Reducing the impact of source structure on the celestial frame: modeling or mitigation strategies?

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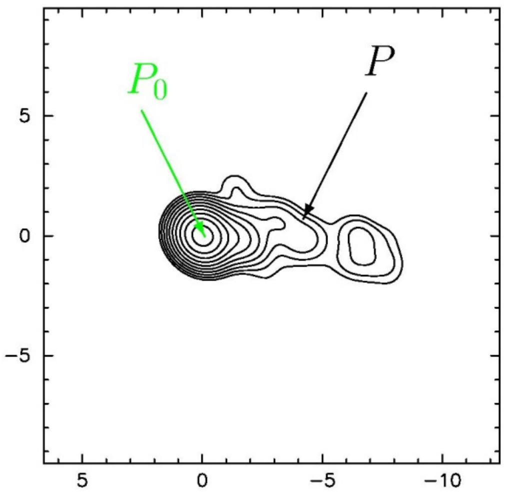
Outline

- Modeling source structure
  - Theory
  - Requirements in practice
- Mitigation strategies
  - Structure indices
- The Bordeaux VLBI Image Database (BVID)
  - Time series of structure indices
- Future plans

Theoretical modeling

Source map



Brightness distribution

$$I = I(P,\omega,t)$$

Total Flux

$$S = \iint_{\Omega_s} I(P,\omega,t)$$

Complex visibility

$$V = \iint_{\Omega_s} I(P,\omega,t)\exp\left(-\frac{i\omega}{c}\vec{B}.\vec{k_P}\right)d\Omega \qquad \vec{k_P} = \vec{k_{P_0}} + \vec{P_0P}$$

$$= \exp\left(-\frac{i\omega}{c}\vec{B}.\vec{k_{P_0}}\right) \times \iint_{\Omega_s} I(P,\omega,t)\exp\left(-\frac{i\omega}{c}\vec{B}.\vec{P_0P}\right)d\Omega$$

$$= A\exp(i\phi)$$

$$\Longrightarrow \quad A = \left|\iint_{\Omega_s} I(P,\omega,t)\exp\left(-\frac{i\omega}{c}\vec{B}.\vec{P_0P}\right)d\Omega\right|$$

$$\Longrightarrow \quad \phi = -\frac{\omega}{c}\vec{B}.\vec{k_{P_0}} + \arg\left[\iint_{\Omega_s} I(P,\omega,t)\exp\left(-\frac{i\omega}{c}\vec{B}.\vec{P_0P}\right)d\Omega\right]$$

$$= \quad \phi_{\mathrm{geom}}\left(\vec{B},P_0\right) \quad + \quad \phi_{\mathrm{struc}}\left(\vec{B},I,P_0\right)$$

VLBI delay

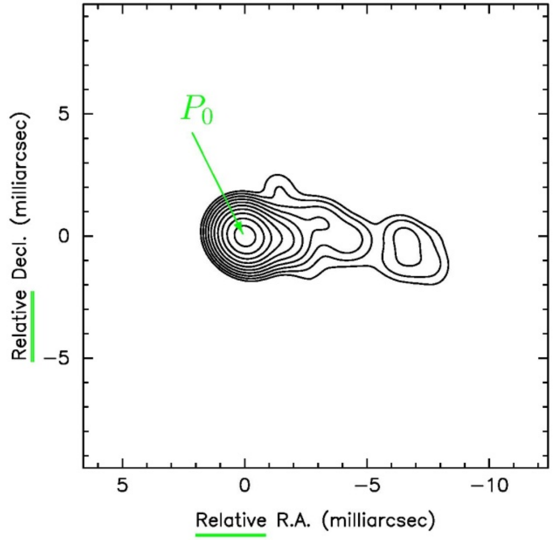
$$\tau = \frac{\partial\phi}{\partial\omega} = -\frac{1}{c}\vec{B}.\vec{k_{P_0}} + \frac{\partial\phi_{\mathrm{struc}}}{\partial\omega}$$

$$= \quad \tau_{\mathrm{geom}}\left(\vec{B},P_0\right) \quad + \quad \tau_{\mathrm{struc}}\left(\vec{B},I,P_0\right)$$

Requirements for modeling (1)

