Clock/TEC separation on long baselines

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Challenges of Long Baselines

- Low sensitivity
- Small field of view
- High ionospheric delays

Challenges of Long Baselines

- Low sensitivity

LOFAR superterp + core stations
- coherently added station signals
- used as single phased array
- reference station

Challenges of Long Baselines

- Low sensitivity
- Small field of view

Need of **calibrator catalogue**
- UV-shift to calibrator necessary
- strong point-like sources
- survey has been proposed

Challenges of Long Baselines

- Low sensitivity
- Small field of view
- High ionospheric delays

- common self calibration not possible

The ionospheric delay

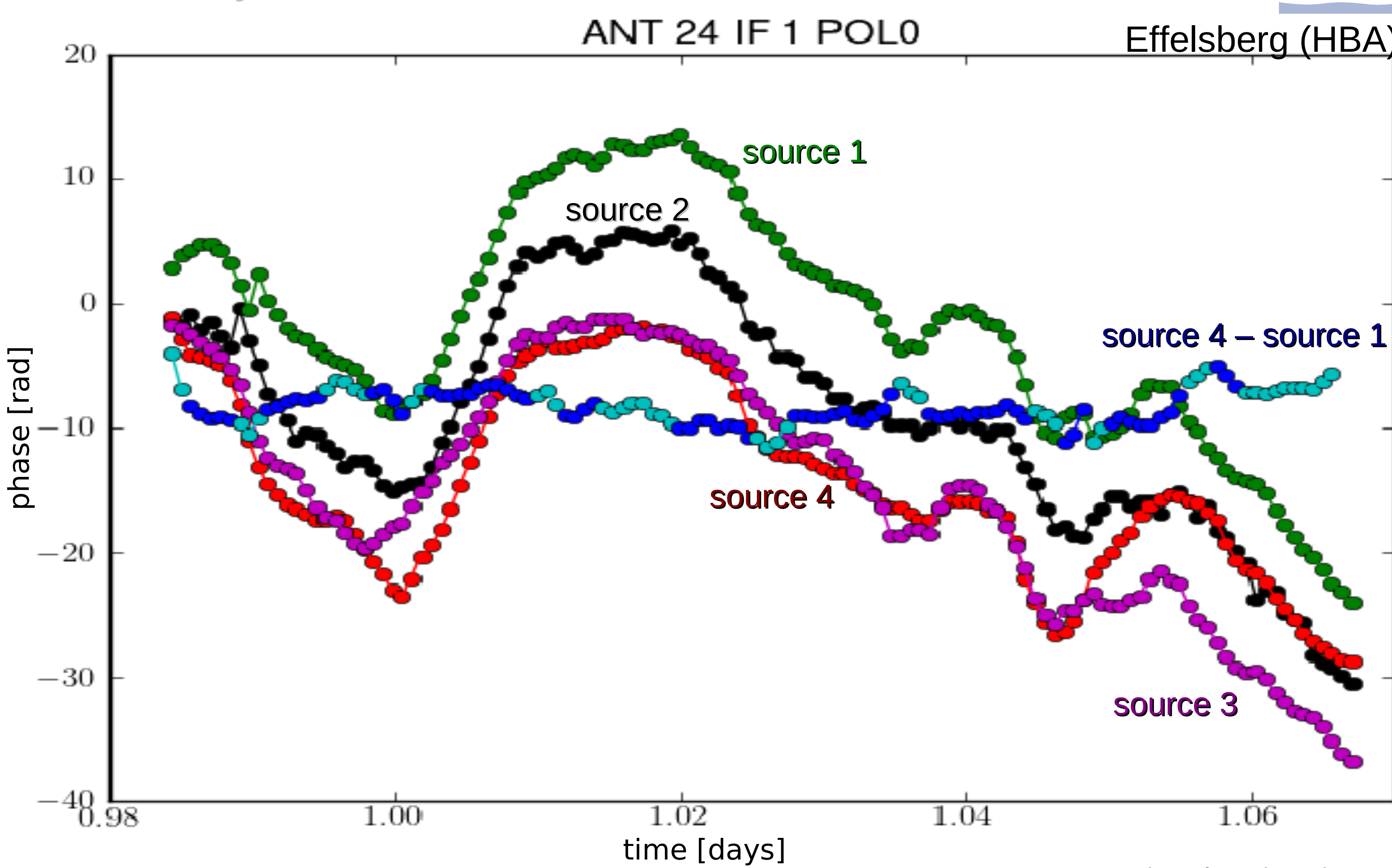
(dispersive delay)

$$\tau_{\text{ion}}(t) := \left[\frac{\partial\phi}{\partial\nu}\right]_{\text{ion}} \propto \Delta\text{TEC}(t)\cdot\nu^{-2}$$

ionospheric delay is caused by the total electron content (**TEC**) of the ionosphere

- typical values @ 150MHz: $\Delta\text{TEC} \approx 1 \triangleq 10^{16}\,\frac{\text{e}^-}{\text{m}^2}$ $\rightarrow$ $\tau_{\text{ion}} \approx 20\ldots100\text{ns}$
- within a frequency range of 3MHz $\rightarrow$ $\Delta\phi \approx 1\text{rad}$
- Ionosphere varies up to several TECs per hour

Delay evolution of different sources in the same field



(Neal Jackson)

The clock issue

- **core** stations have a single clock
- **remote** and **international** stations have their own clock (synchronized via **GPS** signals)

✗ additional delay → $\tau_{\text{clock}} \approx 20 \ldots 100\text{ns}$

✗ clock difference is drifting → $\tau_{\text{clock}} = \tau_{\text{clock}}(t)$

Total delay

$$\boxed{\tau := \tau_{\text{clock}} + \tau_{\text{ion}}}$$

Let's assume we have: $\tau = 150\text{ns}$

$$\longrightarrow \quad \Delta\nu_{\max} \approx \frac{1}{\tau} \approx 6.7\text{MHz}$$

✗ higher delay → decorrelation + **phase wraps**

✗ averaging bandwidth very limited

→ need for seperating **clock** ⇔ **TEC**

trusted source for **delays**

Getting the total delay

- AIPS: **`FRING`**
  - fit also for **rates** $:= \dfrac{\partial \phi}{\partial t}$

    (solutions more stable if significant changes within solint)
  - takes all baselines for fitting (**global fringe-fitting**)
  - solves for delays for each spectral window separately (assuming constant delay within spw)

Getting the total delay

- AIPS: **`FRING`**
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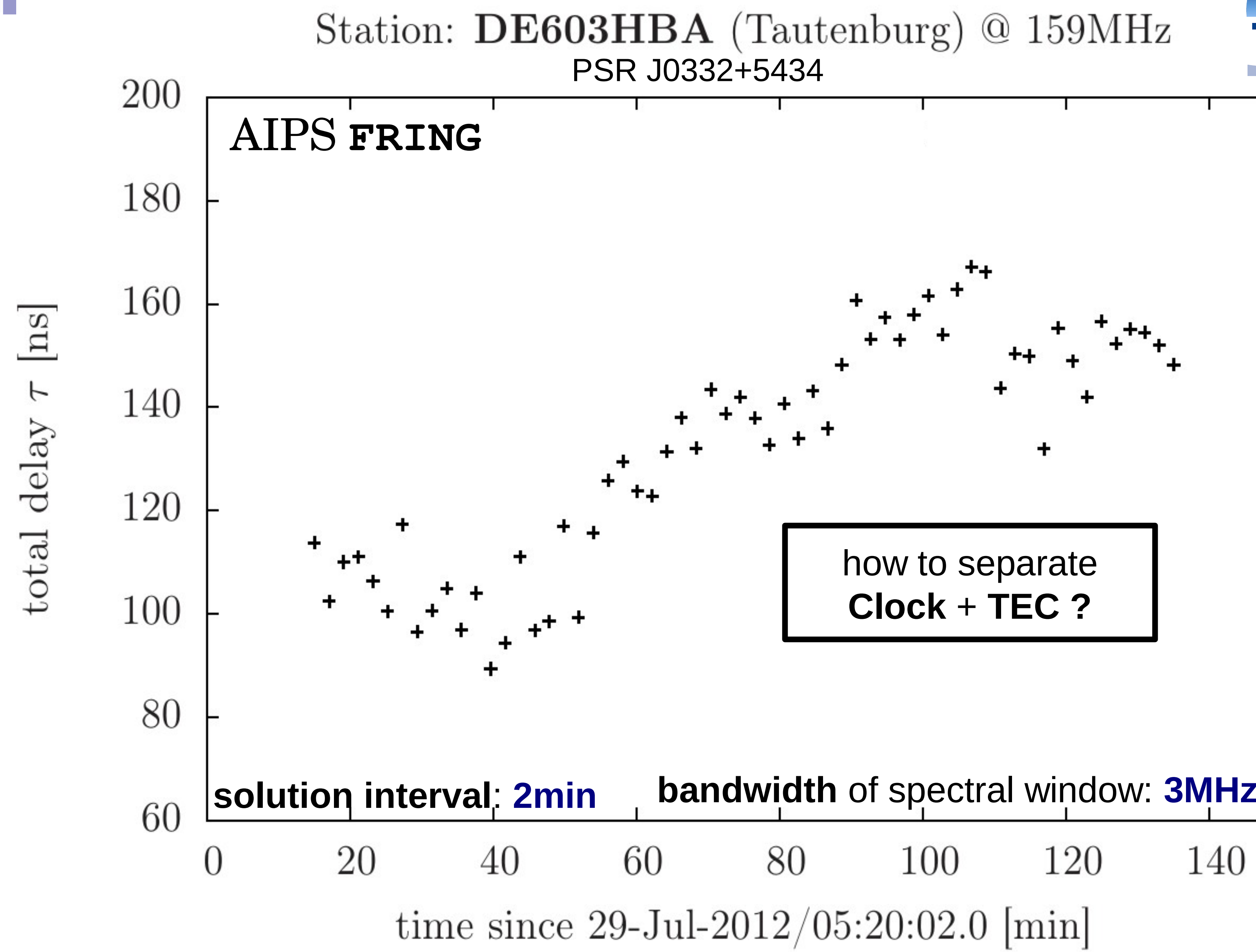
→ **Task in order to get clock + TEC:**
solve for delays at least for three different spectral windows

