PAON-4 &IDROGEN digital front-end for IM

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On behalf of PAON & IDROGEN teams

PUMA (virtual) workshop

August 2020

- Development context : a brief historic introduction
  - From CRT@Pittsburgh to Tianlai
- PAON : prototype for transit dish array interferometer
- IDROGEN : a new front-end electronic (digitiser / F-engine) for interferometer arrays and Intensity Mapping
  - White Rabbit clock synchronisation technology

- 2006 : Jeff Peterson (@Moriond) proposed to build large cylindrical radio-telescope to carry BAO redshift survey using the 21cm line …
- 2007 : BAORadio project in France to carry R&D on electronics (digital) for CRT and large radio arrays (**LAL-CNRS/IN2P3, Irfu-CEA, Observatoire de Paris** collaboration)
- 2007-2009 : development of some of components of the electronic system (digitisation/FFT board, clock distribution …) - Tests at Nançay on the NRT
- 2009-2010 : Tests on the CRT prototype at Pittsburgh - Site testing in Morocco (with **Fermilab**) - Ifrane meeting in July 2009 …
- 2011-2012 : FAN (Phased array prototype for the NRT), HICluster program with the NRT , contacts with **NAOC**
- 2012-2014 : **PAON** project initiated . **Tianlai** project (**NAOC**) , contributions to the instrument design
- 2015-2016 : PAON4 deployed at Nançay, development of the new NEBuLA digitiser board (White Rabbit, LAL & Obs. de Paris/Nançay) started - Developments later incorporated into the IDROGEN board, part of the DAQGEN project
- 2017-2019 : Tianlai (data analysis), PAON4 data analysis , **IDROGEN** board development
- 2020 : deployment of IDROGEN boards on PAON4 (slightly delayed due to Covid-19)

BAORadio 21 cm

Observatoire de Paris

P. Colom
J.M. Martin
J. Borsenberger
J. Pezzani
F. Rigaud
S. Torchinsky
C. Viou

LAL - IN2P3/CNRS

R. Ansari
J.E. Campagne
M. Moniez
A.S. Torrento
D. Breton
C. Beigbeder
T. Cacaceres
D. Charlet
B. Mansoux
C. Pailler
M. Taurigna

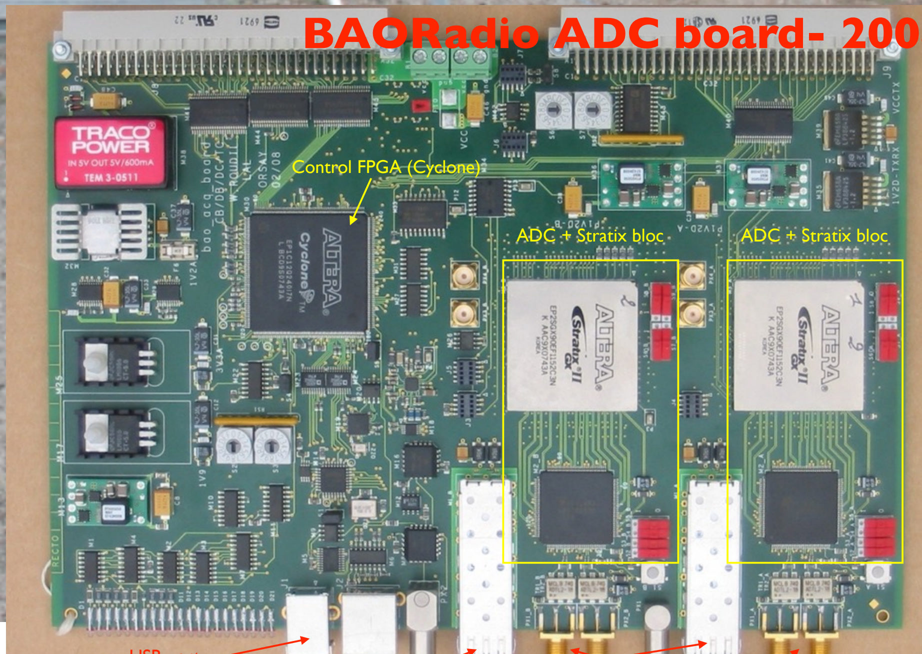
IRFU - CEA

C. Magneville
C. Yèche
J. Rich
J.M. Legoff
P. Abbon
E. Delagnes
H. Deschamps
C. Flouzat
P. Kestener

CRT (CMU, Pittsburgh)

