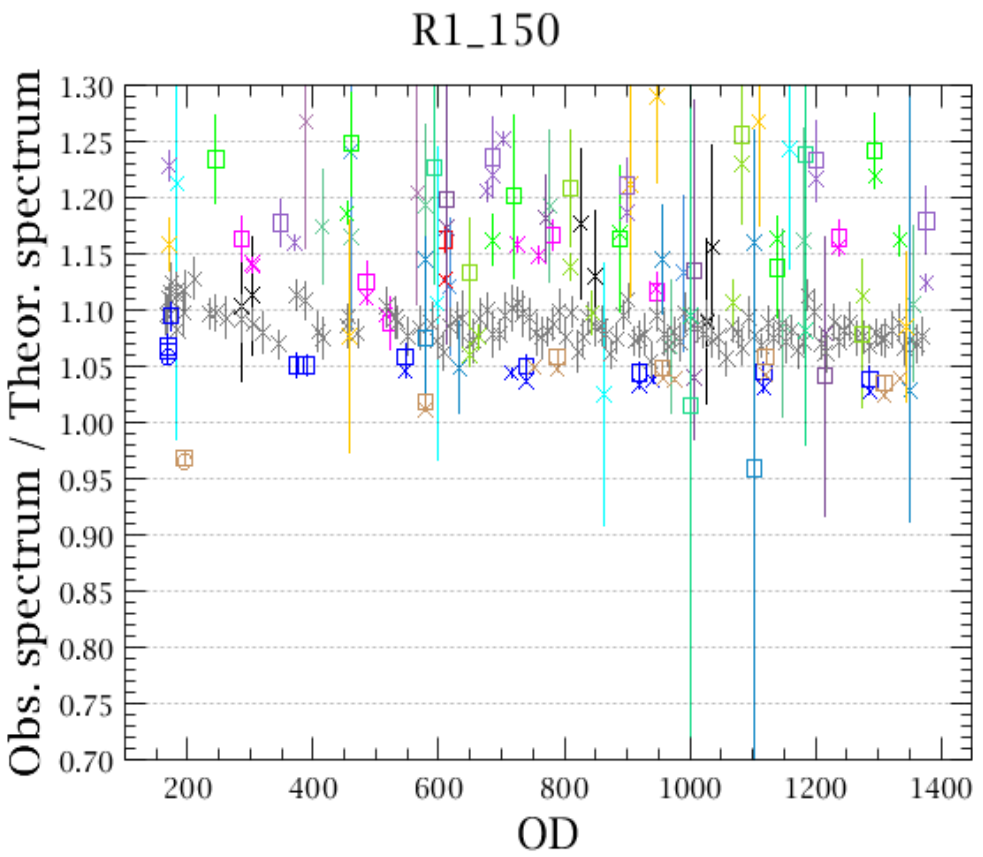


Cal. Block

Tel. Background

Calibration block ↔ Tel. Normalization





Cal. Block

Tel. Background

Systematic error σ_{sys} = STDDEV / $\sqrt{n}$

All celestial calibrators

B3A_60							
Mode	Modules	N	Mean	Std dev.	Min	Max	Peak-to-peak
Calibration block	Central	136	0.9613	0.1343	0.1629	1.1415	0.9786
Calibration block	Central + correct3x3	136	1.0038	0.0752	0.7718	1.1590	0.3871
Calibration block	3 × 3	136	1.0000	0.0776	0.7573	1.2122	0.4550
Normalization	Central	136	0.9750	0.1335	0.1643	1.1446	0.9803
Normalization	Central + correct3x3	136	1.0148	0.0733	0.7766	1.1560	0.3794
Normalization	3 × 3	136	1.0107	0.0758	0.7819	1.2305	0.4486
B2A_60							
Mode	Modules	N	Mean	Std dev.	Min	Max	Peak-to-peak
Calibration block	Central	134	0.9696	0.1316	0.2144	1.1645	0.9501
Calibration block	Central + correct3x3	134	1.0116	0.0800	0.7657	1.1705	0.4048
Calibration block	3 × 3	134	1.0099	0.0798	0.7695	1.1689	0.3994
Normalization	Central	134	0.9842	0.1274	0.2155	1.1560	0.9404
Normalization	Central + correct3x3	134	1.0233	0.0729	0.7925	1.1577	0.3653
Normalization	3 × 3	134	1.0218	0.0728	0.7955	1.1496	0.3541
B2B_75							
Mode	Modules	N	Mean	Std dev.	Min	Max	Peak-to-peak
Calibration block	Central	134	0.9594	0.1490	0.2202	1.2018	0.9816
Calibration block	Central + correct3x3	134	1.0049	0.0840	0.7659	1.1858	0.4199
Calibration block	3 × 3	134	1.0000	0.0886	0.7701	1.2006	0.4305
Normalization	Central	134	0.9794	0.1472	0.2233	1.1725	0.9492
Normalization	Central + correct3x3	134	1.0238	0.0800	0.7934	1.1947	0.4012
Normalization	3 × 3	134	1.0176	0.0845	0.7968	1.1821	0.3853

Ignoring model Uncert:

