Bivariate long-range dependent time series models with general phase

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Recent developments in statistics for complex dependent data
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Outline

1. Motivation from real data of U.S. inflation rates
2. Definitions and models for bivariate long-range dependent (LRD) time series
3. New parametric bivariate LRD model with general phase and estimation
4. Application to U.S. inflation rates

The talk is based on: Kechagias, S. and Pipiras, V. (2015a), ‘A bivariate long-range dependent time series model with general phase’, *Preprint*.

Motivation from real data

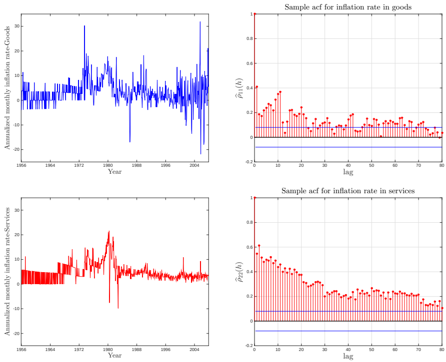

Figure: *Annualized monthly U.S. inflation rates for goods (top) and services (bottom) from February 1956 to January 2008.*

- Slow decay of the two acfs suggests LRD.
- Services inflation appears to have stronger LRD than goods inflation.

Motivation from real data

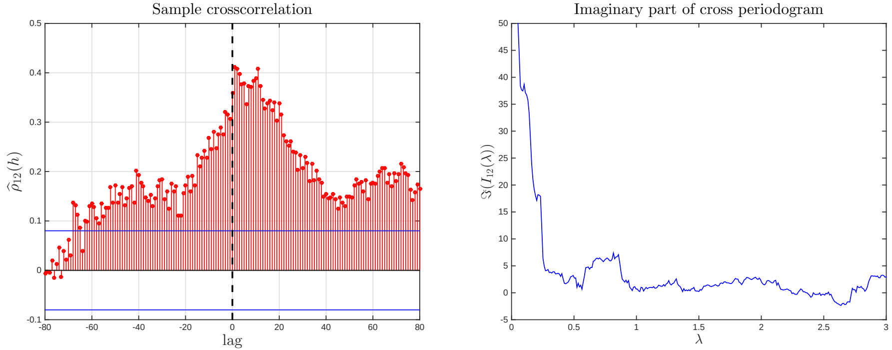

Figure: *Left: Sample crosscorrelation function of U.S. inflation rates in goods and services. Right: Imaginary part of cross periodogram.*

- Note asymmetry in crosscorrelation of the bivariate time series (for large lags), also reflected in $\Im(I_{12}(\lambda)) \neq 0$ (for λ close to 0)
- Bivariate LRD models that allow for general asymmetric behavior?

Definitions of bivariate LRD series

A bivariate stationary time series $\{X_n\}_{n\in\mathbb{Z}}=\{(X_{1,n},X_{2,n})'\}_{n\in\mathbb{Z}}$ is LRD if, for the so-called LRD parameters $d_1, d_2 \in (0,1/2)$,[1]

Time domain: As $h \to \infty$, its autocovariance matrix $\gamma(h)$ satisfies

$$\gamma(h) = \begin{pmatrix} \gamma_{11}(h) & \gamma_{12}(h) \\ \gamma_{21}(h) & \gamma_{22}(h) \end{pmatrix} \sim \begin{pmatrix} R_{11} h^{2d_1-1} & R_{12} h^{d_{12}-1} \\ R_{21} h^{d_{12}-1} & R_{22} h^{2d_2-1} \end{pmatrix},$$

where $d_{12} = d_1 + d_2$ and $R = (R_{jk})_{j,k=1,2}$ is some 2×2 real matrix.

Spectral domain: As $\lambda \to 0^+$, its spectral density matrix $f(\lambda)$ satisfies

$$f(\lambda) = \begin{pmatrix} f_{11}(\lambda) & f_{12}(\lambda) \\ f_{21}(\lambda) & f_{22}(\lambda) \end{pmatrix} \sim \begin{pmatrix} g_{11}\lambda^{-2d_1} & g_{12}e^{i\phi}\lambda^{-d_{12}} \\ g_{12}e^{-i\phi}\lambda^{-d_{12}} & g_{22}\lambda^{-2d_2} \end{pmatrix},$$

where $g_{11}, g_{12}, g_{22} \in \mathbb{R}$ and the phase parameter $\phi \in (-\pi, \pi]$.

Note: The spectral domain definition has 6 parameters.