→ solutions by AIPS serve as an input for a model


Station: DE603HBA (Tautenburg) @ 159MHz
PSR J0332+5434
AIPS FRING
how to separate
Clock + TEC ?
solution interval: 2min
bandwidth of spectral window: 3MHz
total delay τ [ns]
time since 29-Jul-2012/05:20:02.0 [min]
200
180
160
140
120
100
80
60
0
20
40
60
80
100
120
140

The delay model

$$\tau_i(\nu) = a_i \cdot \nu^{-2} + c_i$$

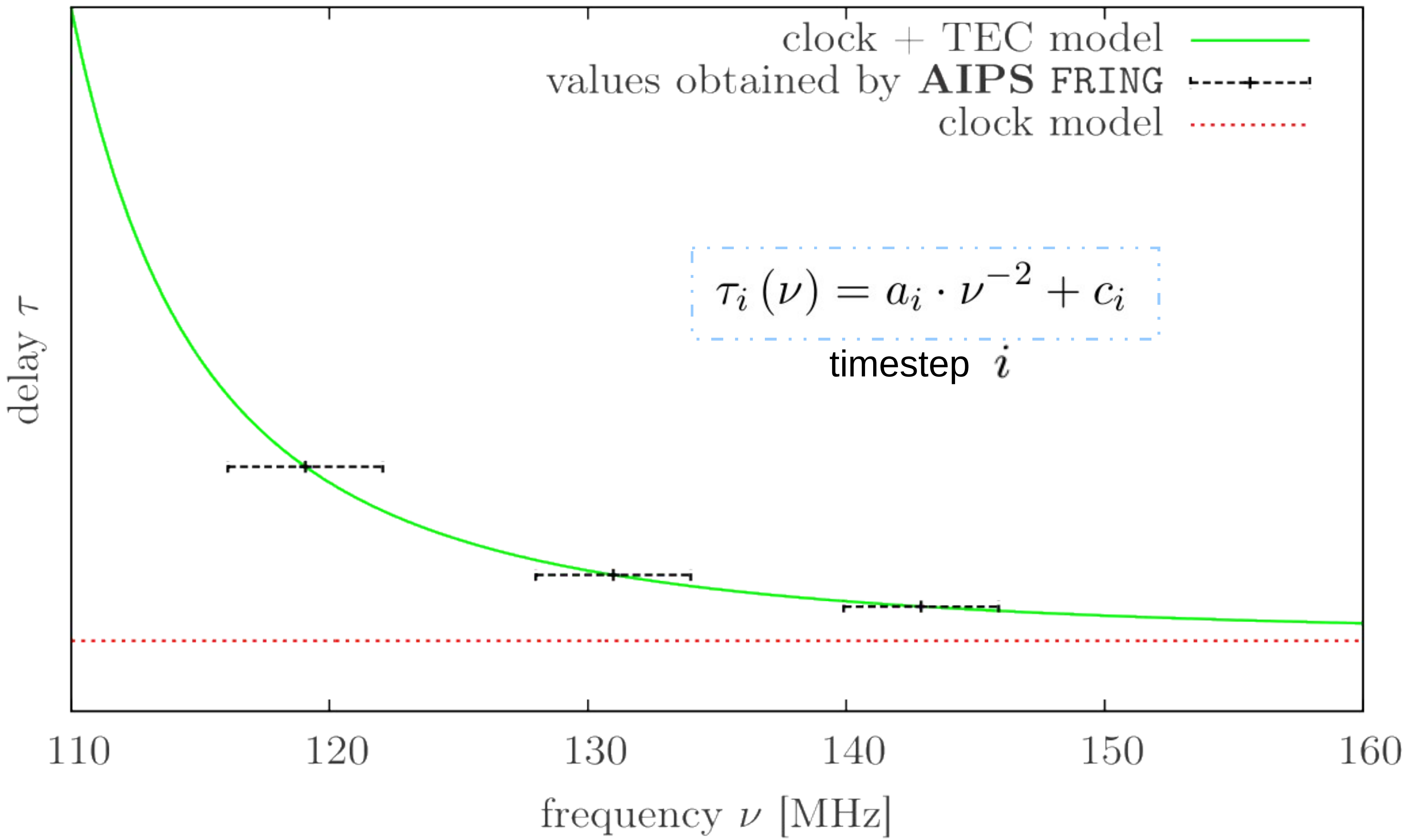
total delay

TEC
(dispersive delay)