σ_{sys} ~ 1%

Tel. Norm. = Calblock

Corr3x3 ~ 5%

BLUE

Systematic error σ_{sys} = STDDEV / $\sqrt{n}$

All celestial calibrators

R1_120							
Mode	Modules	N	Mean	Std dev.	Min	Max	Peak-to-peak
Calibration block	Central	136	0.9456	0.1435	0.3211	1.2292	0.9081
Calibration block	Central + correct3x3	136	0.9894	0.0800	0.7900	1.2641	0.4741
Calibration block	3 × 3	136	0.9844	0.0826	0.7856	1.2483	0.4626
Normalization	Central	136	1.0027	0.1374	0.3334	1.2263	0.8929
Normalization	Central + correct3x3	136	1.0581	0.0628	0.9121	1.2148	0.3027
Normalization	3 × 3	136	1.0523	0.0647	0.8806	1.2147	0.3341
R1_150							
Mode	Modules	N	Mean	Std dev.	Min	Max	Peak-to-peak
Calibration block	Central	134	0.9558	0.1300	0.4474	1.1923	0.7449
Calibration block	Central + correct3x3	134	1.0042	0.0727	0.8525	1.1658	0.3132
Calibration block	3 × 3	134	1.0000	0.0755	0.7821	1.1721	0.3900
Normalization	Central	134	1.0635	0.1417	0.4709	1.3060	0.8350
Normalization	Central + correct3x3	134	1.1260	0.0758	0.9560	1.3634	0.4073
Normalization	3 × 3	134	1.1273	0.0796	0.9598	1.4369	0.4772
R1_180							
Mode	Modules	N	Mean	Std dev.	Min	Max	Peak-to-peak
Calibration block	Central	136	0.9676	0.1418	0.5317	1.2970	0.7653
Calibration block	Central + correct3x3	136	1.0359	0.1423	0.6785	1.7499	1.0714
Calibration block	3 × 3	136	1.0365	0.1440	0.1495	1.6333	1.4838
Normalization	Central	136	1.0865	0.1503	0.6226	1.4006	0.7781
Normalization	Central + correct3x3	136	1.1460	0.1466	0.7929	1.7909	0.9980
Normalization	3 × 3	136	1.1365	0.1511	0.1733	1.6631	1.4898

Ignoring model Uncert:

σ_{sys} ~ 1%

Tel. Norm. > Calblock

Corr3x3 ~ 5%

RED

Stochastic error σ_{sto} = STDDEV
Reproducibility source – HD 169716

B3A_60							
Mode	Modules	N	Mean	Std dev.	Min	Max	Peak-to-peak
Calibration block	Central	114	0.9231	0.0433	0.7137	0.9916	0.2779
Calibration block	Central + correct3x3	114	0.9687	0.0255	0.8682	1.0232	0.1550
Calibration block	3 × 3	114	0.9693	0.0253	0.8707	1.0251	0.1544
Normalization	Central	114	0.9271	0.0434	0.7087	0.9919	0.2832
Normalization	Central + correct3x3	114	0.9749	0.0240	0.8718	1.0184	0.1466
Normalization	3 × 3	114	0.9757	0.0238	0.8757	1.0180	0.1423
B2A_60							
Mode	Modules	N	Mean	Std dev.	Min	Max	Peak-to-peak
Calibration block	Central	114	0.9051	0.0509	0.7302	0.9814	0.2512
Calibration block	Central + correct3x3	114	0.9578	0.0402	0.8041	1.0435	0.2394
Calibration block	3 × 3	114	0.9583	0.0403	0.8037	1.0451	0.2414
Normalization	Central	114	0.9364	0.0419	0.7177	0.9916	0.2739
Normalization	Central + correct3x3	114	0.9891	0.0240	0.8776	1.0268	0.1492
Normalization	3 × 3	114	0.9898	0.0240	0.8834	1.0270	0.1436
B2B_75							
Mode	Modules	N	Mean	Std dev.	Min	Max	Peak-to-peak
Calibration block	Central	114	0.8391	0.0522	0.6402	0.9112	0.2710
Calibration block	Central + correct3x3	114	0.8976	0.0339	0.7896	0.9588	0.1692
Calibration block	3 × 3	114	0.8980	0.0338	0.7871	0.9596	0.1726
Normalization	Central	114	0.8529	0.0493	0.6355	0.9154	0.2799
Normalization	Central + correct3x3	114	0.9129	0.0273	0.8081	0.9531	0.1451
Normalization	3 × 3	114	0.9133	0.0270	0.8131	0.9523	0.1392