Single-epoch observations

- Knowledge of brightness distribution



- Choice of reference point P_0 ➔ arbitrary

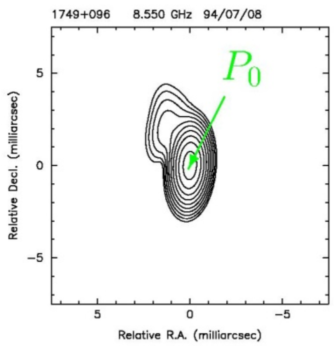
  No influence on VLBI delay residuals but estimated source coordinates will be different

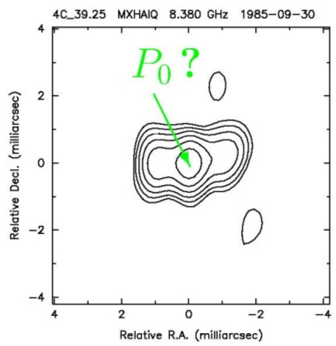
Requirements for modeling (2)

Multi-epoch observations

- Alignment of maps ➔ based on a priori physical considerations
- Choice of reference point P_0 ➔ well identified feature in all images

Epoch 1



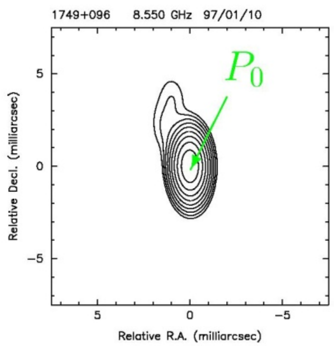


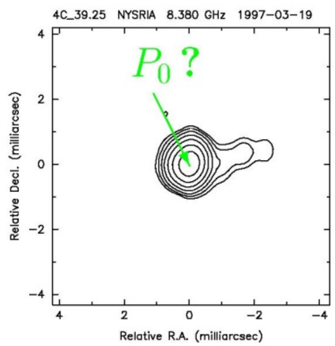
Epoch 1

core-jet source

complex source

Epoch 2





Epoch 2

Plausible

?

Requirements for modeling (3)

Dual-frequency S/X observations

$$\tau_{\text{struc}} = a\ \tau_{\text{strucX}} + b\ \tau_{\text{strucS}}$$

$$a = \frac{\omega_X^2}{\omega_X^2 - \omega_S^2}\ , \qquad b = \frac{-\omega_S^2}{\omega_X^2 - \omega_S^2}$$

$\tau_{\text{strucS}} =$ structure delay at S band

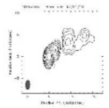
$\tau_{\text{strucX}} =$ structure delay at X band

$(\omega_S = 2.3\ \text{GHz},\ \omega_X = 8.4\ \text{GHz})$

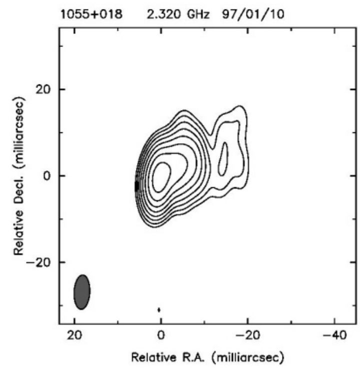
Needs alignment of maps + consistent choice of reference point at S band and X band

➔ a priori critical but errors are reduced by a factor of 13 (a/b ~ 13 for S/X observations)

X band



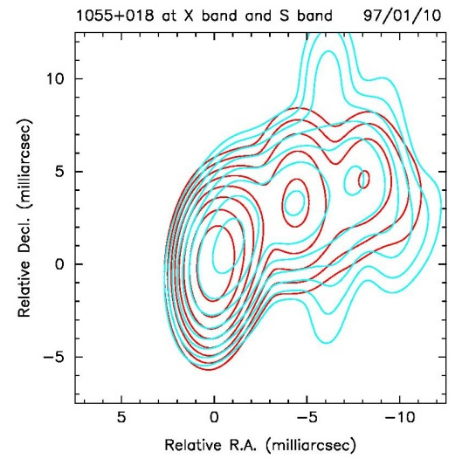
S band



?