J. Peterson, K. Bandura …

BAORadio @ CRT-Pittsburgh - Nov 2009



Au pays de l'énergie noire

Par Christophe Magneville et Christophe Yèche

Le contenu énergétique de l'Univers est dominé par une composante qui n'est ni de la matière ni du rayonnement : l'énergie noire. Cette composante mystérieuse, détectée pour la première fois en 1998, a révolutionné notre vision de l'évolution de l'Univers et constitue une des découvertes majeures de la fin du XXe siècle. Le projet CRT de radiotélescope au Maroc permettra une meilleure compréhension de l'origine et des propriétés de cette énergie noire.

Ch. Yèche, E. Delagnes, P. Abbon, Ch. Magneville (Irfu) et R. Ansari (LAL)

électronique dans la gamme des fréquences autour du GHz, utilisés par la téléphonie mobile, rendent ce projet technologiquement réalisable.

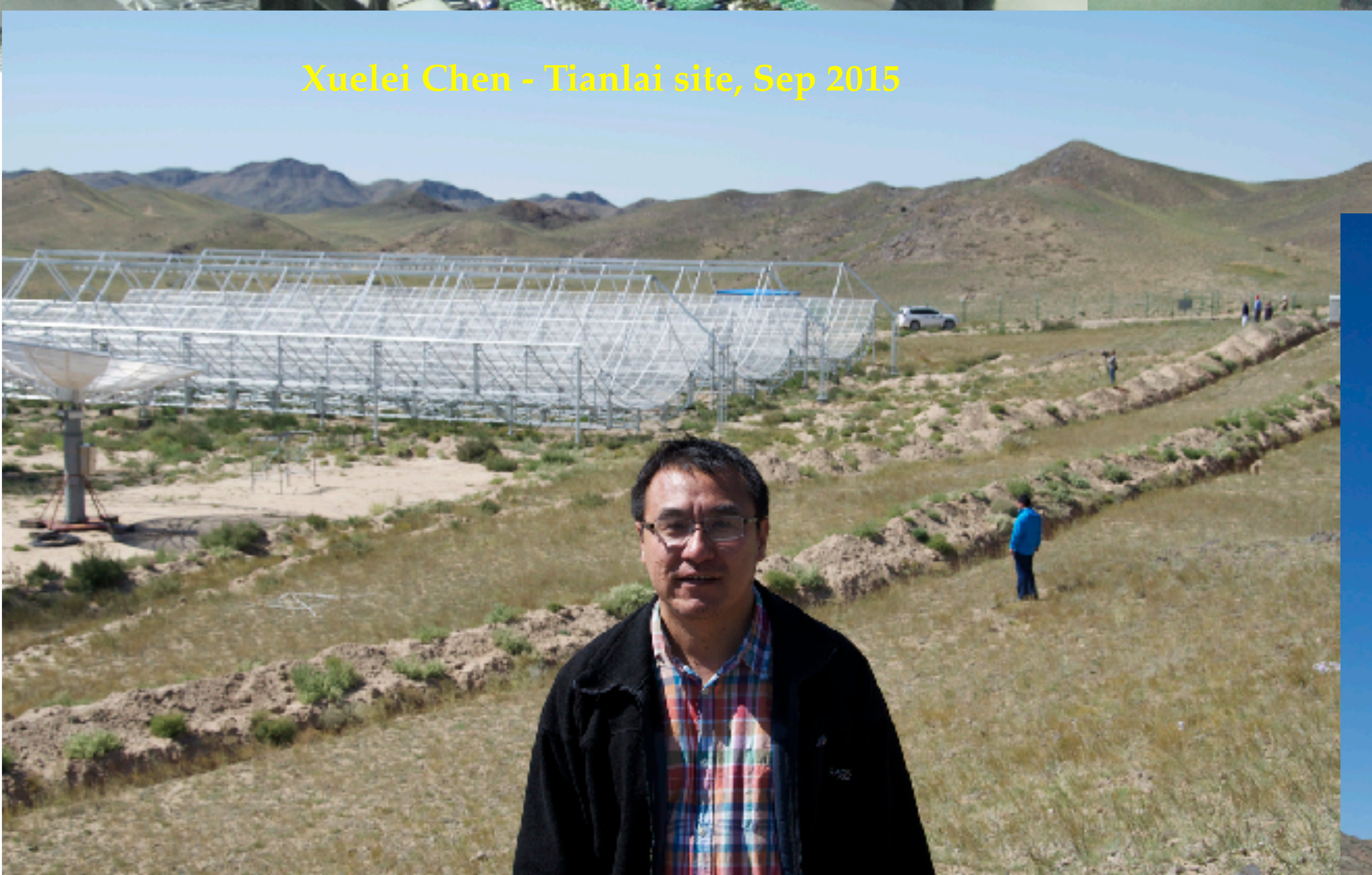
Le CRT va explorer la nature de l'énergie noire avec une sensibilité dix fois supérieure aux instruments actuels. Il pourrait être construit sur un site au Maroc, grâce à un partenariat entre l'université d'Al Akhawayn à Ifrane (Maroc), l'université Carnegie-Mellon et Fermilab (Etats-Unis), l'Irfu et le LAL (France). Le Maroc constitue un excellent pays d'accueil pour ce projet car il allie un bon niveau de développement technologique et universitaire avec la possibilité de disposer de régions peu affectées par les bruits des ra-