$\sigma_{sto} \lesssim 4\%$

$\Delta_{max} \lesssim 15\%$

BLUE

Stochastic error σ_{sto} = STDDEV
Reproducibility source – HD 169716

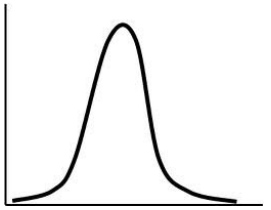
R1_120							
Mode	Modules	N	Mean	Std dev.	Min	Max	Peak-to-peak
Calibration block	Central	114	0.8067	0.0668	0.5881	0.9255	0.3374
Calibration block	Central + correct3x3	114	0.9044	0.0414	0.7882	0.9941	0.2059
Calibration block	3 × 3	114	0.9038	0.0414	0.7881	0.9934	0.2053
Normalization	Central	114	0.8891	0.0595	0.6666	0.9587	0.2921
Normalization	Central + correct3x3	114	0.9857	0.0291	0.8996	1.0329	0.1333
Normalization	3 × 3	114	0.9844	0.0290	0.8971	1.0312	0.1341
R1_150							
Mode	Modules	N	Mean	Std dev.	Min	Max	Peak-to-peak
Calibration block	Central	114	0.8952	0.0494	0.7152	0.9710	0.2558
Calibration block	Central + correct3x3	114	0.9897	0.0146	0.9598	1.0370	0.0772
Calibration block	3 × 3	114	0.9857	0.0149	0.9538	1.0347	0.0809
Normalization	Central	114	0.9814	0.0523	0.7934	1.0527	0.2593
Normalization	Central + correct3x3	114	1.0896	0.0149	1.0590	1.1317	0.0726
Normalization	3 × 3	114	1.0855	0.0147	1.0549	1.1286	0.0737
R1_180							
Mode	Modules	N	Mean	Std dev.	Min	Max	Peak-to-peak
Calibration block	Central	114	0.8856	0.0536	0.7476	1.0692	0.3216
Calibration block	Central + correct3x3	114	0.9695	0.0392	0.8754	1.1214	0.2460
Calibration block	3 × 3	114	0.9695	0.0387	0.8886	1.1238	0.2352
Normalization	Central	114	0.9652	0.0573	0.8196	1.1399	0.3203
Normalization	Central + correct3x3	114	1.0376	0.0451	0.9345	1.2003	0.2657
Normalization	3 × 3	114	1.0371	0.0442	0.9412	1.1935	0.2523

$\sigma_{sto} \lesssim 4\%$

$\Delta_{max} \lesssim 15\%$

RED

Absolute flux calibration accuracy – summary



- Absolute accuracy: single line / continuum in any spaxel
- Calibration uncertainty << reproducibility
  - Calibration dominated by model uncertainties
  - Reproducibility dominated by pointing

  → new pointing products & pointing correction
- Normalisation and calibration block

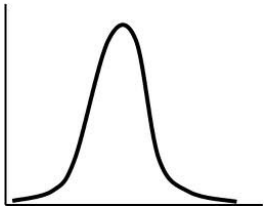
  . Agree within 1-2% in the blue

  . ~ 10% ≠ @150 μm

    – Consistent with previous calibration

    – Origin under investigation

Absolute flux calibration accuracy

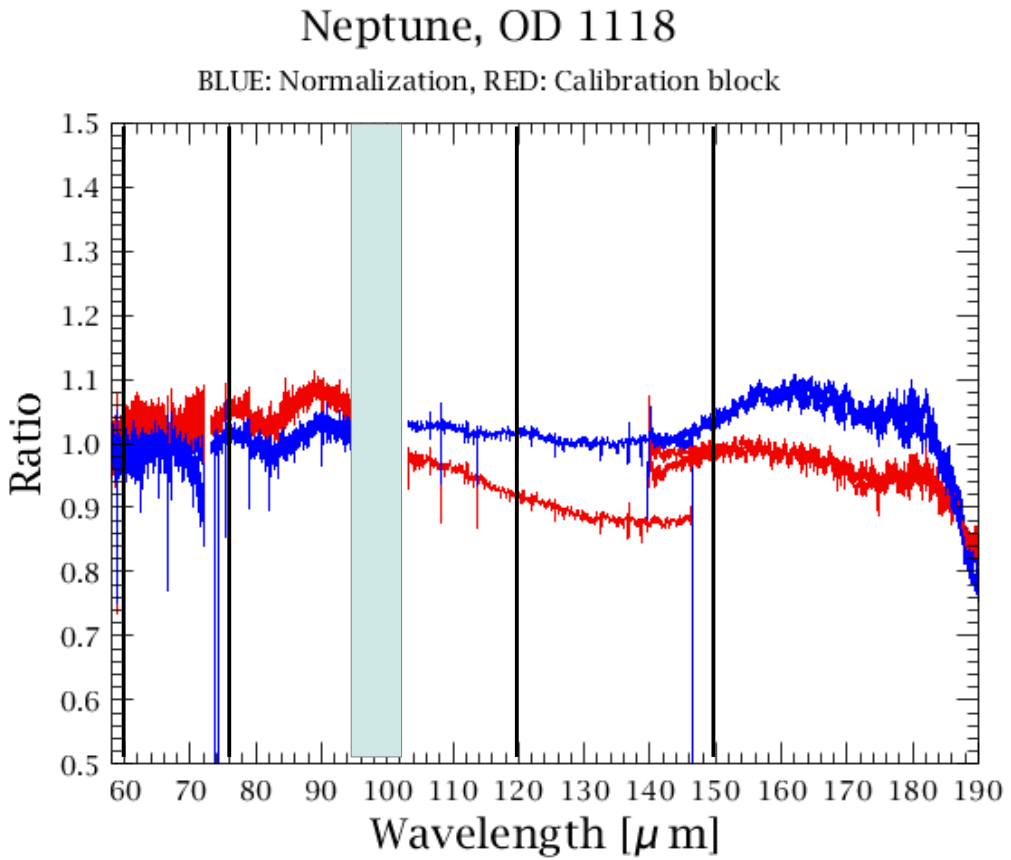


- Summing 3x3 spaxels improves reproducibility ~x2
  - Point Source Correction 3x3 → total is in cal. Tree.
  - extractCentralSpectrum will also offer the corrected 3x3 spectrum (hipe 11)
  - Central spaxel
    - Higher S/N
    - Point sources: extra “central/3x3” correction (extractCentralSpectrum, hipe 9)
    - Weak sources, central/3x3 correction noisy → should not be applied
      → add. uncertainty: 5%