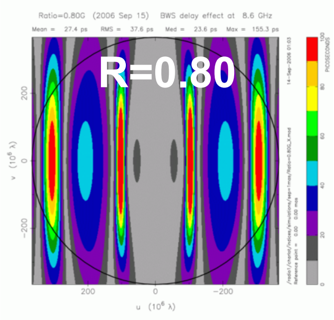
$\Longrightarrow$

Superimposed X- and S-band maps at intermediate resolution

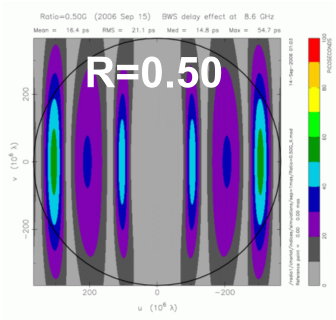


Case of a two-component source

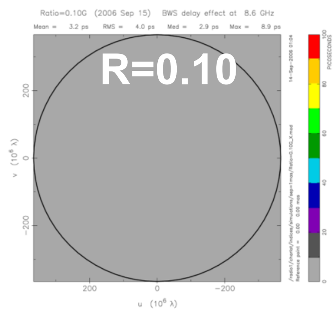
- Two components separated by 1 mas (flux ratio R, FWHM=0.0,0.3)



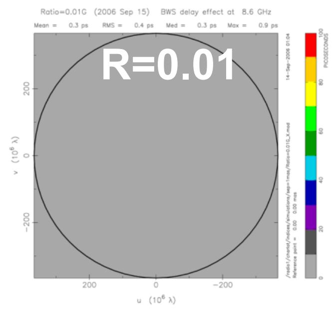
Max= 155 ps



Max= 55 ps

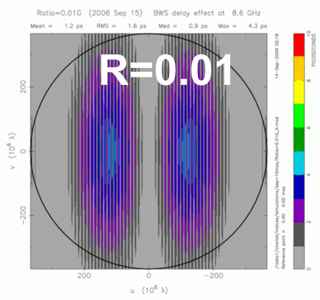


Max= 8.9 ps

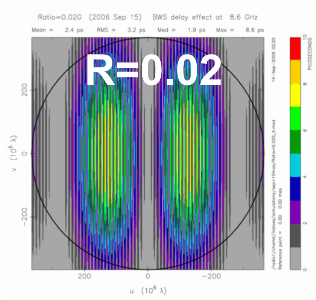


Max= 0.9 ps

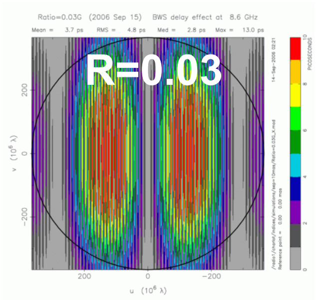
- 1 weak component (1-3%) 10 mas away from the core



Max= 4.3 ps



Max= 8.6 ps



Max= 13 ps

→ Needs high dynamic range
→ Must be at the right epoch

If not high dynamic range or not at the right epoch, it is best NOT to correct for structure, otherwise it may make things worse…

Structure corrections not useful if…

- You do not have high dynamic range maps at the proper epochs
- You are not able to identify and locate accurately a compact feature (source core) that is stable over time
  - misalignement directly translates into source position errors from epoch to epoch…
  - a few 10s of μas accuracy desirable
- You are not able to properly register the S and X band maps at the sub-mas level
  - not so easy because of difference in resolution and opacity problems…

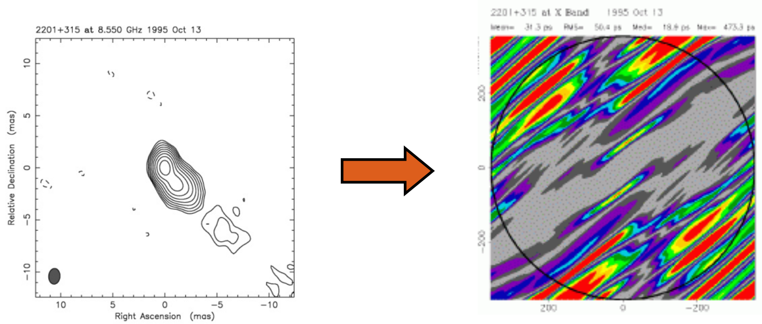
Additional complication: structure corrections biased if data are missing in one or several IF and you do not know it.