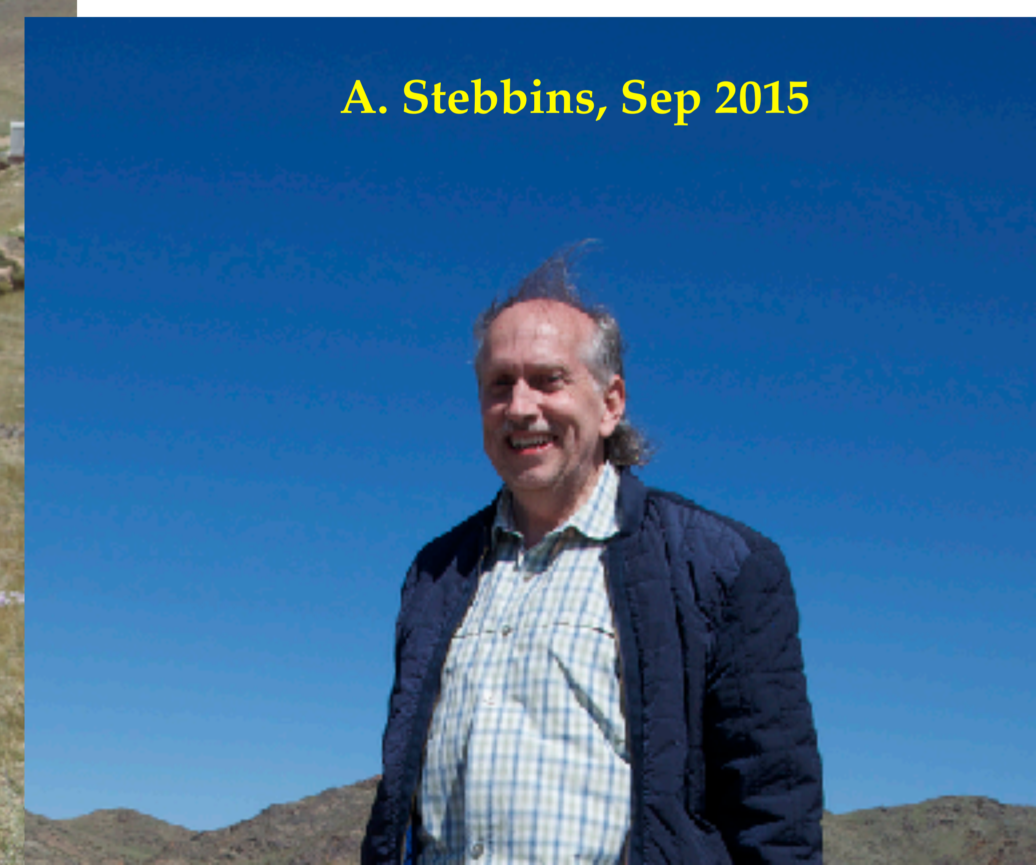
Site testing in Morocco - Jan 2009
(Dave Mc. Ginnis, FNAL - blue jacket)

Site testing in Morocco - Jan 2009
C. Magneville, C. Yèche, P. Abbon (Irfu-CEA)