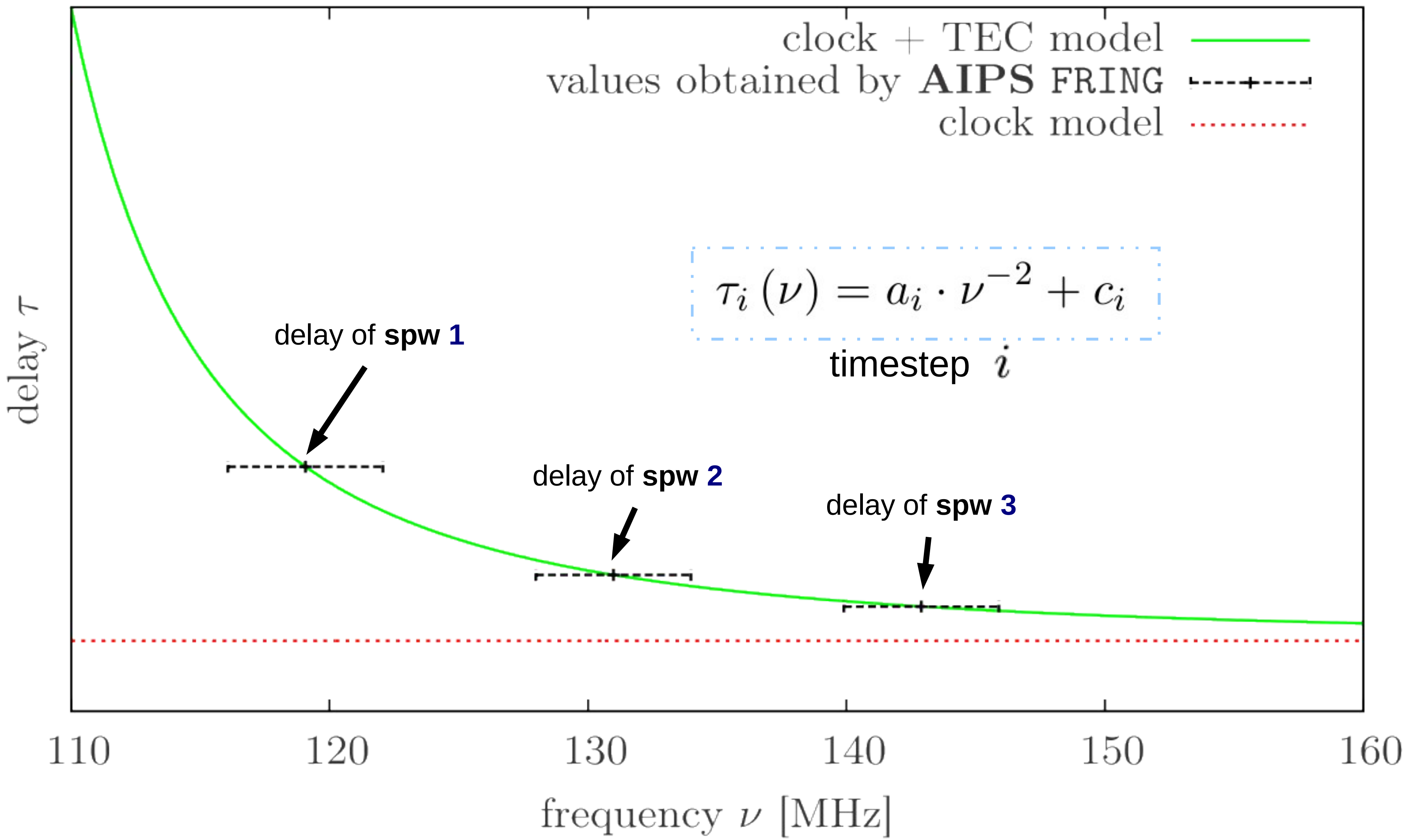
clock

- ✔ one fit for each timestep i

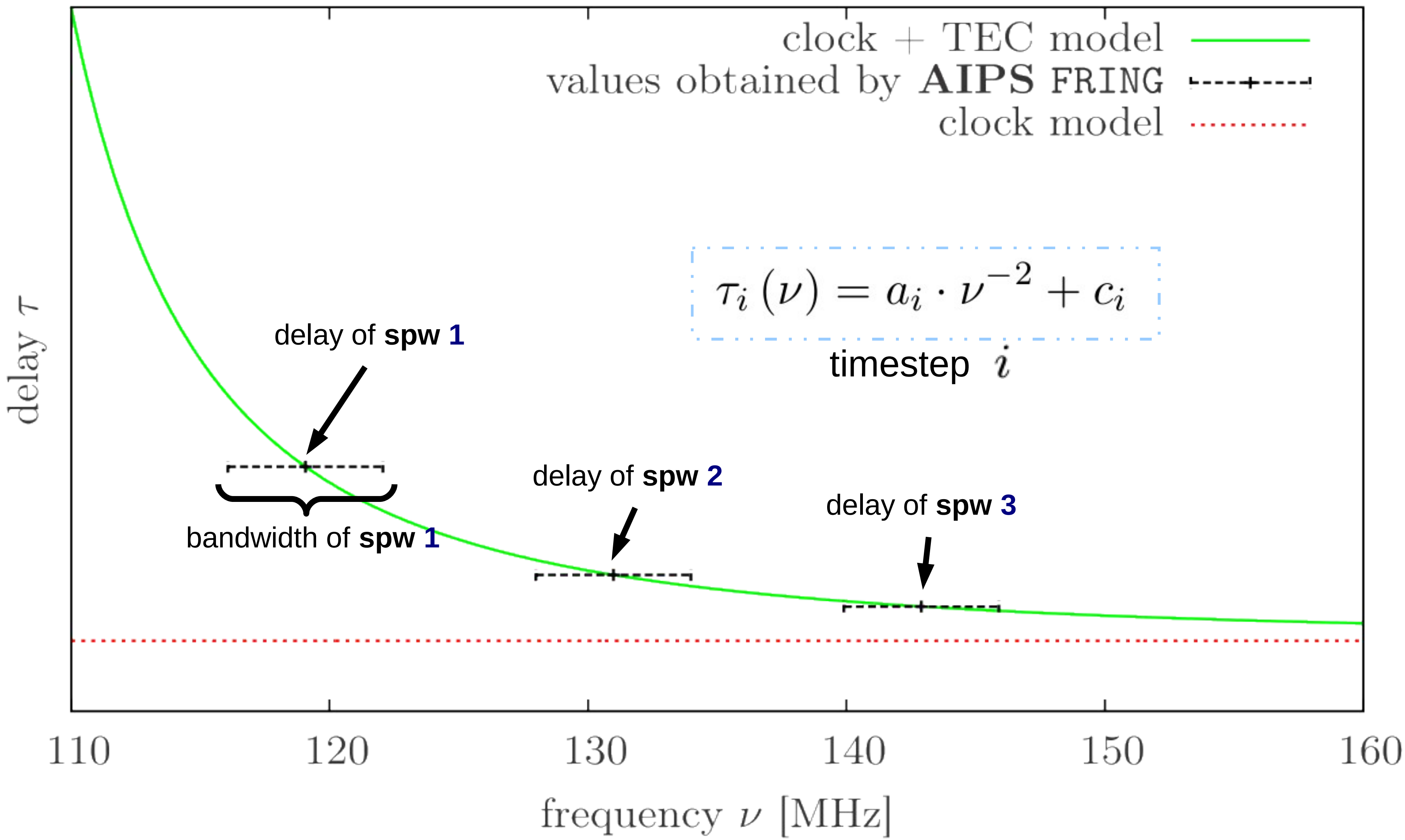
assumed model for fitting clock and TEC

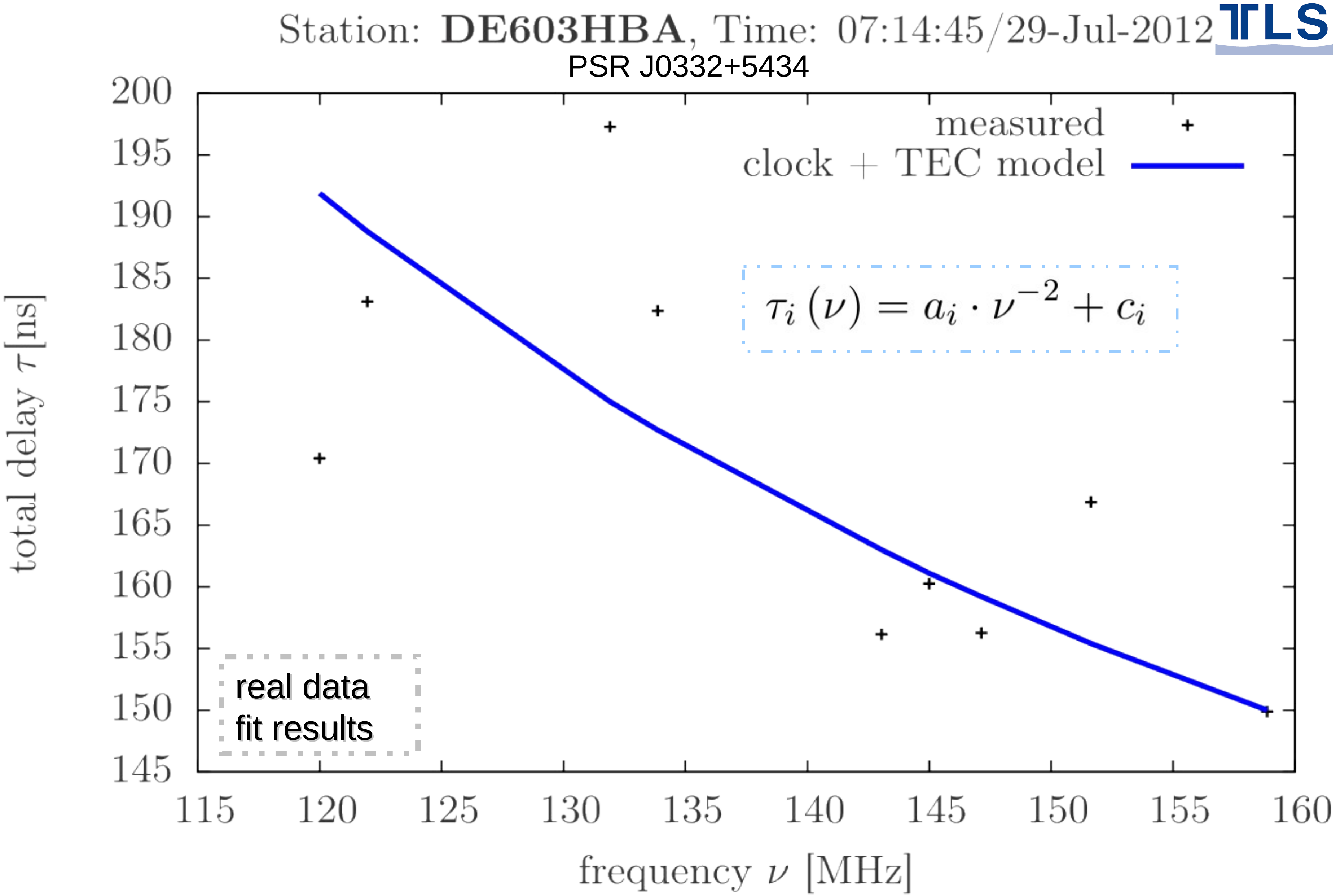


assumed model for fitting clock and TEC

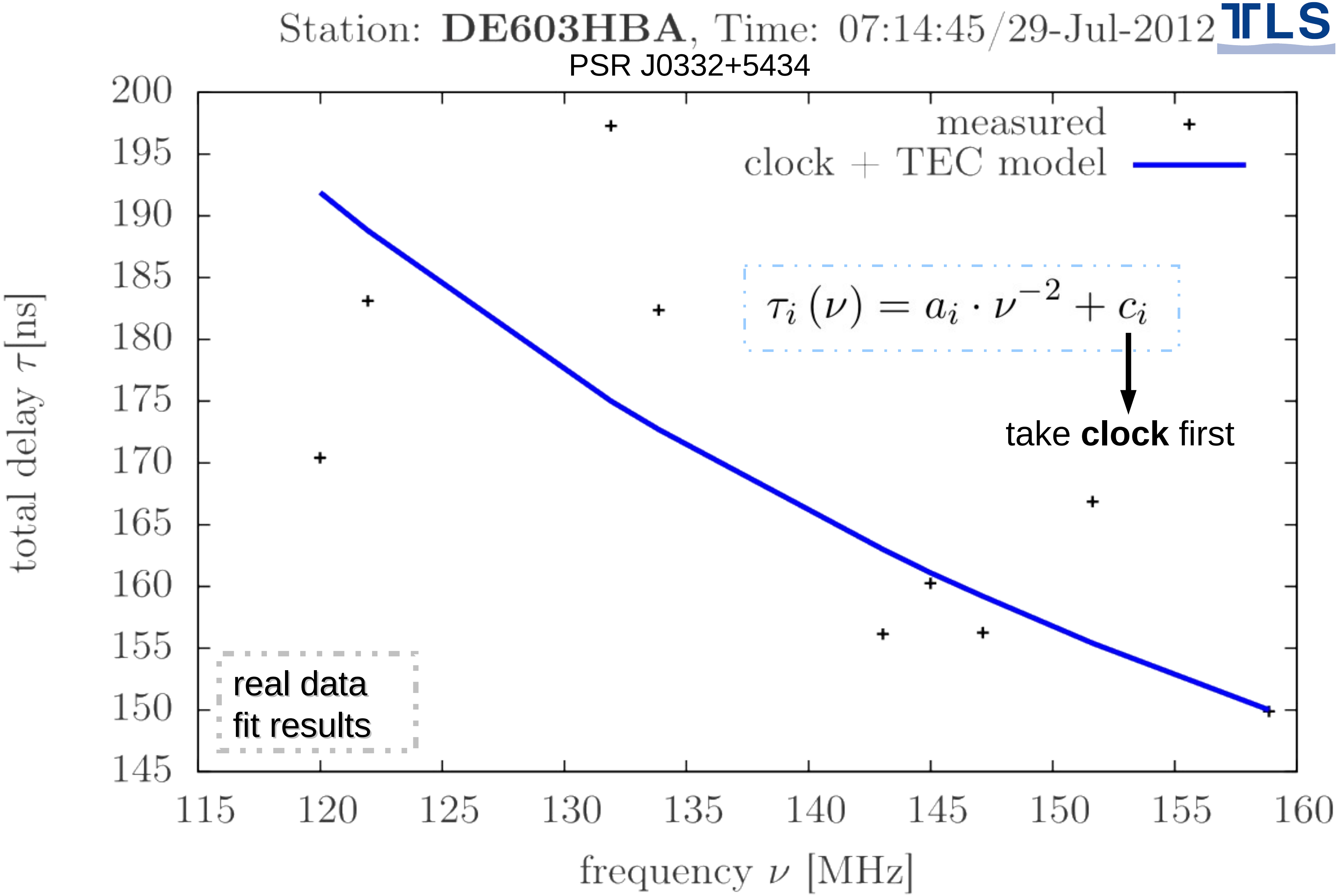


assumed model for fitting clock and TEC

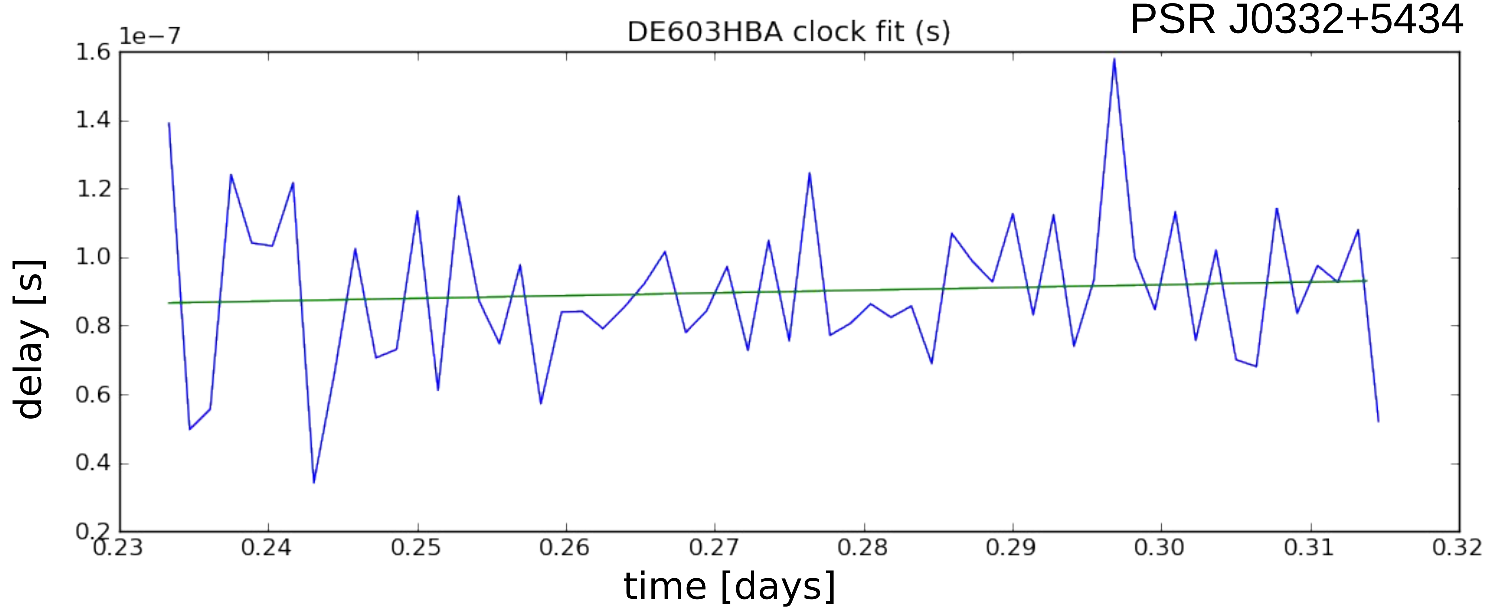




Station: DE603HBA, Time: 07:14:45/29-Jul-2012
PSR J0332+5434
measured
clock + TEC model
$\tau_i(\nu) = a_i \cdot \nu^{-2} + c_i$
real data
fit results
total delay τ[ns]
frequency ν [MHz]
200
195
190
185
180
175
170
165