One cannot mix data with/without corrections (source positions different)

Mitigation strategies

- Require VLBI images of the sources to assess magnitude of structure effects
- <u>Basic approach</u>: calculation of structure index (SI)

$$\mathbf{SI=1+2\log\tau_{median}} \quad (\text{if } \tau \geq 0.316 \text{ ps})$$
$$\mathbf{SI=0} \quad (\text{if } \tau < 0.316 \text{ ps})$$

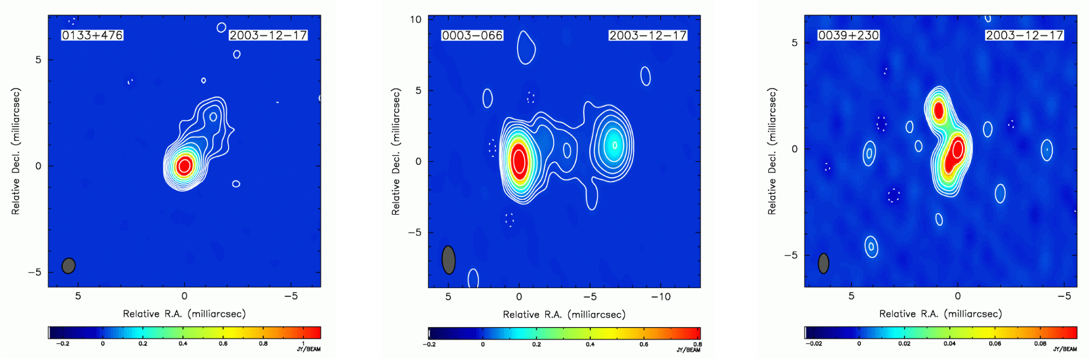


- <u>More sophisticated</u>: includes knowledge of schedule to predict effects on actual observations
  - e.g. observe only with baselines orthogonal to the structure?

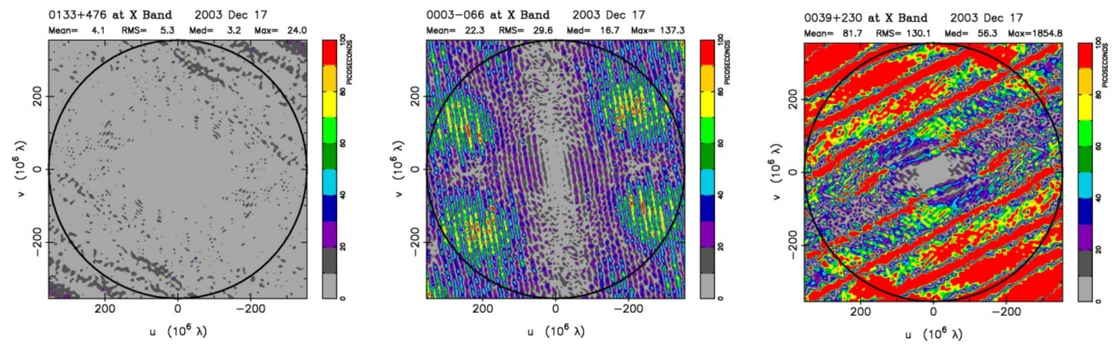
The Bordeaux VLBI Image Database

4007 images for 1170 different sources

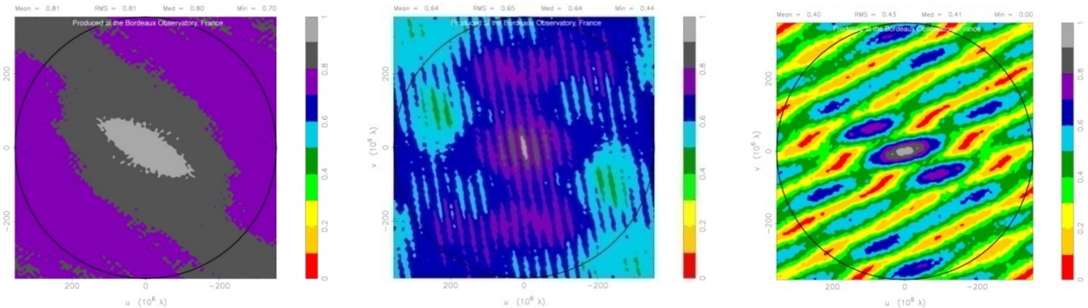
(+ links to 6775 USNO maps)