CRT meeting at Ifrance, Morocco, June 2009
Jim Rich, Jeff. Peterson

Visiting electronic and antenna factories in China, Tianlai project meeting, Feb. 2012





HI-Cluster program at NRT and PAON4

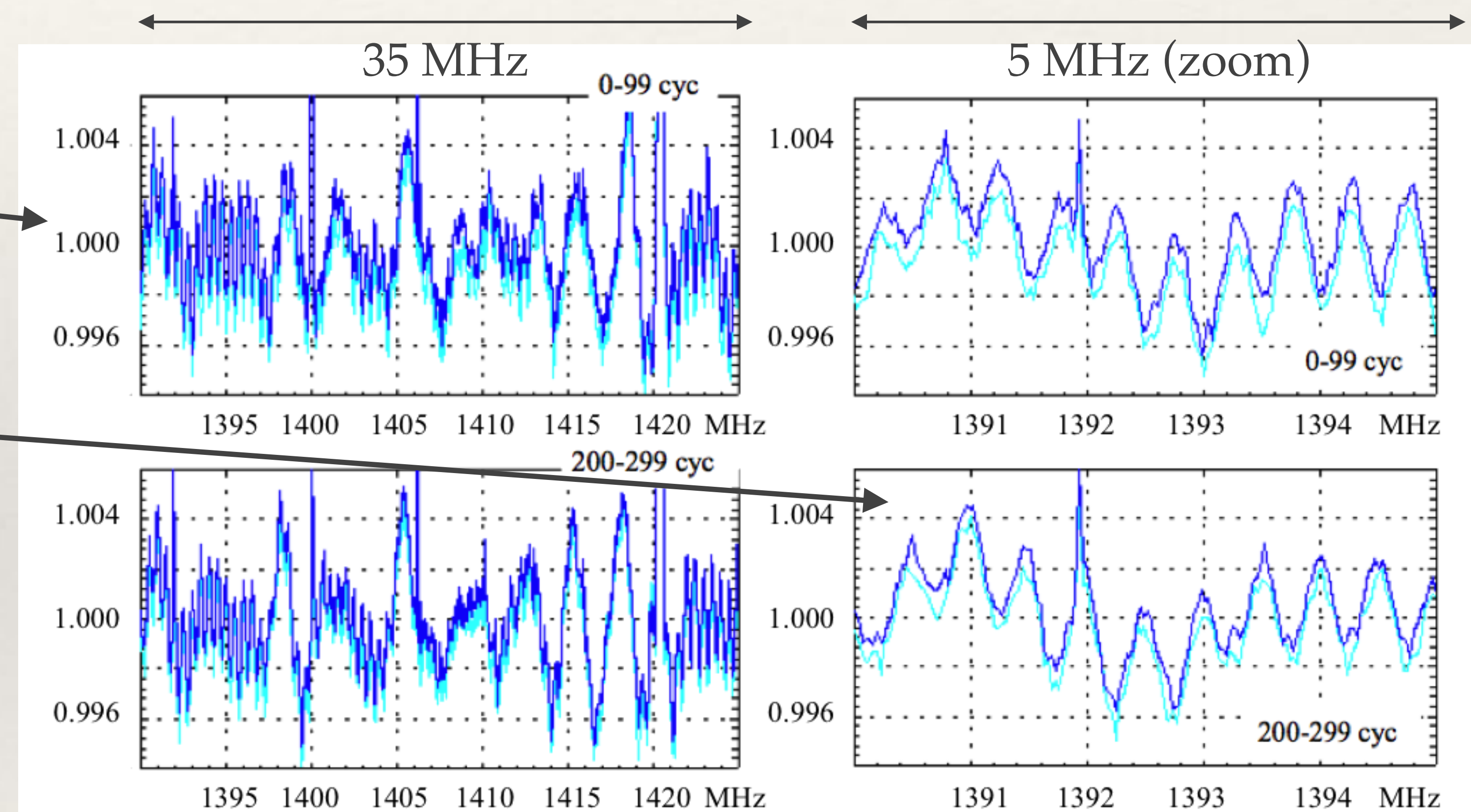
What did we learn from these programs ?