160
155
150
145
115
120
125
130
135
140
145
150
155
160


Station: DE603HBA, Time: 07:14:45/29-Jul-2012
PSR J0332+5434
measured
clock + TEC model
$\tau_i(\nu) = a_i \cdot \nu^{-2} + c_i$
take **clock** first
real data
fit results
total delay τ [ns]
frequency ν [MHz]
200
195
190
185
180
175
170
165
160
155
150
145
115
120
125
130
135
140
145
150
155
160

PSR J0332+5434



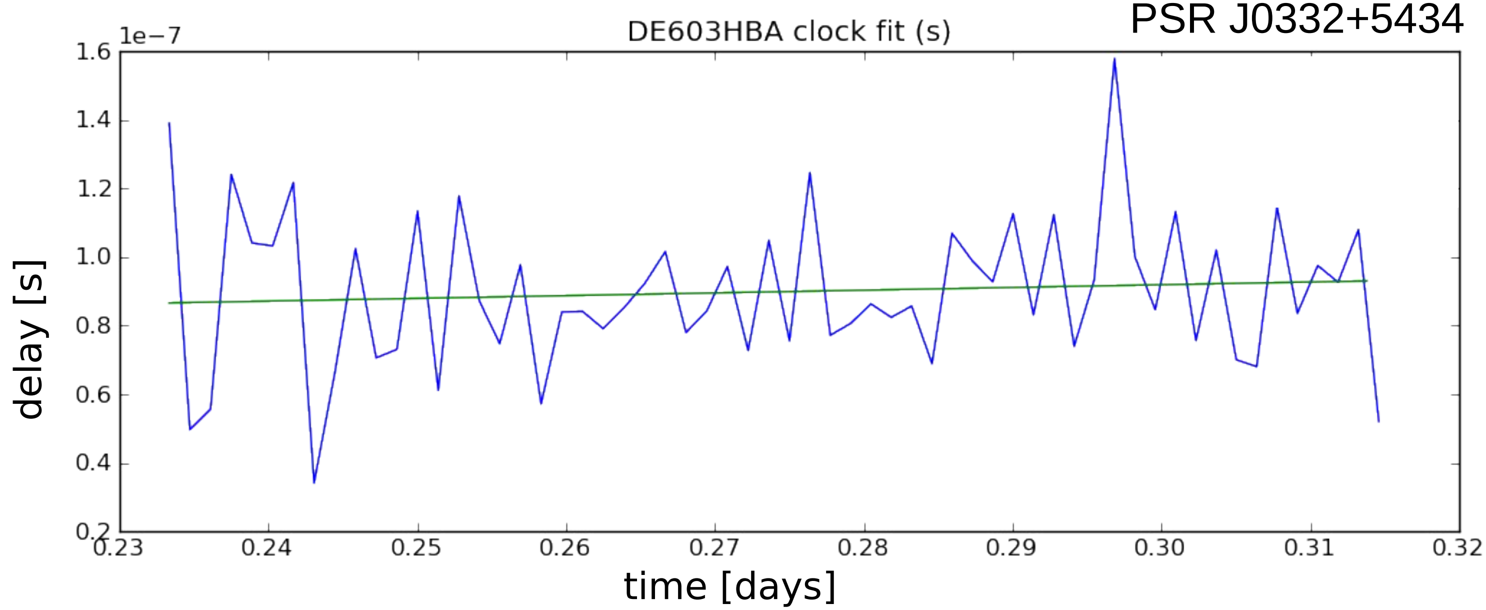
$$\{c_i\}$$

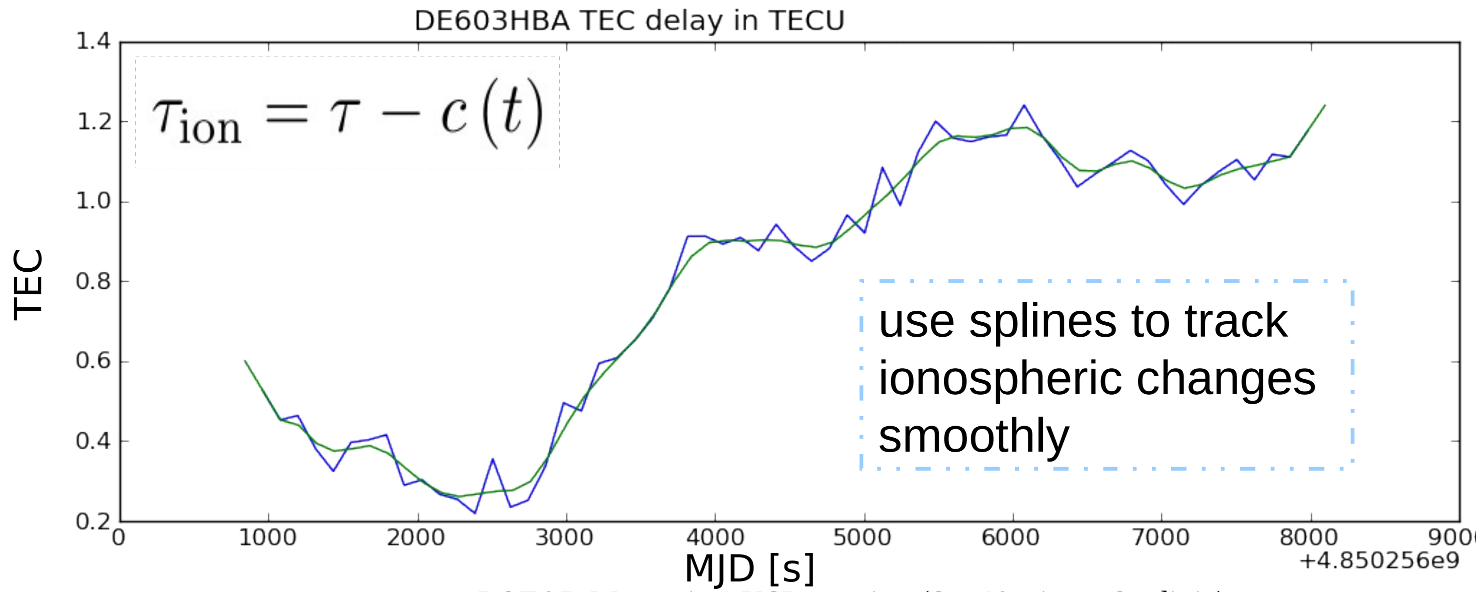
$$c(t) = c_0 + \underbrace{c_1 \cdot t}_{\text{linear clock drifts}}$$

✔ now we have already a **model** for the clock (drift).