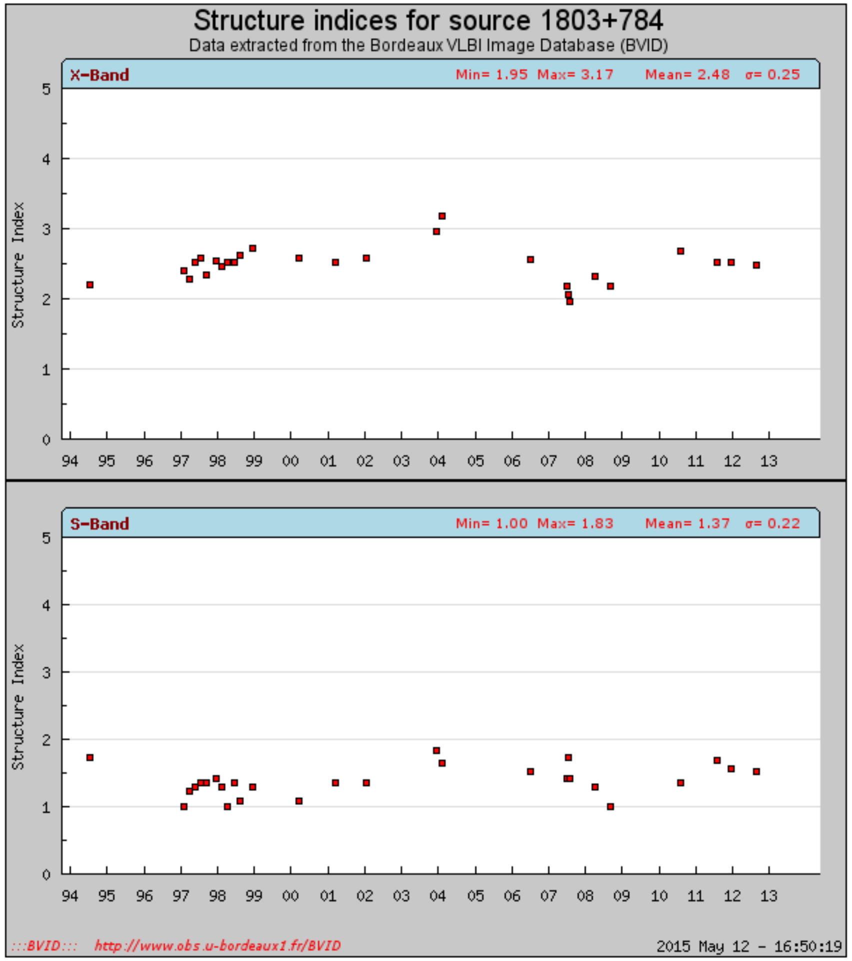
10572 structure correction maps + structure indices