HICluster : search for HI signal from nearby clusters

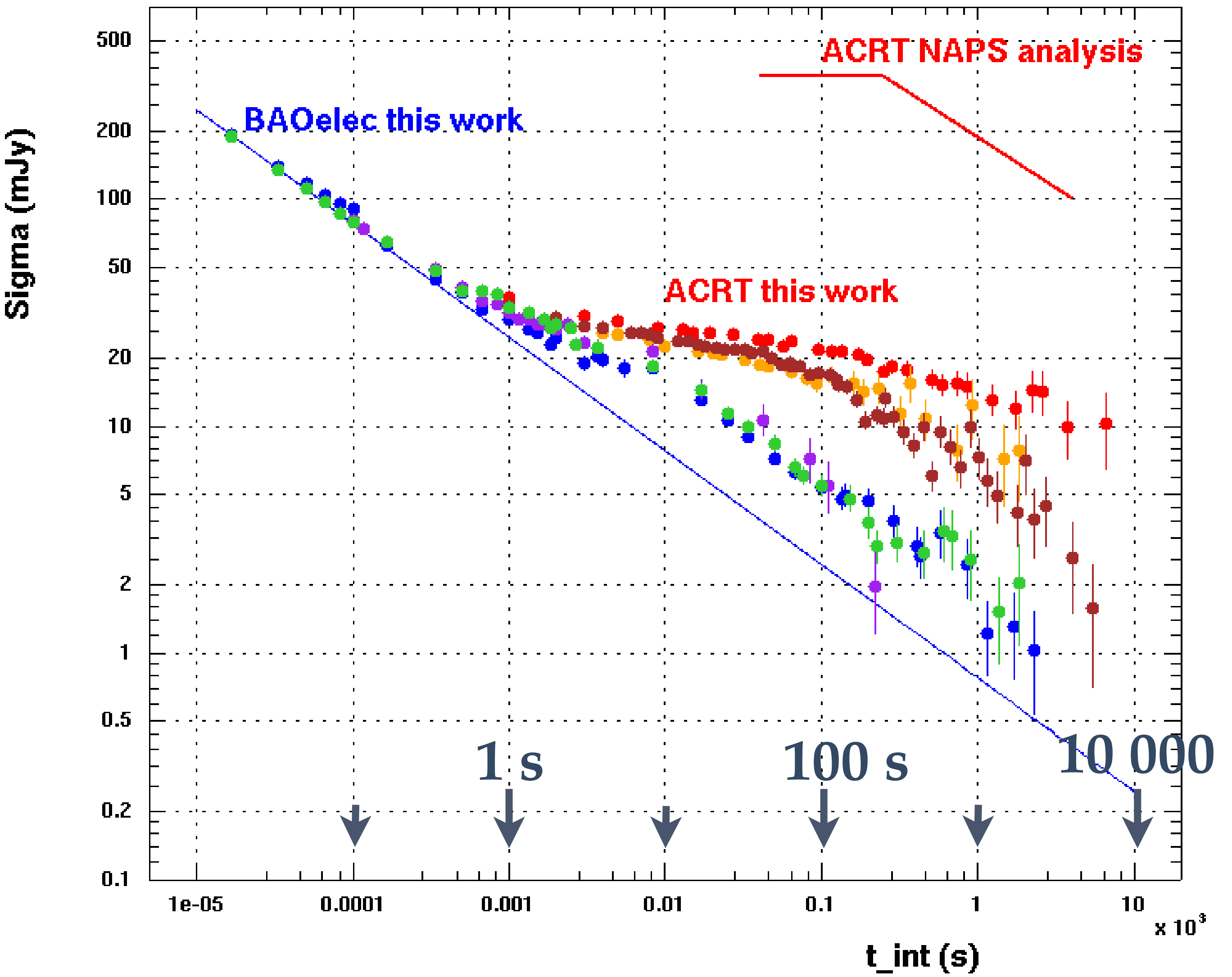
- Use of the NRT (Nançay large radio-telescope), ~ 7000 m^2, cryogenic receiver, equipped with the BAORadio ADC board, to detect HI signals from galaxies in nearby clusters
- Observations carried from march 2011 to Jan. 2012, toward three clusters A85, A1205, A2440 z~0.06-0.09

• wiggles (3-4 MHz , about 30 m cable) in the bandpass due to standing wave in the cables