➢ Separate ionospheric delay part: $\tau_{\text{ion}} = \tau - c(t)$

PSR J0332+5434

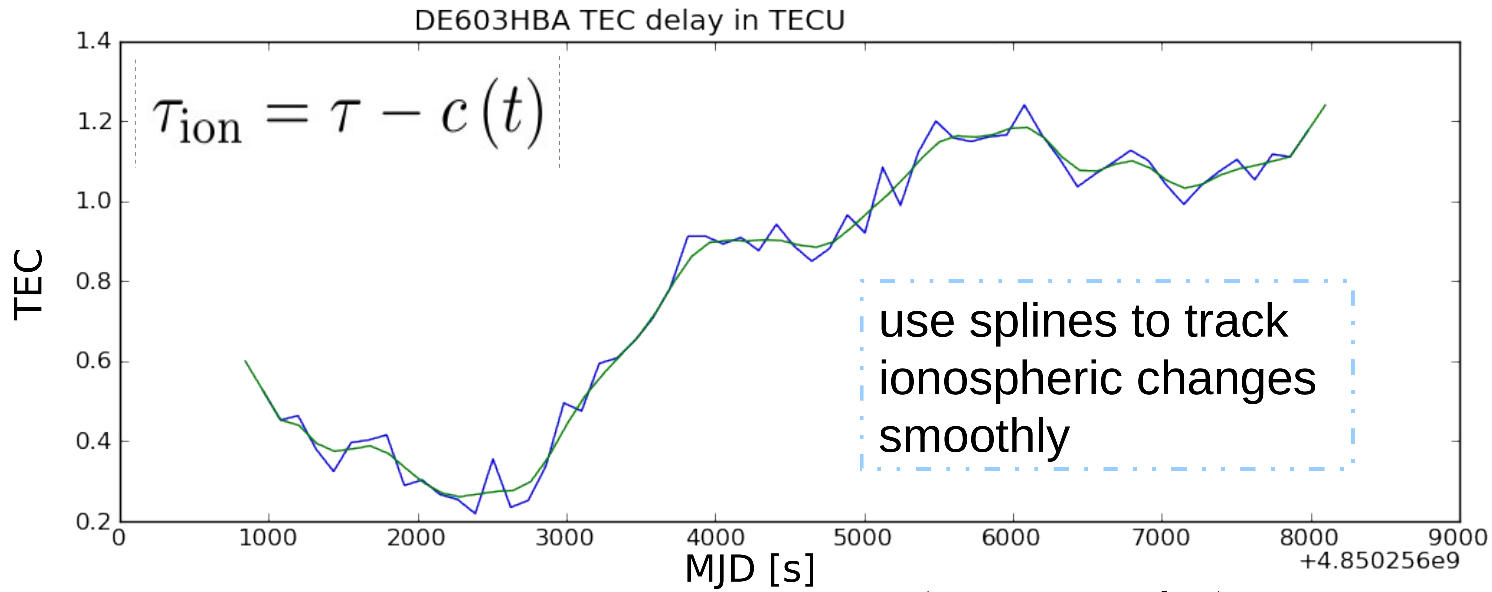




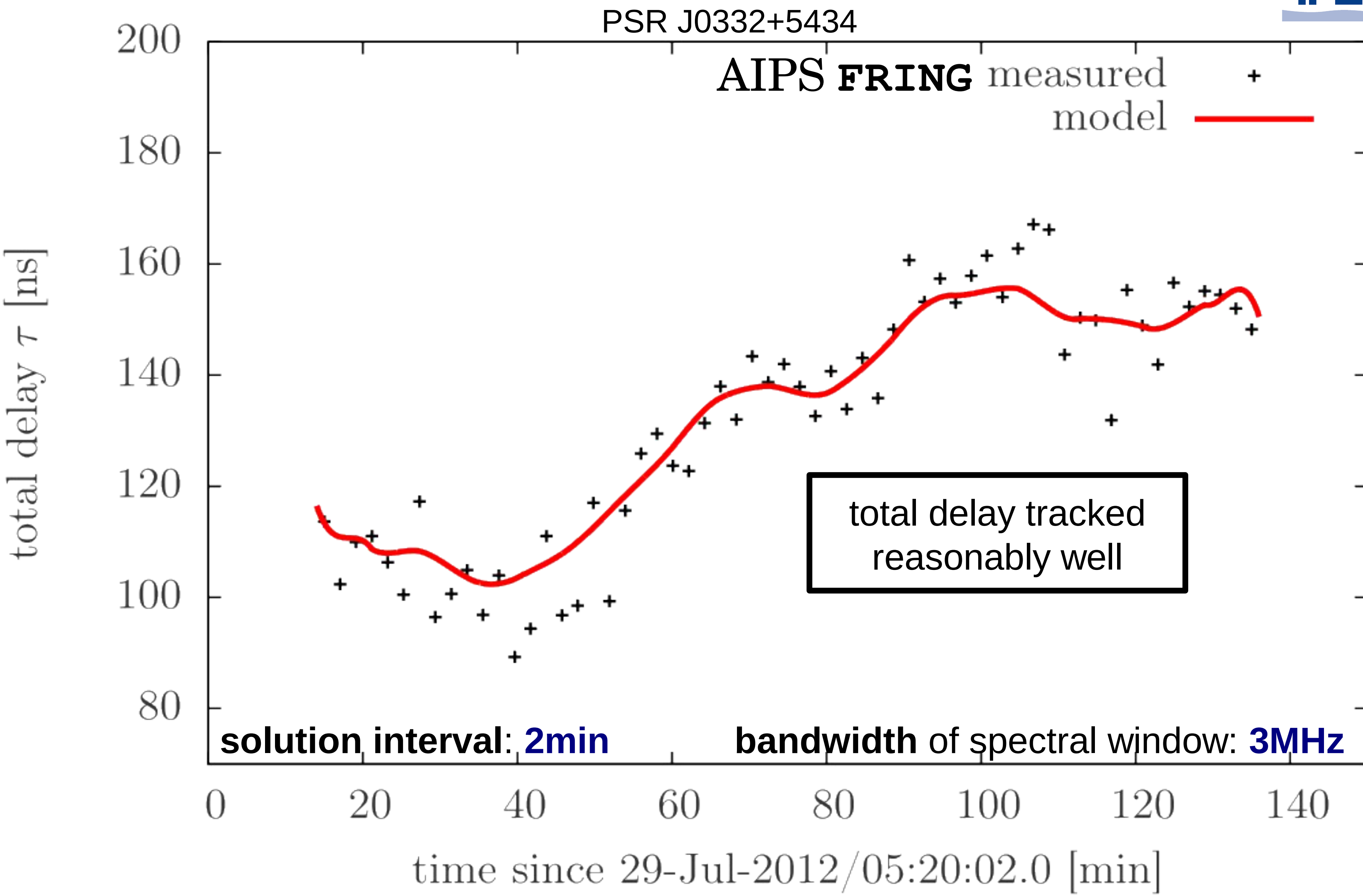
- ✔ a **model** for the clock
- ✔ a **model** for the TEC

