Concordance: In-Flight Calibration of X-ray Telescopes without Absolute References

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Updates:

1: Added 2 simulations

2: Accepted to AJ; arxiv:2108.13476

The Goal

- The problems
  - Discrepant results from X-ray observatories in orbit
    - Cluster temperatures and fluxes
    - Blazar fluxes from simultaneous observations
    - SNR line fluxes
  - Imperfect ground cal, performance changes in flight
    - Instrument area priors a_i differ from "true values" A_i
  - No absolute calibrators across all bands in flight: no "true" F_j
- Specific task: derive $\hat{A}_i$ for optimal agreement

➡ Let flux $f_{ij} = c_{ij}/T_{ij}/a_i$

where a_i = prior on A_i

c_{ij} = observed counts

T_{ij} = known exposure time

Some Poor Methods

- Use the average flux as the 'true' flux: $F_j = < f_{ij} >$
  - If statistical weighting, answer depends on T_{ij} and a_i
  - If no weighting, then "agnostic" but not stable
  - Problematic statistical inference: $\hat{A}_i = \dfrac{c_{ij}}{T_{ij} F_j}$
- Use one instrument as "given": $F_j = f_{Xj}$ for some X
  - Reference choice is subjective
  - Still problematic statistically

➡ Let flux $f_{ij} = c_{ij} / T_{ij} / a_i$

where a_i = prior on A_i

c_{ij} = observed counts

T_{ij} = known exposure time

Better: Multiplicative Shrinkage

(Chen+ '19, JASA)

$$y_{ij} = B_i + G_j - \frac{\sigma_i^2}{2} + e_{ij} \quad , \quad y_{ij} \equiv \log(c_{ij}/T_{ij}) \quad , \quad B_i \equiv \log A_i \quad , \quad G_j \equiv \log F_j$$

$$\hat{B}_i = W_i(\bar{y}'_{i\cdot} - \bar{G}_i) + (1 - W_i)b_i \quad \text{and} \quad \hat{G}_j = \bar{y}'_{\cdot j} - \bar{B}_j$$