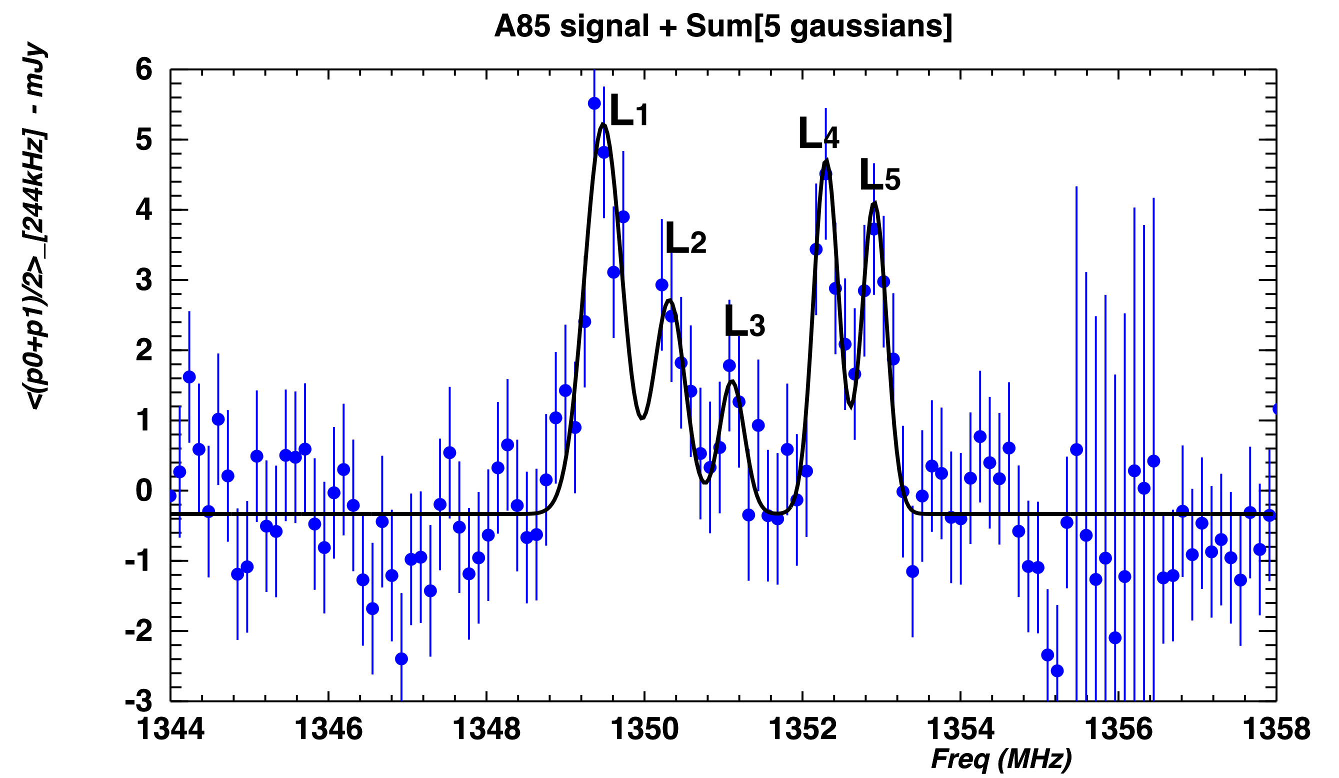
• Wiggles in the bandpass (500 kHz ~250 m) due to standing wave between the reflector and the feed Phase changes with time …