Spectral Band	RMS	Peak-Peak accuracy
B2A (50-70 micrometer)	4 %	+/- 15%
B3A (50-70 micrometer)	4 %	+/- 15%
B2B (70-100 micrometer)	4 %	+/- 15%
R1 (100-220 micrometer)	4 %	+/- 15%

In-band accuracy

- In-band accuracy : $\Delta\ \lambda$ vs λ_{key}
  - < 10% in all bands
  - ~ 10% > 160 μm in Tel. Normalization (under investigation)
  - ~10% > 185 μm



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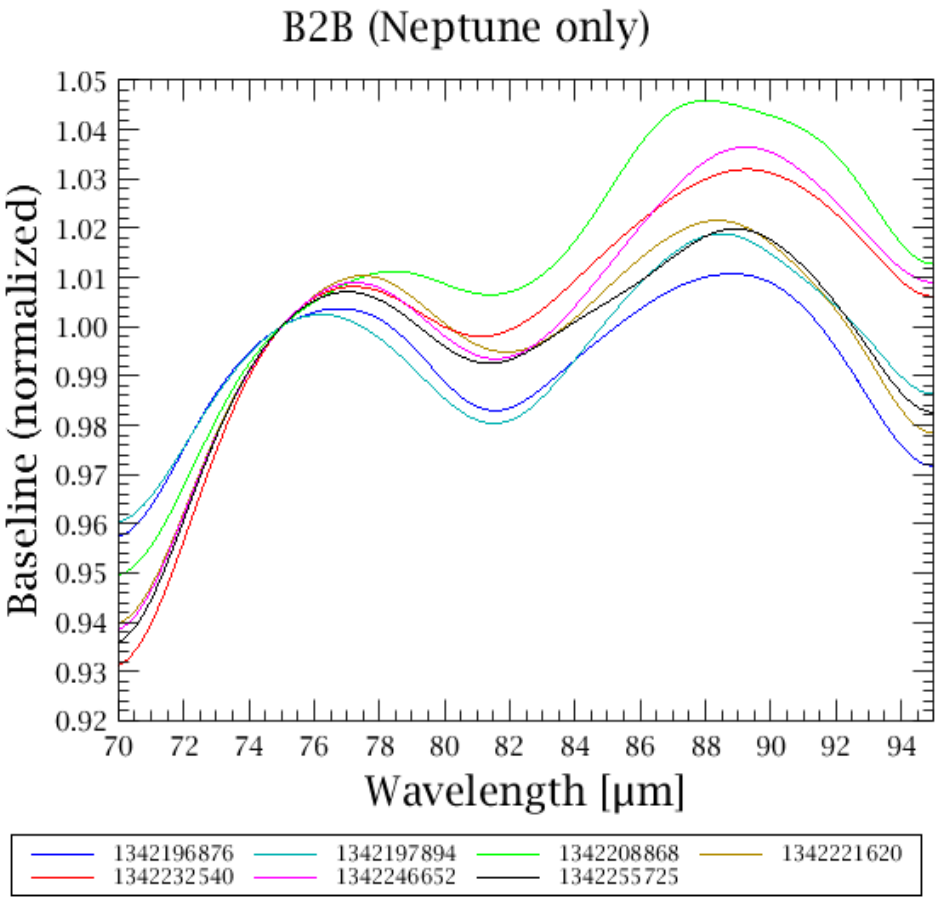
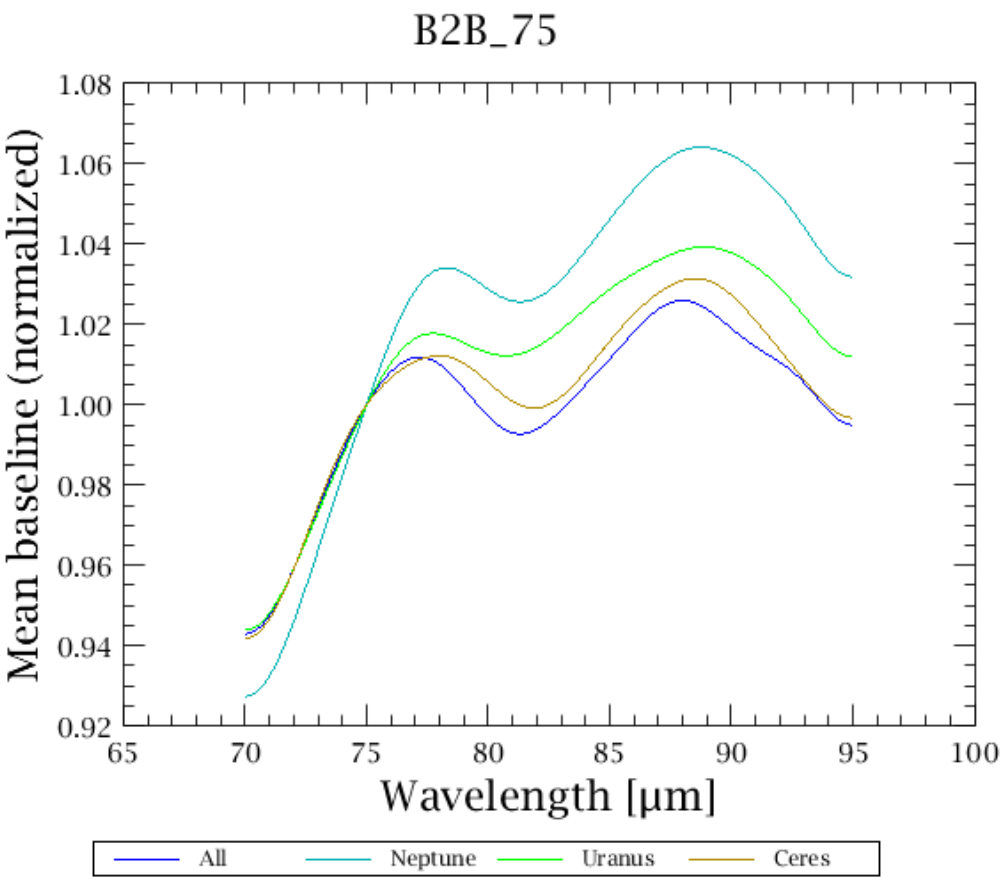
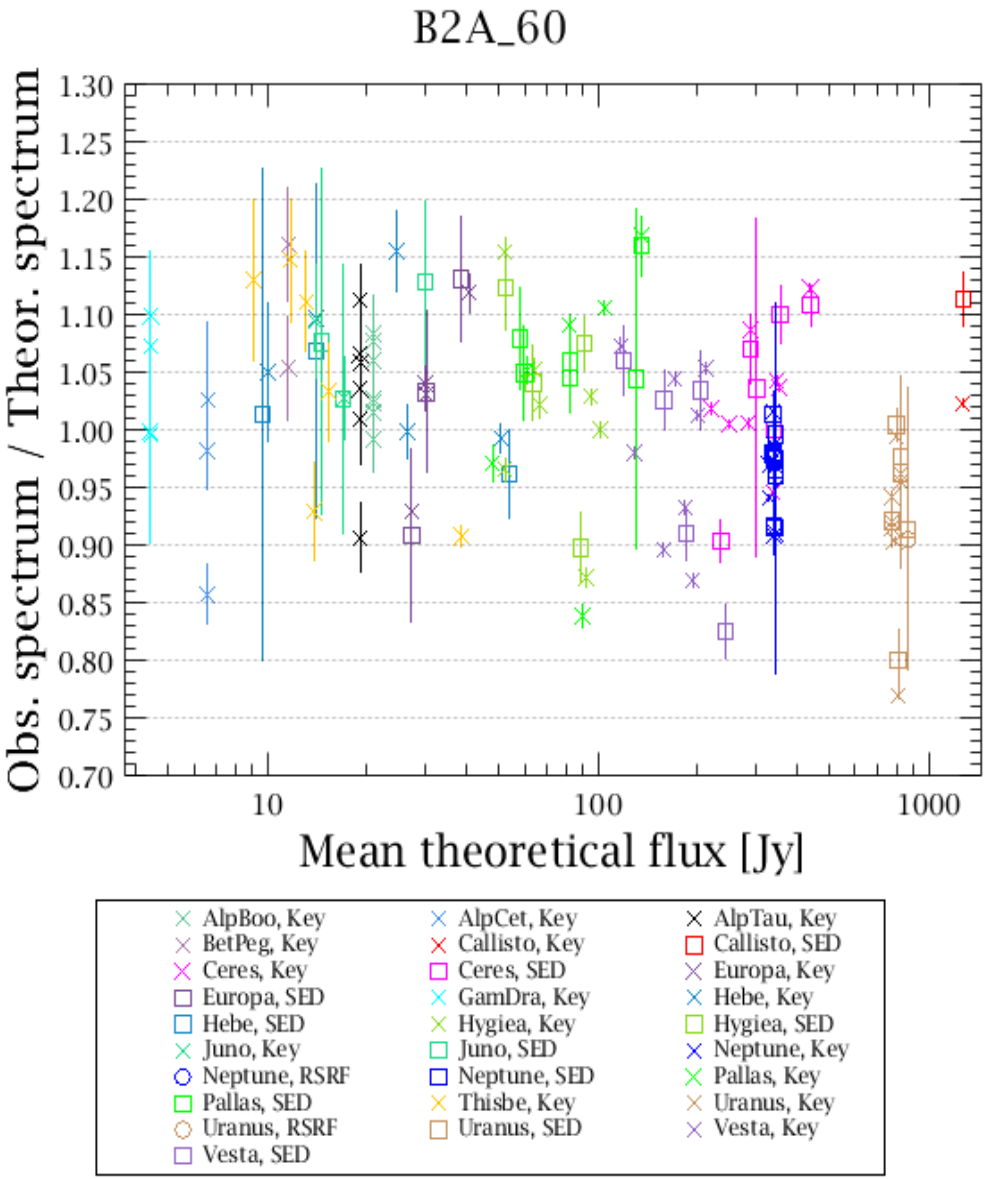
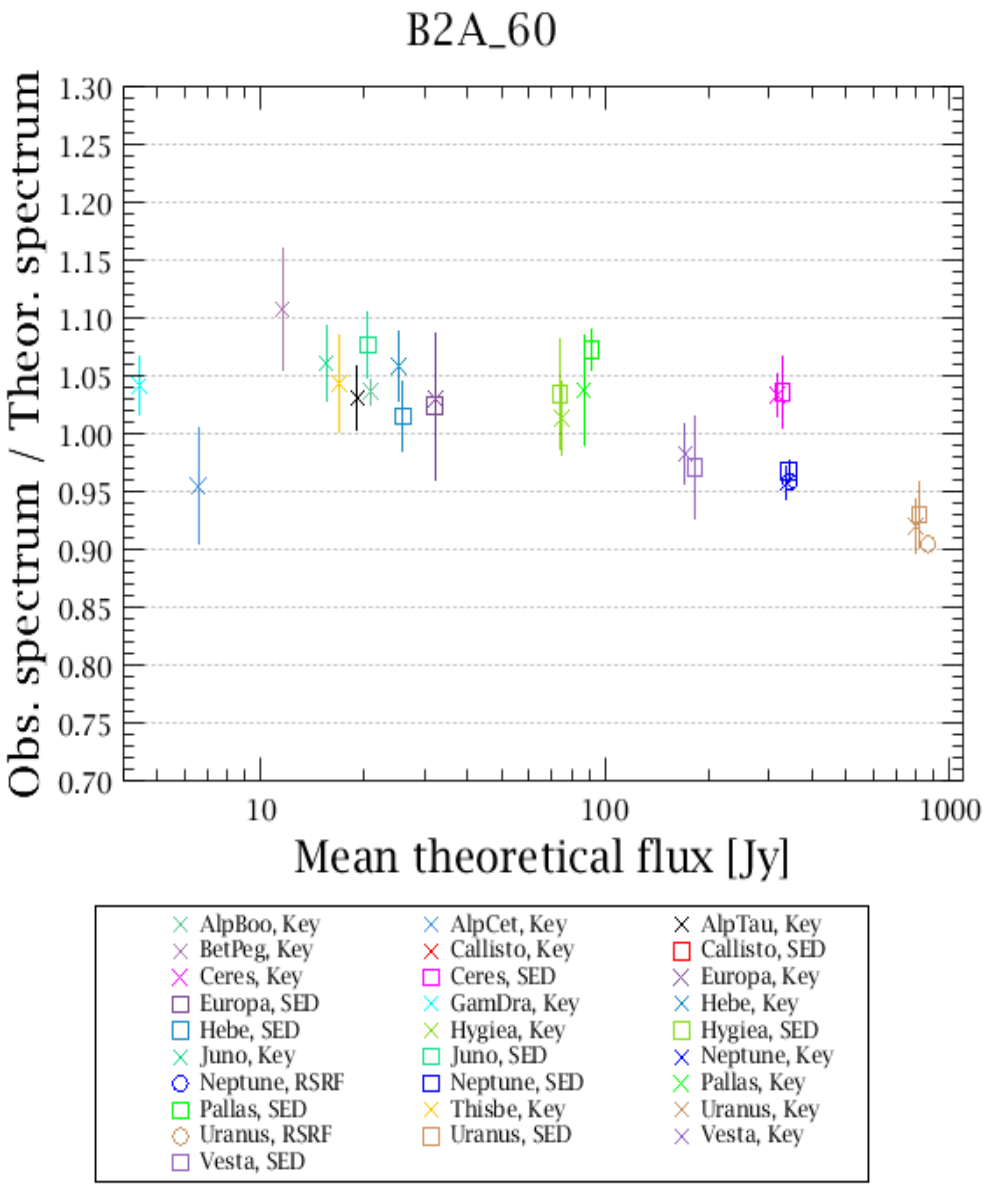