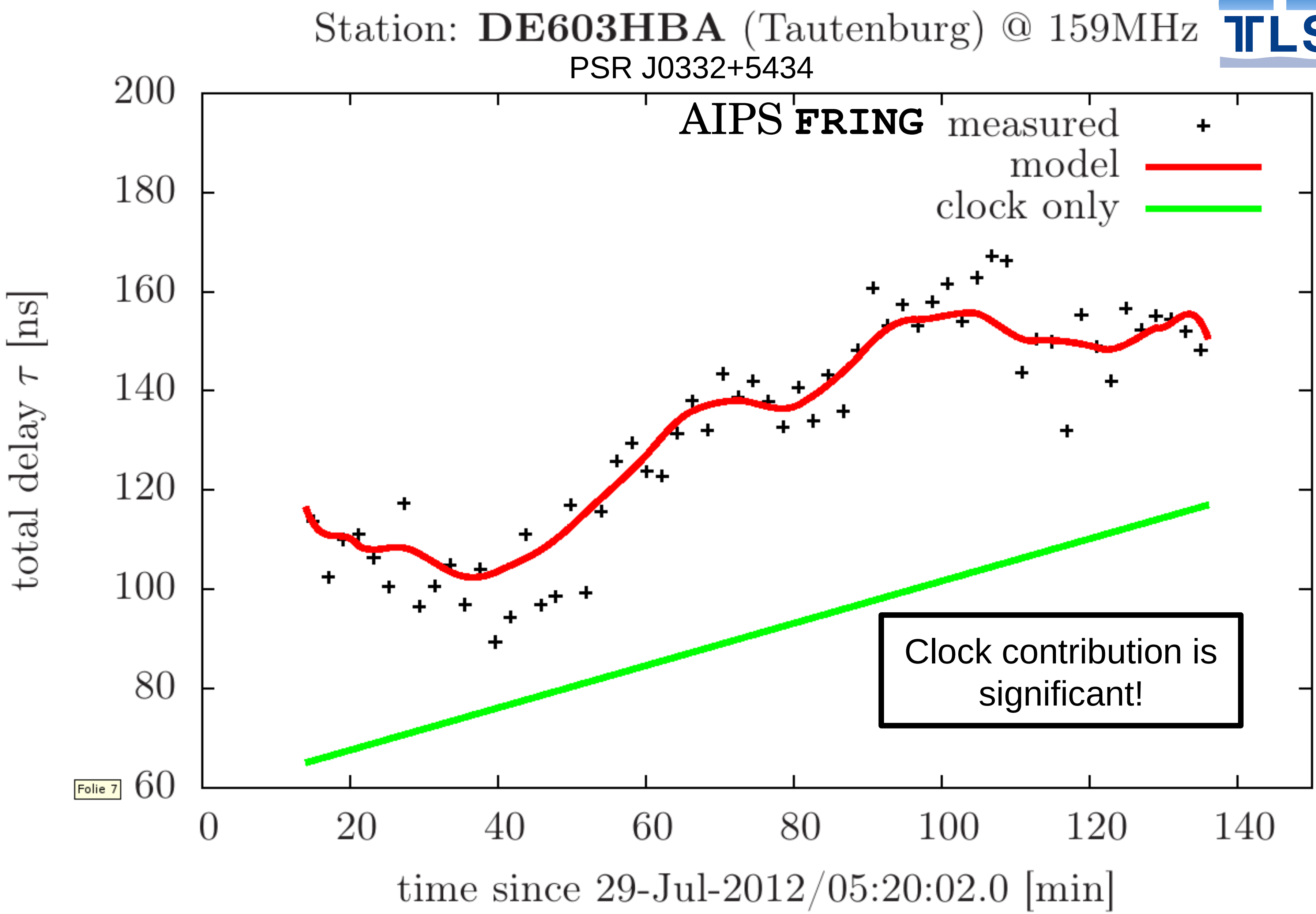
→ plausability check?

go the way back – what is the expected delay given a certain **clock** and **TEC** evolution?

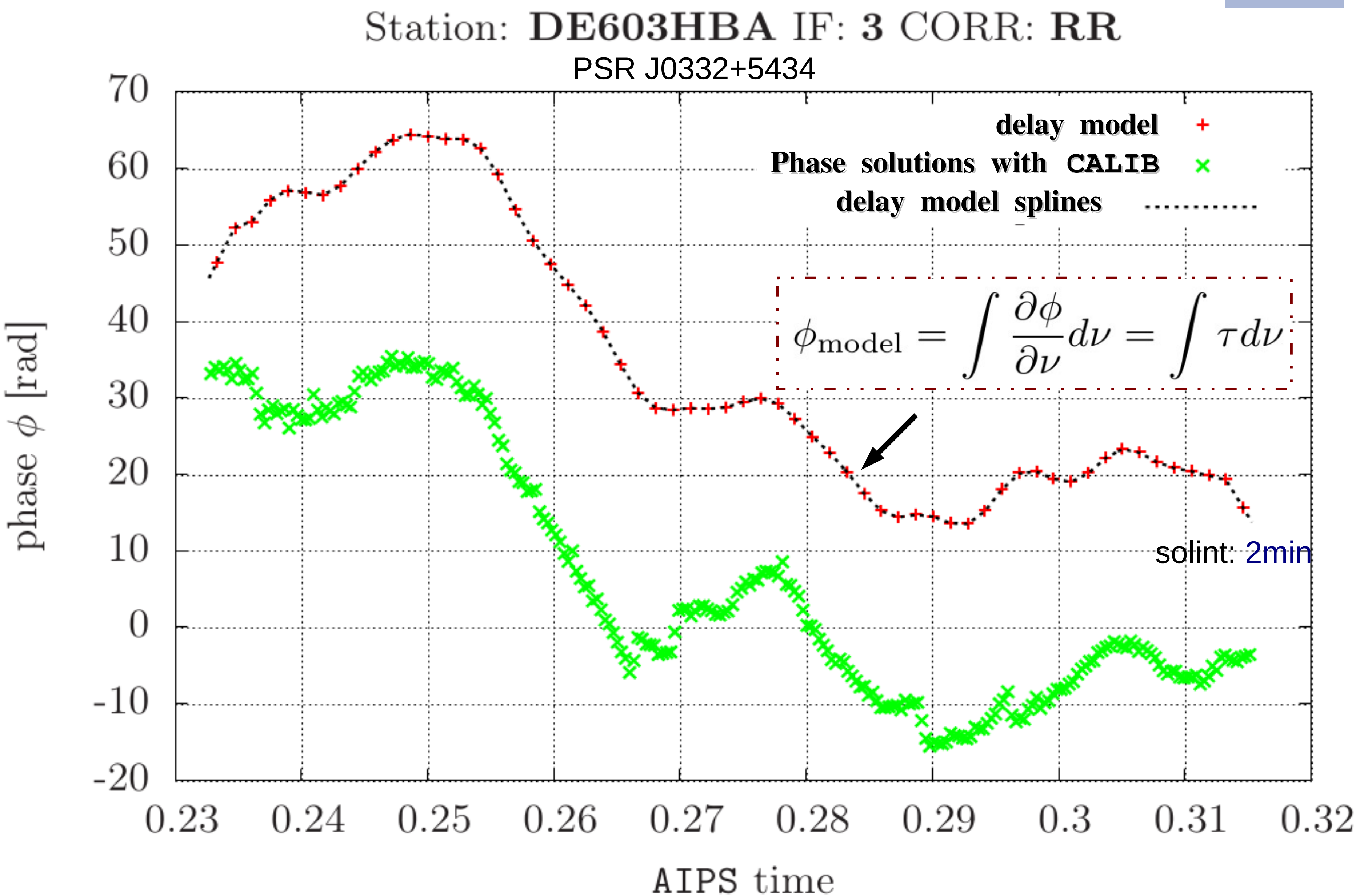


Station: **DE603HBA** (Tautenburg) @ 159MHz

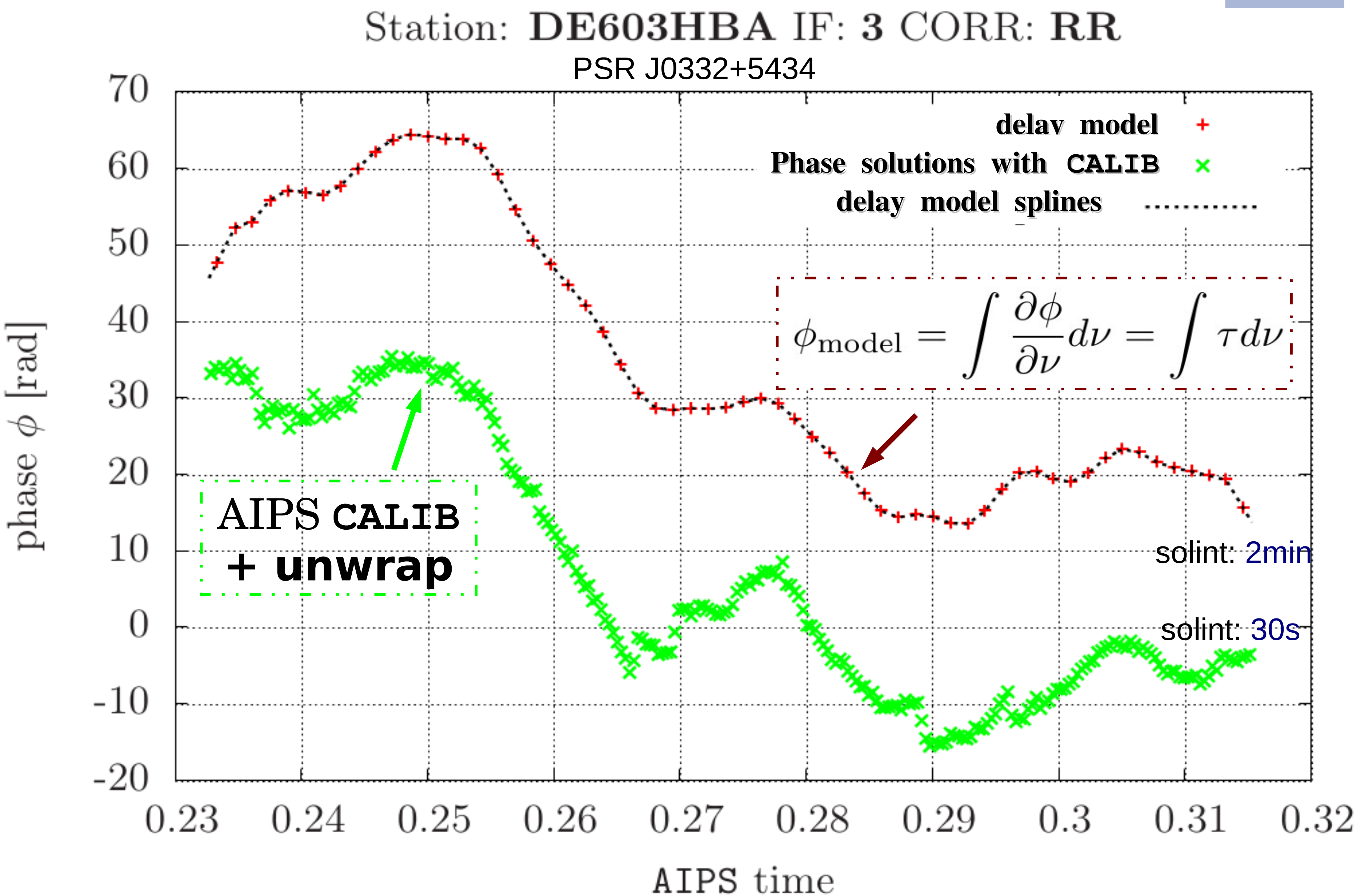



Station: DE603HBA (Tautenburg) @ 159MHz
PSR J0332+5434
AIPS FRING measured
model
clock only
total delay τ [ns]
time since 29-Jul-2012/05:20:02.0 [min]
Clock contribution is significant!