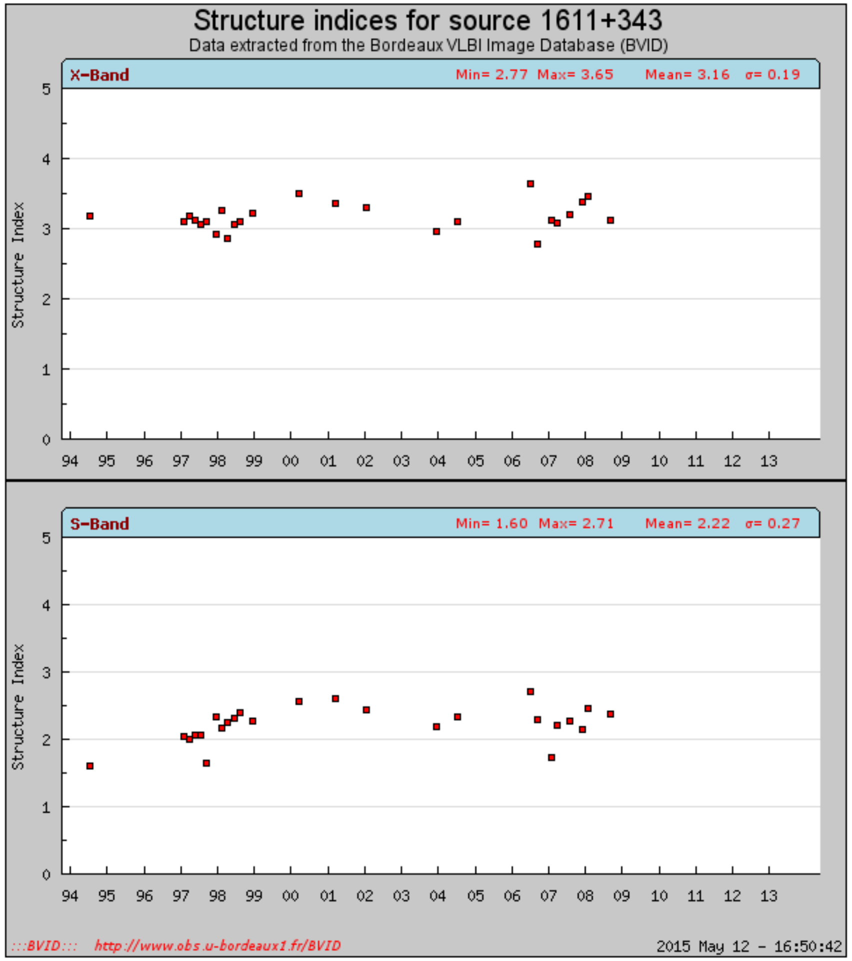


10572 visibility maps + values of compactness