[1] Robinson (2008), AoS; Kechagias and Pipiras (2015b), JTSA

Definitions of bivariate LRD series

Remark 1: The phase parameter is unique to LRD. Indeed, for *short-range dependent* (SRD) series $f(\lambda) = (2\pi)^{-1} \sum_{h=-\infty}^{\infty} e^{-ih\lambda}\gamma(n)$ and $f(0) = (2\pi)^{-1} \sum_{h=-\infty}^{\infty} \gamma(h)$ has real entries.

Remark 2: Under mild assumptions (and letting $G_{12} = g_{12}e^{i\phi}$)

$$f_{12}(\lambda) \underset{\lambda\to 0^+}{\sim} G_{12}\lambda^{-2d_{12}} \quad \Leftrightarrow \quad \gamma_{12}(h) \underset{h\to\infty}{\sim} R_{12}h^{d_{12}-1},$$

with

$$\phi = -\text{atan}\left\{\frac{R_{12} - R_{21}}{R_{12} + R_{21}} \tan\left(\frac{\pi d_{12}}{2}\right)\right\}.$$

Remark 3: $\phi = 0 \Leftrightarrow R_{12} = R_{21}$. This corresponds to $\gamma(h)$ being symmetric at the two tails, that is, $\gamma_{12}(h) \underset{h\to\infty}{\sim} \gamma_{21}(h) = \gamma_{12}(-h)$.

Bivariate LRD models

- A common model for bivariate LRD series is the VARFIMA$(0, D, 0)$ defined as

$$X_n = \begin{pmatrix} X_{1,n} \\ X_{2,n} \end{pmatrix} = \begin{pmatrix} (I-B)^{-d_1}\eta_{1,n} \\ (I-B)^{-d_2}\eta_{2,n} \end{pmatrix} = (I-B)^{-D}\eta_n = (I-B)^{-D}Q_+\epsilon_n,$$

  where $D = \mathrm{diag}(d_1, d_2)$, $\{\eta_n\} \sim \mathrm{WN}(0, \Sigma)$, $\Sigma = Q_+Q_+'$ and $\{\epsilon_n\} \sim \mathrm{WN}(0, I)$.

- **Fact:** The spectral density matrix of the VARFIMA series above satisfies

$$f(\lambda) \sim \begin{pmatrix} g_{11}\lambda^{-2d_1} & g_{12}e^{-i\phi}\lambda^{-d_{12}} \\ g_{12}e^{i\phi}\lambda^{-d_{12}} & g_{22}\lambda^{-2d_2} \end{pmatrix}, \quad \text{as} \quad \lambda \to 0^+,$$

  with the special phase parameter $\phi = \frac{\pi}{2}(d_1 - d_2)$.

Question: *Can one define a bivariate LRD model that allows for general phase parameter? Would it make any difference (e.g. in prediction)?*

Bivariate LRD models

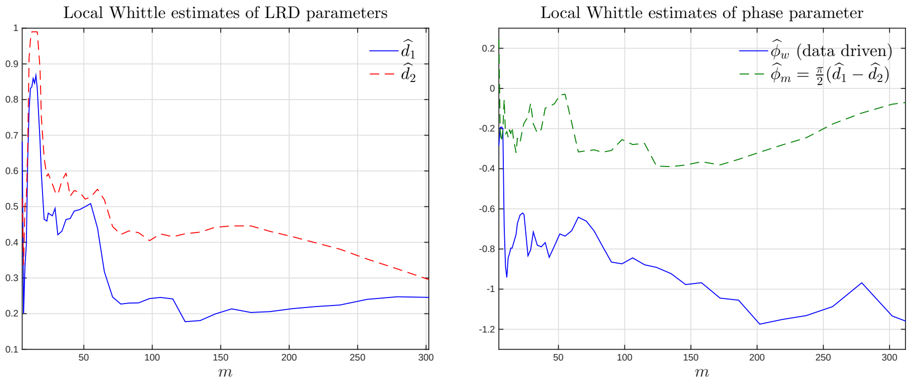

Figure: Left: Local Whittle estimates of d_1, d_2 for the inflation data plotted as functions of a tuning parameter $m = N^{0.25}, \ldots, N^{0.9}$, where N is the sample size. Right: Local Whittle phase estimates, one corresponding to the VARFIMA (dashed line) and one estimated directly from the data (solid line).