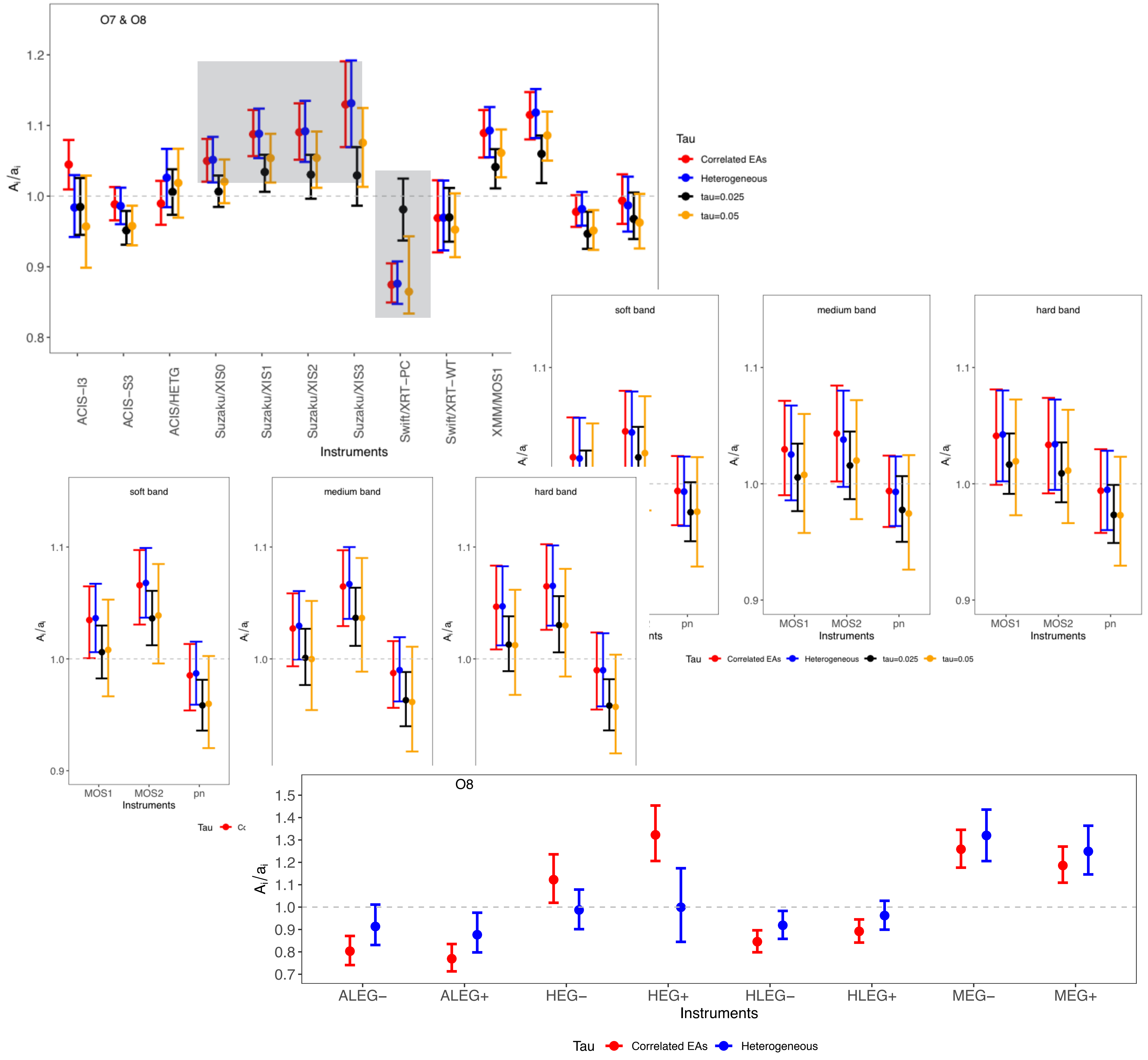
$$\tilde{y}'_{ij} = \tilde{y}_{ij} + 0.5\sigma_i^2 \ , \ \bar{y}'_{i\cdot} = \frac{\sum_{j=1}^{M} \tilde{y}'_{ij}\sigma_i^{-2}}{\sum_{j=1}^{M} \sigma_i^{-2}}, \quad \bar{y}'_{\cdot j} = \frac{\sum_{i=1}^{N} \tilde{y}'_{ij}\sigma_i^{-2}}{\sum_{i=1}^{N} \sigma_i^{-2}}, \quad \bar{G}_i = \frac{\sum_{j=1}^{M} \hat{G}_j\sigma_i^{-2}}{\sum_{j=1}^{M} \sigma_i^{-2}}, \quad \bar{B}_j = \frac{\sum_{i=1}^{N} \hat{B}_i\sigma_i^{-2}}{\sum_{i\in I_j} \sigma_i^{-2}}$$

$$W_i = \frac{M\sigma_i^{-2}}{\tau_i^{-2} + M\sigma_i^{-2}}$$

EA prior uncertainties (τ_i^{-2}) — Data uncertainties ($M\sigma_i^{-2}$)