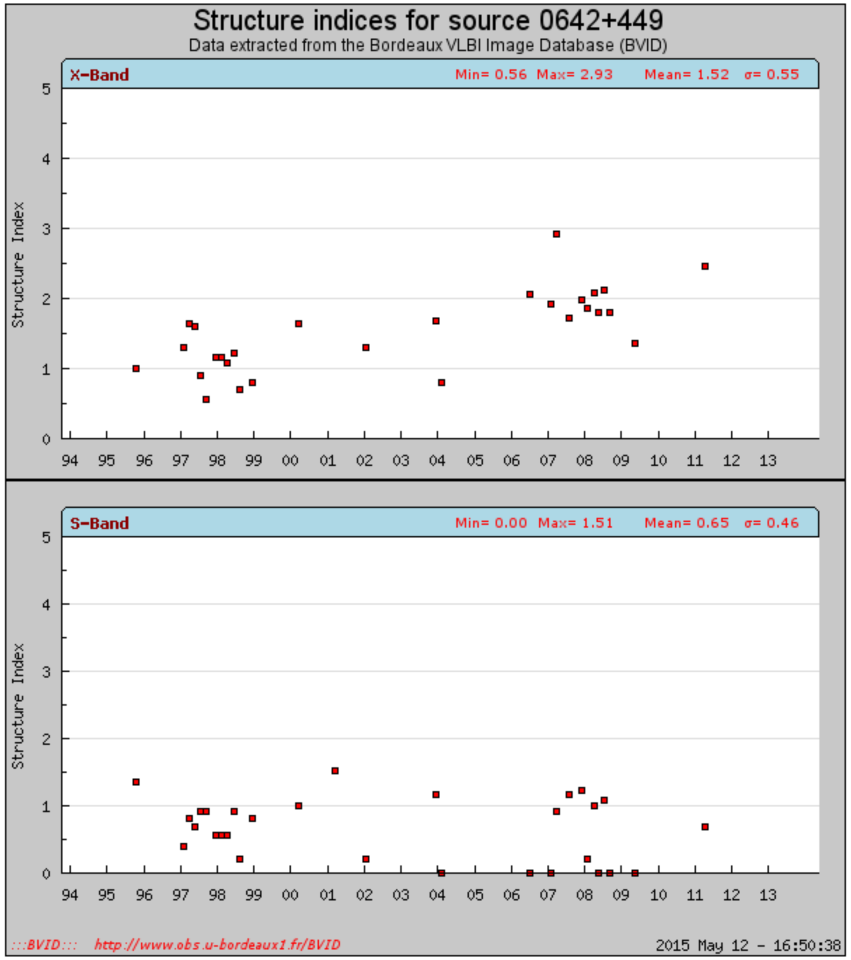


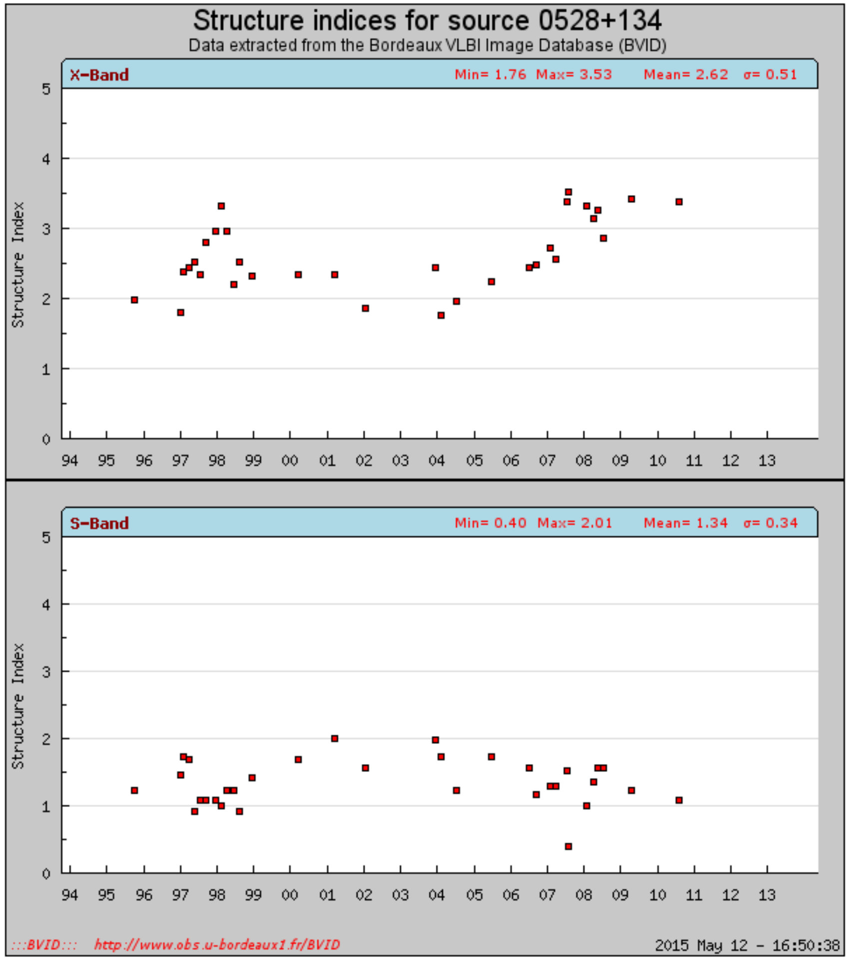
Structure index series (1)