1-sided VARFIMA$(0, D, 0)$

- The VARFIMA$(0, D, 0)$ series $X_n = (I - B)^{-D} Q_+ \epsilon_n$ has a *1-sided* linear representation of the form

$$X_n = \sum_{m \in I} \Psi_m \epsilon_{n-m},$$

where $I = \mathbb{Z}^+$, $\{\epsilon_n\} \sim WN(0, I)$ and the entries $(\psi_{jk,m})_{j,k=1,2}$ of $\{\Psi_m\}_{m \in I}$ have a power-law behavior

$$\psi_{jk,m} \underset{m \to \infty}{\sim} \alpha_{jk}^{+} |m|^{d_j - 1}, \quad \text{for some} \quad \alpha_{jk}^{+} \in \mathbb{R}.$$

- **Fact:** The 1-sided bivariate series with power-law coefficients always have the special phase $\phi = \frac{\pi}{2}(d_1 - d_2)$.

Question: *How can one modify the 1-sided series with power-law coefficients to obtain a series with general phase?*

General phase LRD models

- **Result 1:** A bivariate LRD series with general phase can be constructed by taking the index $I = \mathbb{Z}$ and coefficients $\psi_{jk,m}$ having different power-law behaviors as $m \to \infty$ and $m \to -\infty$ (2-sided series).

- **Result 2:** A 1-sided bivariate LRD series with general phase can be constructed by taking *trigonometric power-law* coefficients

$$\psi_{jk,m} = \alpha_{jk} m^{-b_j} \cos(2\pi m^a) + \beta_{jk} m^{-b_j} \sin(2\pi m^a), \quad m \geq 0,$$

where $\alpha_{jk}, \beta_{jk} \in \mathbb{R}$, $0 < a < 1$, $\frac{1}{2} < b_j \leq 1 - \frac{1}{2}a$, $j = 1, 2$.

Question: *What about a parametric 2-sided bivariate LRD model with general phase?*

2-sided VARFIMA$(0, D, 0)$

- Define the bivariate 2-sided VARFIMA$(0, D, 0)$ series as

$$X_n = \left((I - B)^{-D} Q_+ + (I - B^{-1})^{-D} Q_-\right) \epsilon_n,$$

where Q_+, Q_- are two real-valued 2×2 matrices.

- **Result 3:** The 2-sided VARFIMA$(0, D, 0)$ series can have a general phase. Moreover, its autocovariance function has an explicit form.

- The 2-sided VARFIMA$(0, D, 0)$ series has 10 parameters. This causes identifiability problems as the same ϕ can be obtained by more than one choice of Q_+, Q_-.

2-sided VARFIMA$(0, D, 0)$

- Taking $\{\eta_n\} \sim WN(0, \Sigma)$ with $\Sigma = Q_+ Q_+'$, and

$$Q_- = CQ_+, \quad C = \begin{pmatrix} c & 0 \\ 0 & -c \end{pmatrix},$$

leads to the 2-sided VARFIMA$(0, D, 0)$ series

$$X_n = \Delta_c(B)^{-1}\eta_n,$$
$$\Delta_c(B)^{-1} = (I - B)^{-D} + (I - B^{-1})^{-D} C.$$

- **Result 4:** For any $\phi_c \in (-\pi/2, \pi/2)$, $\exists!$ $c \in (-1, 1)$ such that X_n has the phase parameter $\phi = \phi_c$. Moreover, c has a closed form given by

$$c = \frac{2(a_1 + a_2) - \sqrt{\Delta}}{2(a_1 - a_2 - \tan(\phi_c))(1 + a_1 a_2)},$$

where $a_k = \tan\left(\frac{\pi d_k}{2}\right)$ and $\Delta = 16 a_1 a_2 + 4(1 + a_1 a_2)^2 \tan^2(\phi_c)$.

Models with SRD components

- Define the 2-sided VARFIMA$(0, D, q)$ series as

$$Y_n = \Delta_c(B)^{-1}\Theta(B)\eta_n, \qquad [= \Theta(B)\Delta_c(B)^{-1}\eta_n]$$

where $\Theta(B) = I_2 + \Theta_1 B + \ldots + \Theta_q B^q$ is the MA matrix polynomial.

- **Result 5:** The autocovariance matrix function of the 2-sided VARFIMA$(0, D, q)$ series has an explicit form.

- **Remark 5:** 2-sided VARFIMA$(0, D, q)$ series has a general phase, and is identifiable.

Models with SRD components

- Define the 2-sided VARFIMA(p, D, q) and FIVARMA(p, D, q) series as

$$
\begin{aligned}
\Phi(B)X_n &= \Delta_c(B)^{-1}\Theta(B)\eta_n, \qquad [= \Theta(B)\Delta_c(B)^{-1}\eta_n] \\
\Phi(B)\Delta_c(B)X_n &= \Theta(B)\eta_n,
\end{aligned}
$$

  where $\Phi(B) = I - \Phi_1 B - \ldots - \Phi_p B^p$ is the AR polynomial.
- **Remark 6:** 2-sided FIVARMA(p, D, q) has a general phase parameter, and is identifiable if the same VARMA(p, q) model is also identifiable.