Does our delay model recover the phases?



Does our delay model recover the phases?



Conclusions

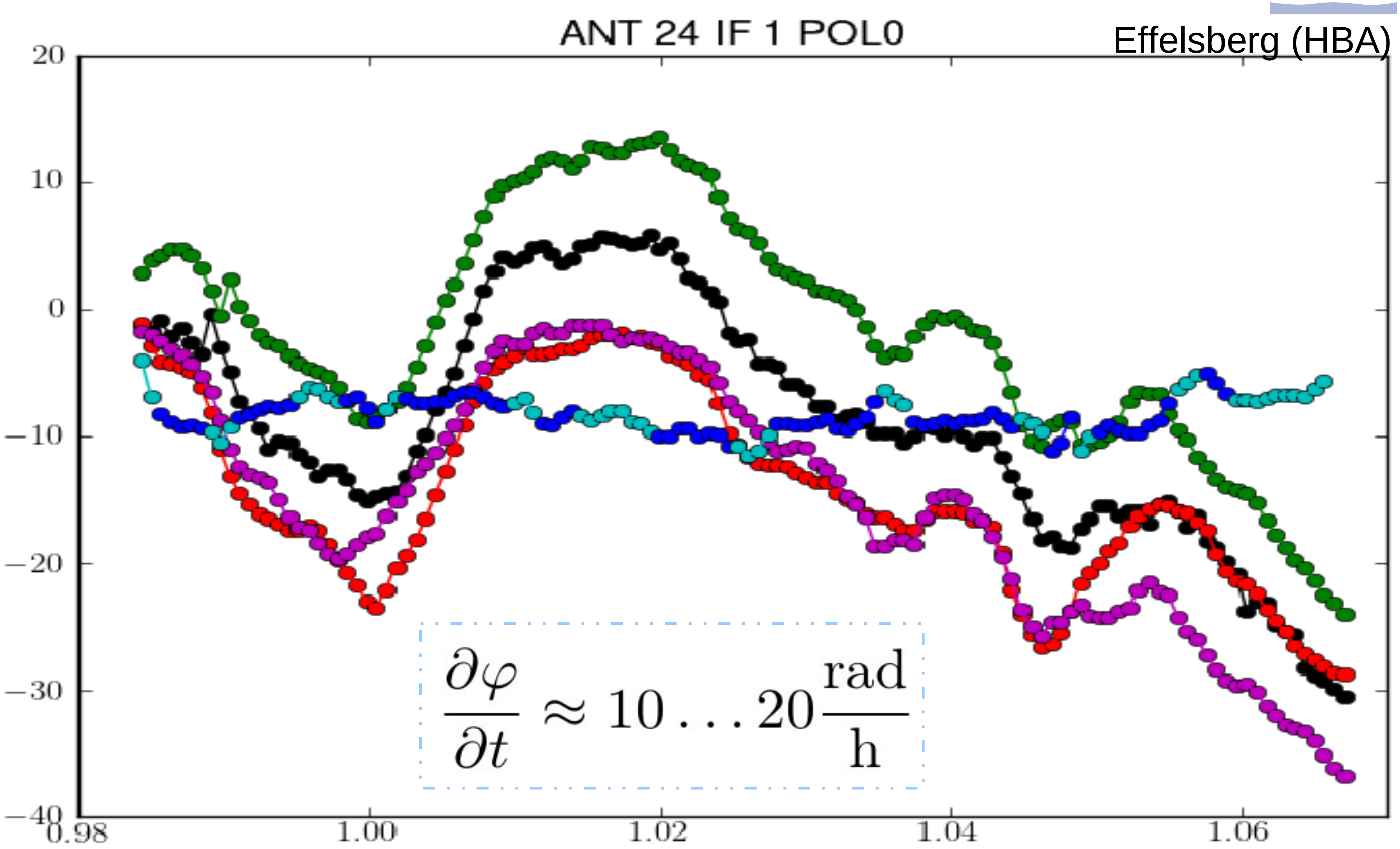
delay-calibration successfull:

- Separation of **Clock/TEC** is possible on long baselines
- **`FRING`** recovers more signal than common phase calibration
  - *Global* fringe-fitting
  - Fit for *delays* + *rates* → more robust parameter set

<u>but:</u>

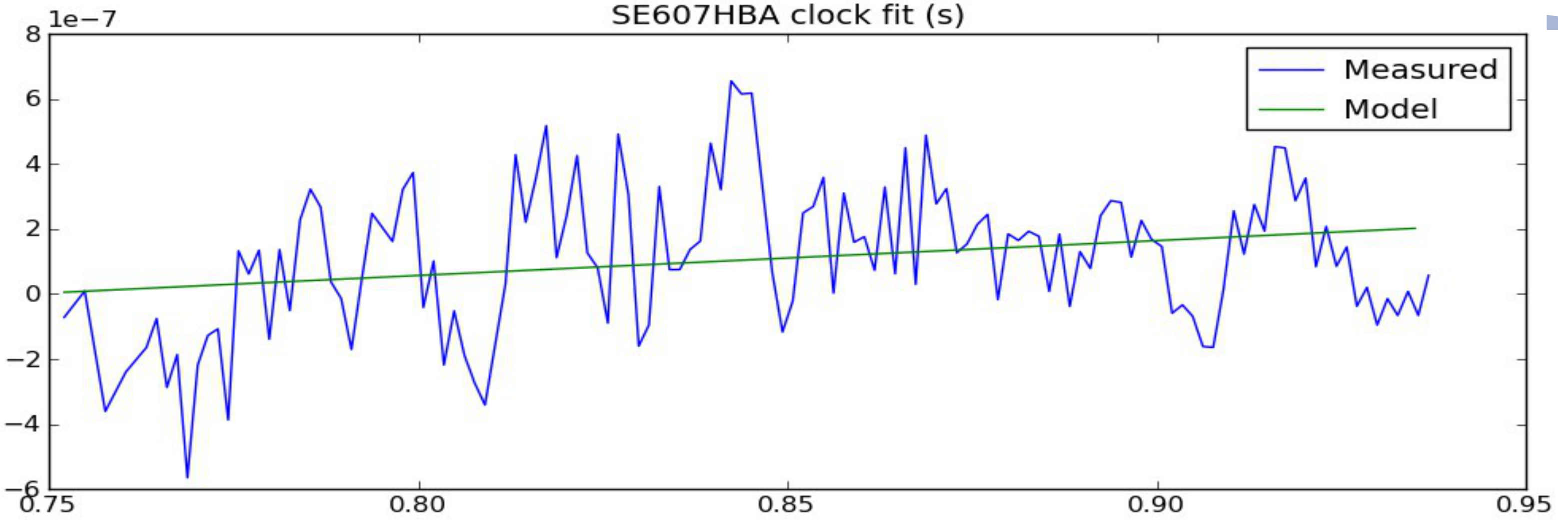
- calibrator survey of sufficently bright **point-like sources** on long baselines is needed

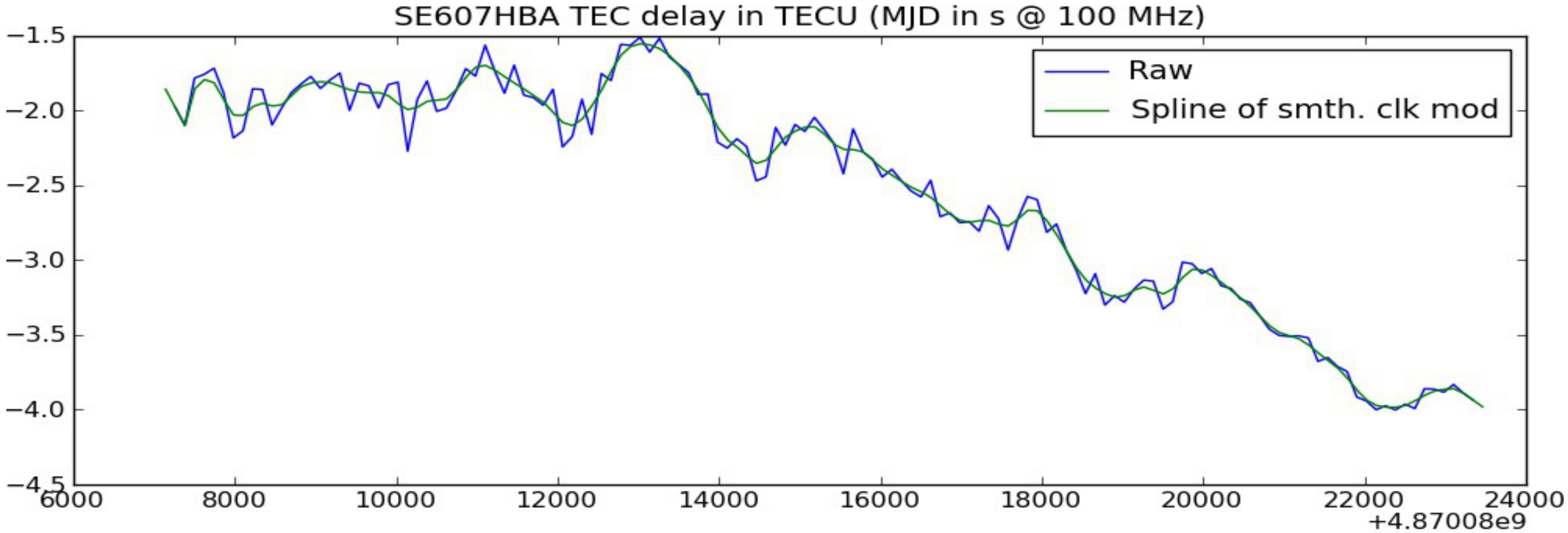
Thank you for your attention!