Concordance Results

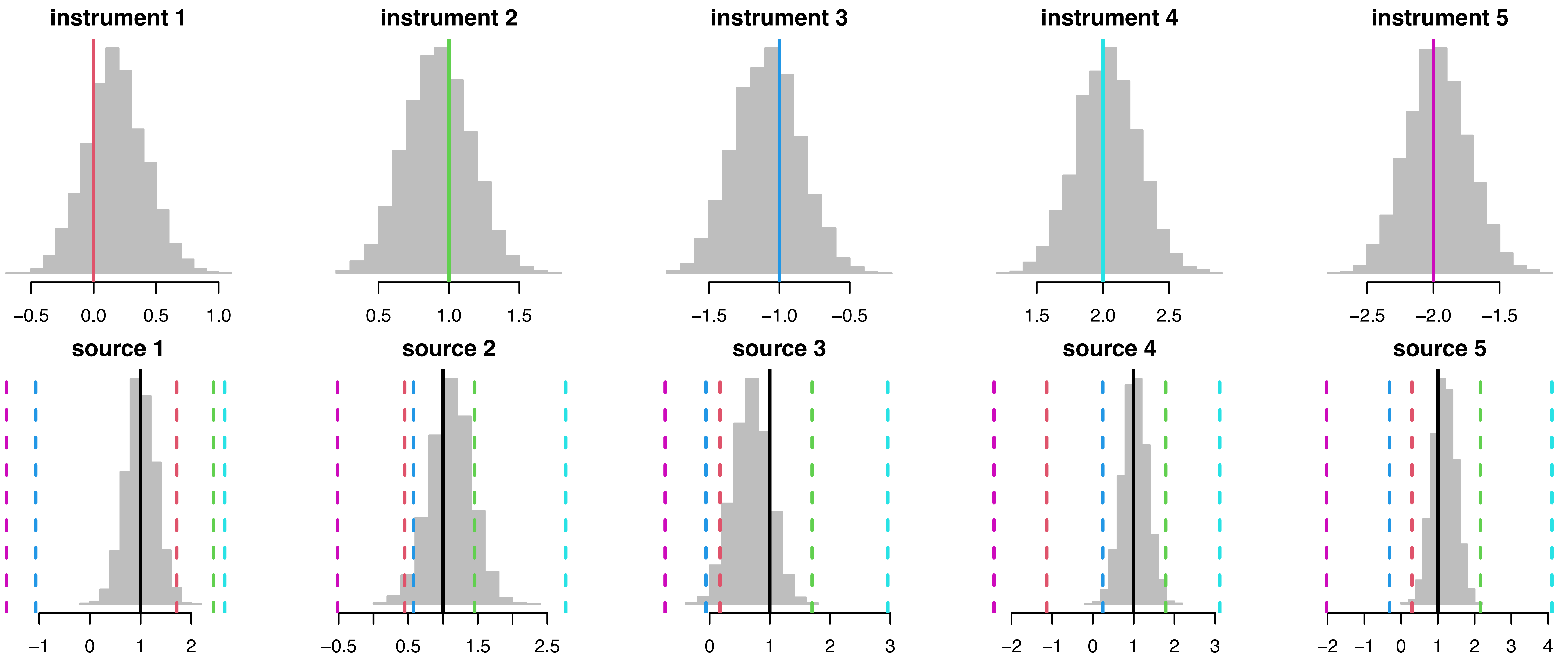
- SNR 1E0102: Correlations change results, tau values matter
- 2XMM sample: slight changes when taus are assigned
- XCAL: same as 2XMM
- Capella, Chandra TGs: ±1 orders agree, LETG is low of HETG



Validation Simulation 1

- 5 Instruments, $\log A_i/a_i$ = [0, 1, -1, 2, -2], τ=1
- 40 sources, $\sigma_i = [0.5,0.5,0.5,0.5,0.1]$ (on $\log f_{ij}$)

- Concordance: unbiased A posteriors, good F posteriors
- Ratio estimates: wide flux ranges



Validation Simulation 2

- 3 instruments, 20 sources, 3% stats, A_i/a_i = [1.0,1.0,0.9]
- Sim 1: poor flux error range coverage but good with Concordance

- Sim 2: same setup but 0.3% stats for $i = 3$
- Concordance is still good
- Ratio estimator ranges don't cover true fluxes

Table 7. Results from Two Concordance Simulations

Simulation Setup[a]	Flux Estimation Method	95% Flux Range[b] F_{lo}	F_{hi}	r_{95}[c]
1	Concordance	0.903	1.033	0.964
1	Ratio Estimator	0.927	0.994	0.372
2	Concordance	0.905	1.031	0.990
2	Ratio Estimator	0.896	0.907	0.000

Conclusions

- We can bring observations into Concordance
- Simple situations give reasonable answers: consistent with other analyses
- Possible improvements
  - Outliers handled with t distribution
  - Fluxes in bands are related globally, not independent
  - Instrument areas are time-dependent