- Focus on models with diagonal Φ:
  - Motivation from VARMA literature
  - FIVARMA series can be written as VARFIMA series with diagonal Φ
  - If Φ is nondiagonal, VARFIMA(p, D, q) can be thought to exhibit a form of *fractional cointegration*

CLDL algorithm for 2-sided VARFIMA(p, D, q)

Let $\theta = (d_1, d_2, c, U, \Theta')'$.[2] Write the VARFIMA$(p, D, q)$ series as

$$\Phi(B)X_n = Y_n, \qquad Y_n = \Delta_c(B)^{-1}\Theta(B)\eta_n.$$

The likelihood function of $\{Y_n\}_{n=p+1,\dots,N}$ conditional on $X_1, \dots, X_p$, Φ is

$$L(\Phi, \theta; X_n | X_1, \dots, X_p) \equiv L(\theta; \Phi(B)X_n), \quad n = p+1, \dots, N.$$

The conditional likelihood estimators of Φ and θ are then given by

$$(\widehat{\Phi}, \widehat{\theta}) = \underset{\Phi, \theta \in S}{\operatorname{argmax}}\ L(\Phi, \theta; X_n | X_1, \dots, X_p),$$

where $S = \{\theta : 0 < d_1, d_2 < 0.5,\ -1 < c < 1\}$ denotes the parameter space for θ. For fixed Φ, the likelihood is computed through the multivariate Durbin-Levinson algorithm. (Tsay, 2010)

[2] $\Sigma = U'U$, where U is upper triangular

Simulation-VARFIMA$(0, D, 0)$

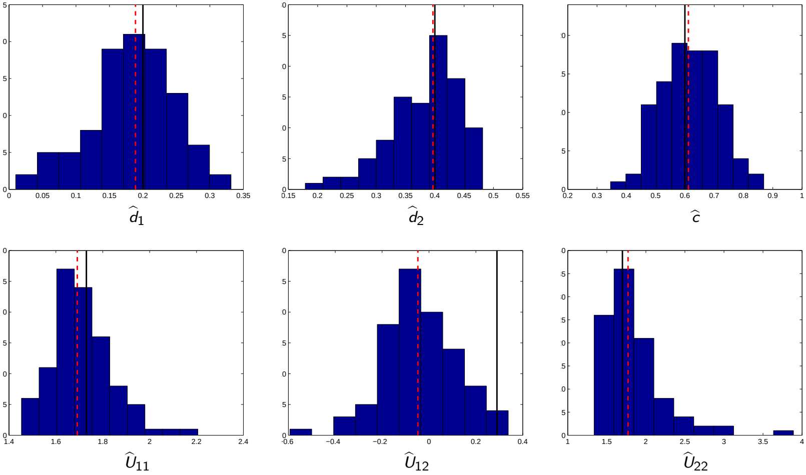

Figure: Sample size $N = 200$, 100 replications. Dotted lines indicate median over all replications while black lines indicate true parameter values.

Application to inflation data

- 1-sided VARFIMA$(1, D, 0)$, Sela 2010

$$
\begin{aligned}
g_t &= 0.30 g_{t-1} + 0.43 s_{t-1} + \eta_{1,t}, \\
s_t &= -0.02 g_{t-1} - 0.31 s_{t-1} + \eta_{2,t},
\end{aligned}
$$

with $\widehat{d}_1 = 0.21, \widehat{d}_2 = 0.48$ and $\widehat{\Delta}_0(B)\eta_t \sim N(0, \widehat{\Sigma}_\eta)$.

- 2-sided VARFIMA$(1, D, 0)$

$$
\begin{aligned}
g_t &= 0.18 g_{t-1} + 0.03 s_{t-1} + e_{1,t}, \\
s_t &= 0.09 g_{t-1} - 0.49 s_{t-1} + e_{2,t},
\end{aligned}
$$

with $\widehat{d}_1 = 0.18, \widehat{d}_2 = 0.36, \widehat{c} = 0.53$ and $\widehat{\Delta}_c(B) e_t \sim N(0, \widehat{\Sigma}_e)$. The corresponding phase estimate is $\widehat{\phi} = -1$.

Application to inflation data

- 2-sided models have smaller AIC and BIC values than 1-sided counterparts
- Models with nondiagonal Φ have smaller AIC and BIC values suggesting fractional cointegration between the two series
- Preliminary results indicate better forecasting performance for 2-sided models, especially for long-range forecast horizons