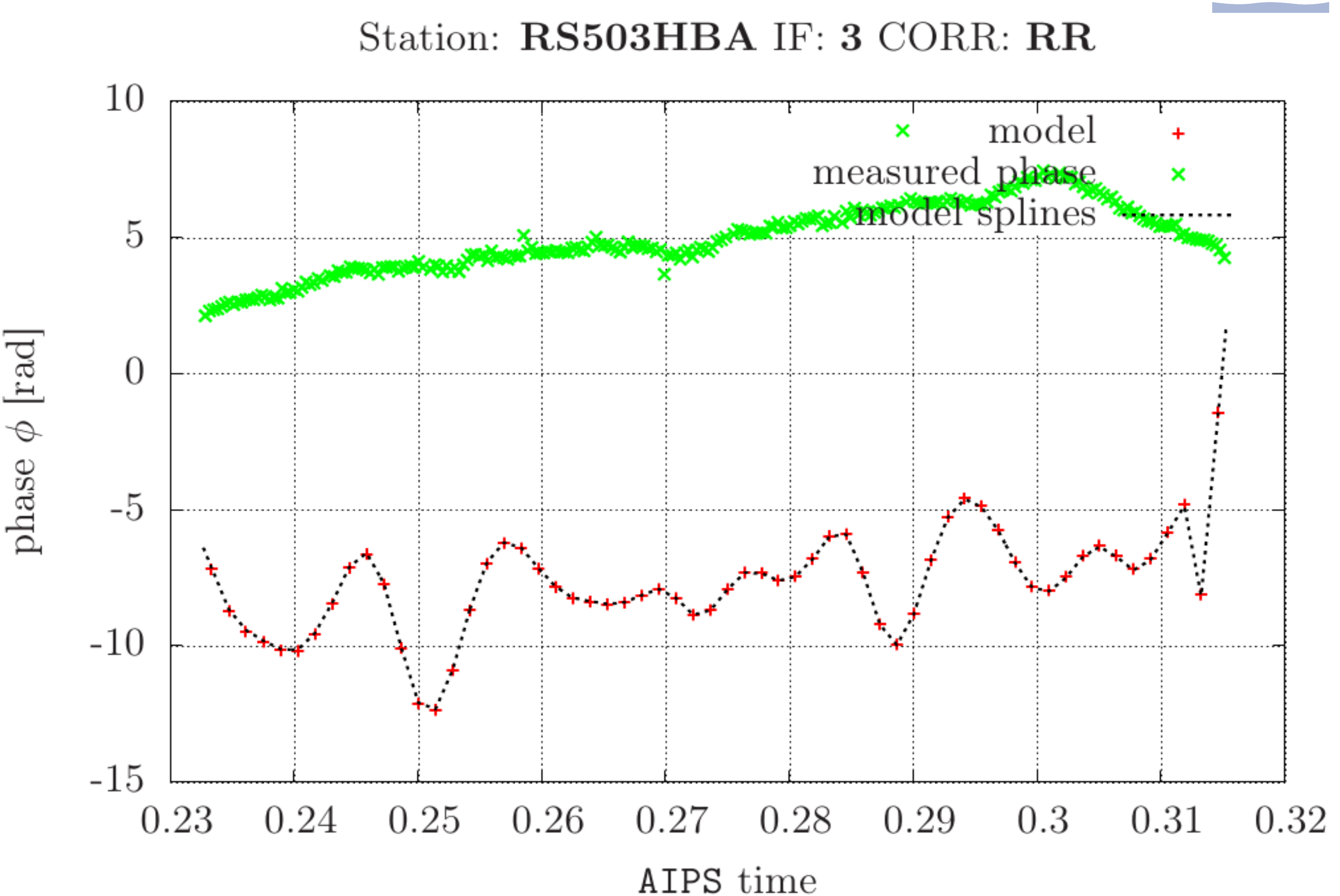


$$\frac{\partial \varphi}{\partial t} \approx 10 \ldots 20 \frac{\mathrm{rad}}{\mathrm{h}}$$

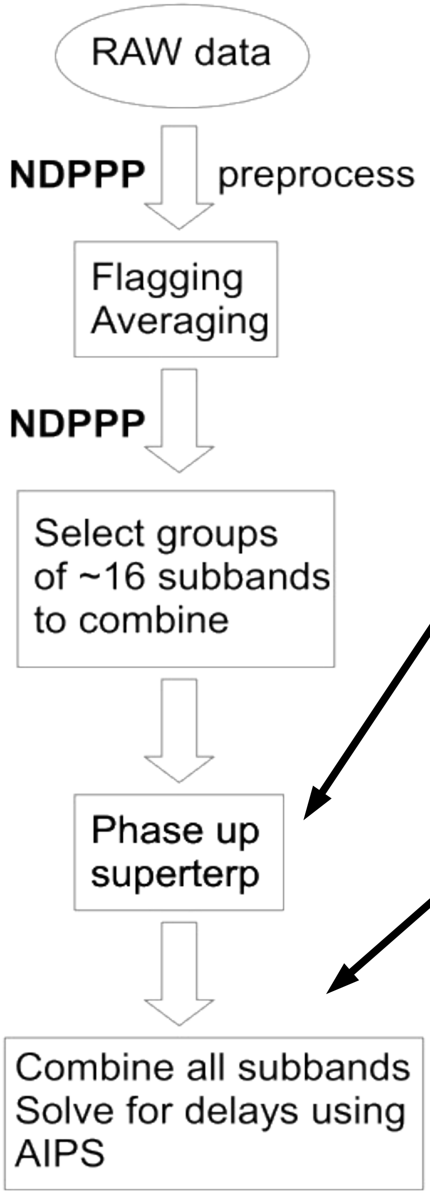
(Neal Jackson)


SE607HBA clock fit (s)
1e−7
Measured
Model
8
6
4
2
0
−2
−4
−6
0.75
0.80
0.85
0.90
0.95


SE607HBA TEC delay in TECU (MJD in s @ 100 MHz)
Raw
Spline of smth. clk mod
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0
−4.5
6000
8000
10000
12000
14000
16000
18000
20000
22000
24000
+4.87008e9



Station: **RS503HBA** IF: **3** CORR: **RR**
model
measured phase
model splines
phase ϕ [rad]
AIPS time
10
5
0
-5
-10
-15
0.23
0.24
0.25
0.26
0.27
0.28
0.29
0.3
0.31
0.32



- ✔ increase sensitivity

$\sqrt{6} = 2.45$ and $\sqrt{12} = 3.46$

- ✔ reduce amount of data
- ✔ limit field of view

- ✗ slow and unhandy if using huge data sets

The modified approach

Select **at least 3 groups** of ~16 subbands to combine

✔ less data to handle with

Phase up superterp

Clock / TEC separation

Combine **these** subbands
Solve for delays using AIPS

- use **model** to obtain solutions for **all** subbands

The modified approach

Select **at least 3 groups** of ~16 subbands to combine

Phase up superterp

Combine **these** subbands
Solve for delays using AIPS

Apply with **BBS**

<u>Script:</u>

- solve for clock + TEC
- create **parmdb**-file

✔ Calibration application with proper beam model possible

The modified approach - consequences

What is needed? —
- „nice“ calibrators (e.g. pulsars are perfect)
- fairly reasonable sky model

What do we have?

Long baselines

small field of view → simpler

higher resolution → more detailled

sky model requirements: simpler | more detailled

⇒ limit calibration to a certain **UV range**

The modified approach - consequences

Compromise: use only small chunks of frequency and fit the rest with a model

Advantage: handy and fast, obtain higher SNR per single solution (which is typically hard to get)

Disadvantage: only *rough calibration* possible, assumption of a constant delay within a frequency range is wrong (strictly speaking)

The modified approach - consequences

Compromise: use only small chunks of frequency and fit the rest with a model.

Approximate answer

→ solution space is better constrained

Advan... single solutio...

Disadv... umption of a constant delay within a frequency range is <u>wrong</u> (strictly speaking) create **parmdb**:

open tablename='ClockTEC_0.db'

add Clock:DE603HBA type='polc', domain=[110000000.0 , 180000000.0 , 4850256843.05 , 4850264098.86], values=[8.664136
08, 6.45721890227753e-09], shape=[1,2]

add TEC:DE603HBA type='polc', domain=[110000000.0 , 180000000.0 , 4850257320.58 , 4850257681.08], values=[0.3947335
-0.12202366277804347, 0.22092343012558058, -0.10506340856862458], shape=[1,4]

use **BBS** to apply:

(**no** solve step)

Strategy.Steps = [correct]

Step.correct.Model.Beam.Enable = T
Step.correct.Model.TEC.Enable = T
Step.correct.Model.Clock.Enable = T