Linearity


B2A_60
Obs. spectrum / Theor. spectrum
1.30
1.25
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
10
100
1000
Mean theoretical flux [Jy]
AlpBoo, Key
AlpCet, Key
AlpTau, Key
BetPeg, Key
Callisto, Key
Callisto, SED
Ceres, Key
Ceres, SED
Europa, Key
Europa, SED
GamDra, Key
Hebe, Key
Hebe, SED
Hygiea, Key
Hygiea, SED
Juno, Key
Juno, SED
Neptune, Key
Neptune, RSRF
Neptune, SED
Pallas, Key
Pallas, SED
Thisbe, Key
Uranus, Key
Uranus, RSRF
Uranus, SED
Vesta, Key
Vesta, SED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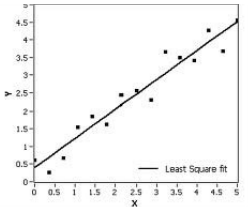
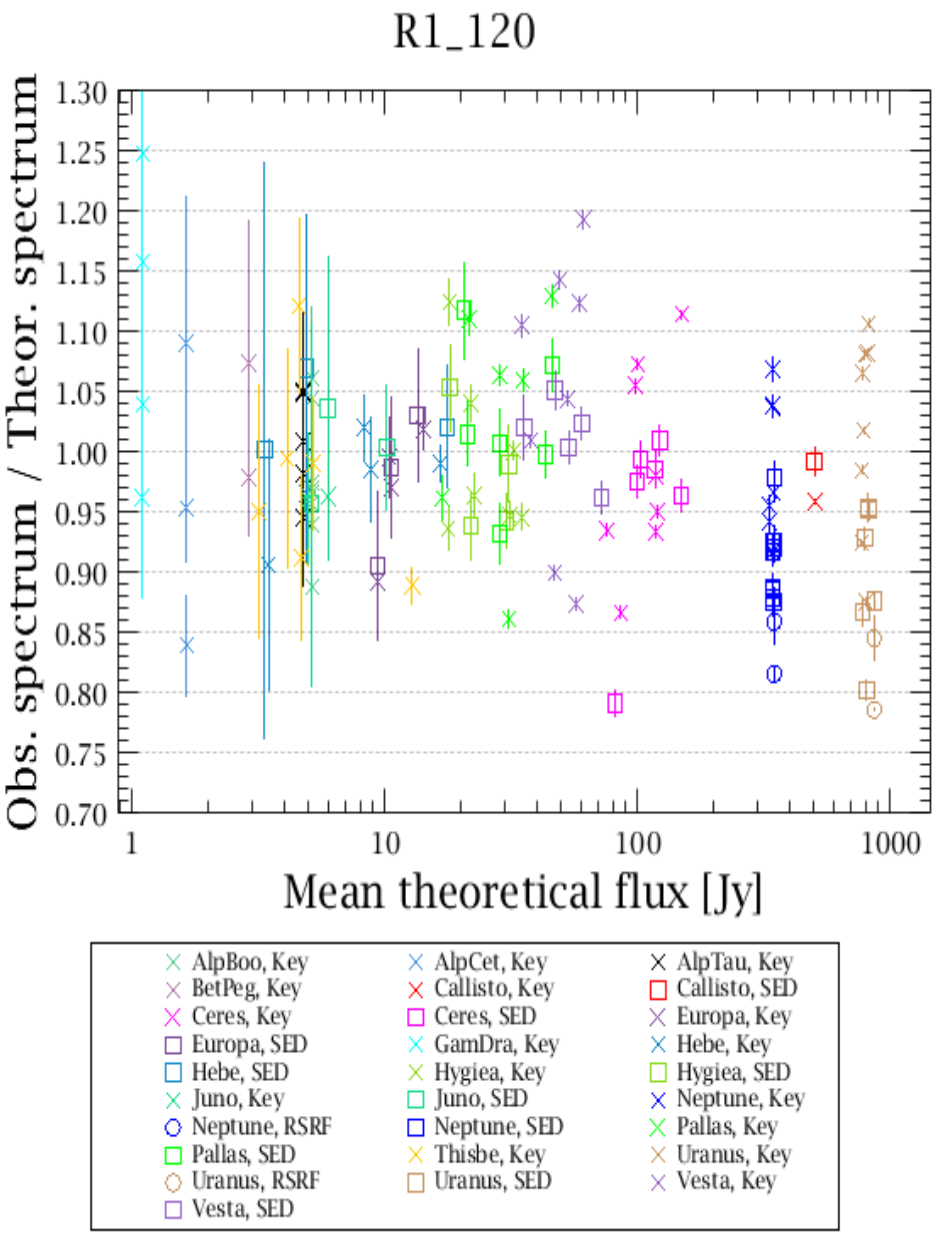
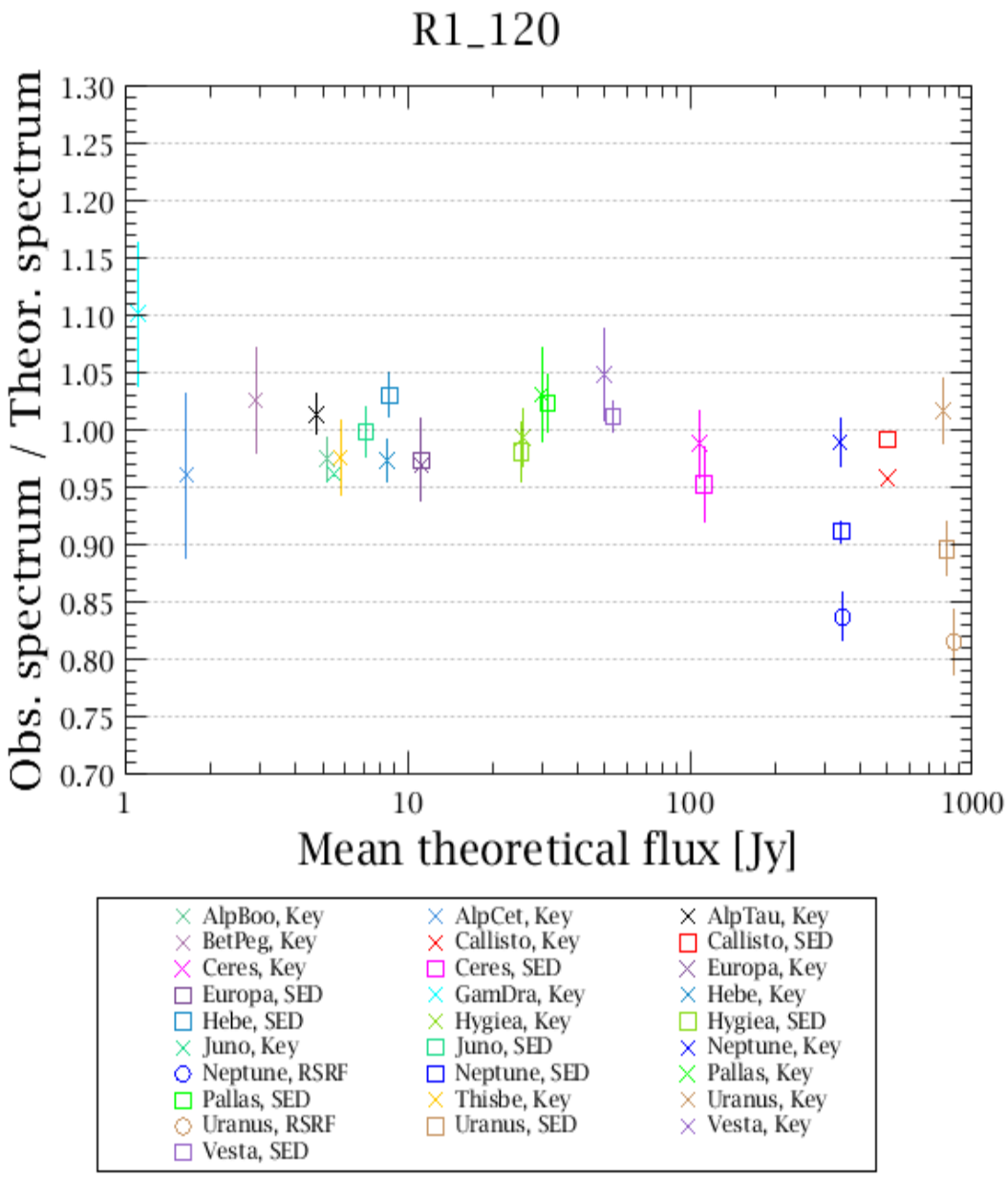
Callisto, SED
Ceres, Key
Ceres, SED
Europa, Key
Europa, SED
GamDra, Key
Hebe, Key
Hebe, SED
Hygiea, Key
Hygiea, SED
Juno, Key
Juno, SED
Neptune, Key
Neptune, RSRF
Neptune, SED
Pallas, Key
Pallas, SED
Thisbe, Key
Uranus, Key
Uranus, RSRF
Uranus, SED
Vesta, Key
Vesta, SED