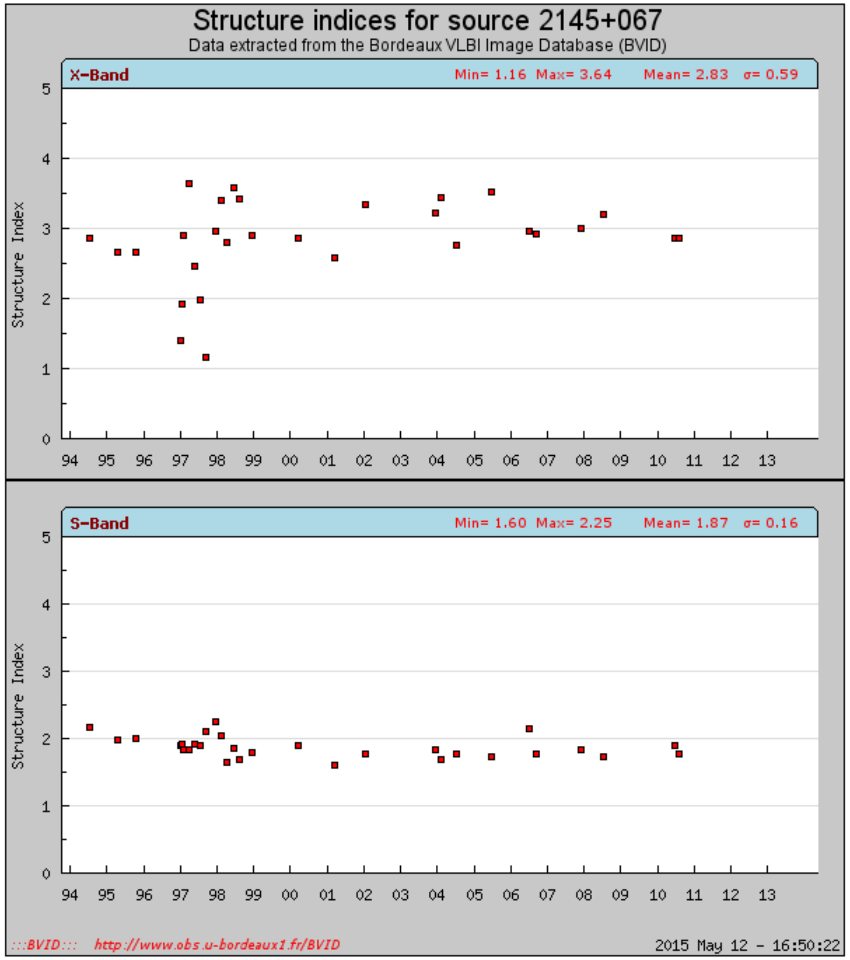


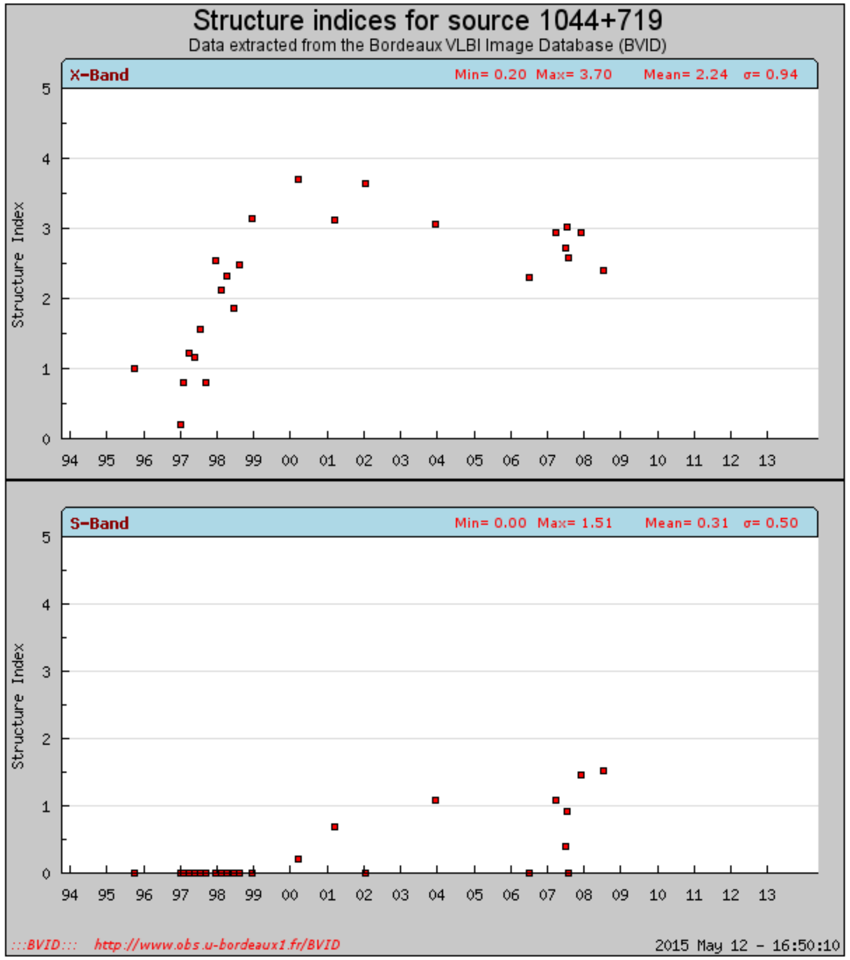
Structure index series (2)





Structure index series (3)





Future plans

- Extend calculations to VCS sources (I & II)
- New functionalities and a new user interface will be implemented for BVID in the future
- VGOS prospects: continuous observing + use of a large network may permit monitoring of the sources on short time scales, potentially offering possibility to correct for structure.