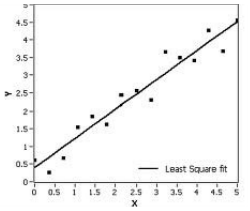
Linearity


Least Square fit
X
Y


R1_120
Obs. spectrum / Theor. spectrum
Mean theoretical flux [Jy]
AlpBoo, Key
BetPeg, Key
Ceres, Key
Europa, SED
Hebe, SED
Juno, Key
Neptune, RSRF
Pallas, SED
Uranus, RSRF
Vesta, SED
AlpCet, Key
Callisto, Key
Ceres, SED
GamDra, Key
Hygiea, Key
Juno, SED
Neptune, SED
Thisbe, Key
Uranus, SED
AlpTau, Key
Callisto, SED
Europa, Key
Hebe, Key
Hygiea, SED
Neptune, Key
Pallas, Key
Uranus, Key
Vesta, Key


R1_120
Obs. spectrum / Theor. spectrum
Mean theoretical flux [Jy]
AlpBoo, Key
BetPeg, Key
Ceres, Key
Europa, SED
Hebe, SED
Juno, Key
Neptune, RSRF
Pallas, SED
Uranus, RSRF
Vesta, SED
AlpCet, Key
Callisto, Key
Ceres, SED
GamDra, Key
Hygiea, Key
Juno, SED
Neptune, SED
Thisbe, Key
Uranus, SED
AlpTau, Key
Callisto, SED
Europa, Key
Hebe, Key
Hygiea, SED
Neptune, Key
Pallas, Key
Uranus, Key
Vesta, Key

Linearity

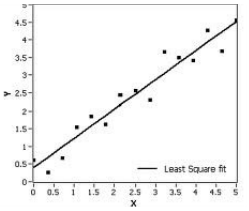


Non-Linearity cannot be excluded > 100Jy (< 10 %)

~ only based on giant planets

- existing indications might also result from
  - other instrumental effects
  - systematic effects from models

Very low fluxes



- For low flux cases (<1 Jy)
  - the absolute flux scale error on the continuum is not driven by signal-flux conversion (in %), but by offsets in telescope background
  - Line-flux not affected
- Recommended approach
  - Process with telescope background normalisation & compare
  - Verify zero level of border spaxels

Conclusions

Conclusions

- Absolute flux calibration, 3x3 : $\lesssim$ 5% RMS, $\lesssim$ 15% peak-to-peak
  - Assumes central/3x3 correction for point sources
  - Improved pointing products will help
  - Uncertainties do not apply for very low fluxes ($\lesssim$ 1 Jy)

- Calblock & Normalization agree within ~10%

- Non-Linearity <100Jy: 0% ; >100Jy: < 10%

Prospects

- Improved spectral shape
  - Improved pointing products
  - Pointing correction (under test)
- De-leaked RSRF for correct line-fluxes > 190 μm *(presentations by Bart & Elena)*

QUESTIONS ?