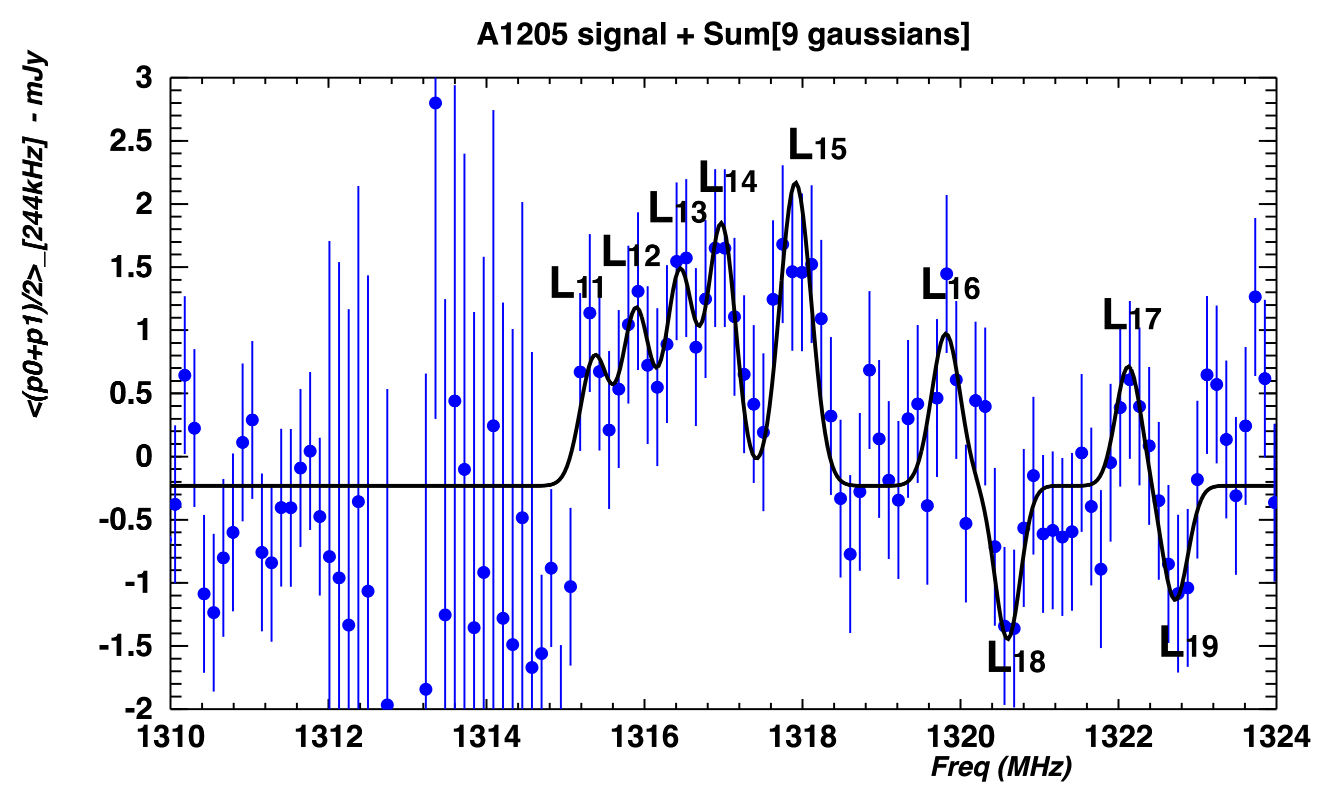


Noise/sensitivity (radiometer curve)
HI-Cluster, BAORadio & NRT correlator



Signal HI A85 / A1205

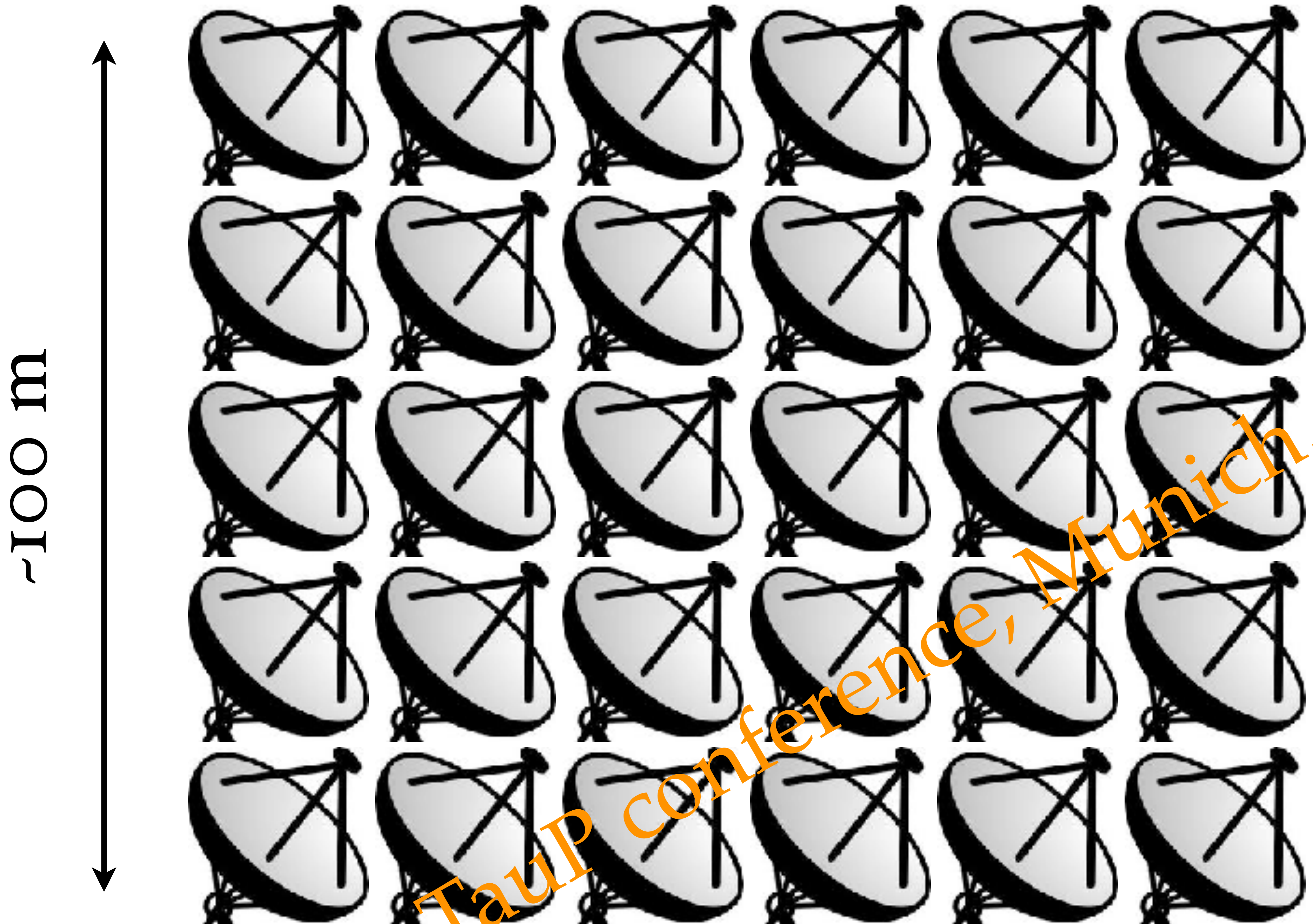




HICluster

Enhanced sensitivity by a factor 5-10
compared to standard NRT analysis

Ansari et al. (2015) - Exp. Astronomy
arXiv:1505:02623



RAID
Radio Array of Inexpensive Dishes

21cm intensity mapping dark energy survey instrument
concept - Dense interferometric array
8-12 cylindrical reflectors (CRT)
OR
100-400 parabolic 5-6 meter diameter dishes **(RAID)**
200-1000 receiver elements - Data flow : 0.1 - 1 TBytes/s

PAON-4 (2014-…)/ NEBuLA-IDROGEN (2016-…)

- PAON : PAraboles à l'Observatoire de Nançay (paon → peacock)
- PAON-4 : 4 × D=5m reflectors, dense array configuration, transit observation mode
- Total surface ~ 75 m^2, 8 = 4 x 2 (pol) récepteurs , 36 visibilities ~ 2 GBytes/s maximum data flow
- 38 S < Elevation < 15 N → 10 < δ < 60 at Nançay
- 250 MHz band , 1250-1450 MHz
- Reconstructed map resolution ~ 1 deg @ 1400 MHz
- Aims: RFI cleaning , Tsys and antennae correlation, test of calibration and 3D transit mode map making
- Sensitivity level ~50 mK (/ 1deg^2 x 1 MHz pixels) over ~ 5000 deg^2
- NEBuLA/IDROGEN : Numériseur à Bande Large pour l'Astronomie - New generation digitiser board that could be deployed close to the antennae, over ~ km sized area …

PAON-4 @ Nançay

4 x 5m dishes, in compact transit interferometer configuration
L-band (~ 1250-1500 MHz → 1275 - 1475 MHz)

PAON-4 building: the team …

J.E. Campagne , J.M. Martin

P. Colom, C. Magneville

J. Pezzani

F. Rigaud

D. Charlet

P. Abbon,

S. Blanc, J.J. Bousquet , J.L. Dourneaux, R. Keller, Y. Younes,

P. Cornebise, C. Pailler, M. Taurigna

C. Viou

Services techniques et administratives du LAL

L. Alsac, S. Garnier

D. Breton, C. Beigbeder, T. Caceres

S. Jenzer, J.L. Borne

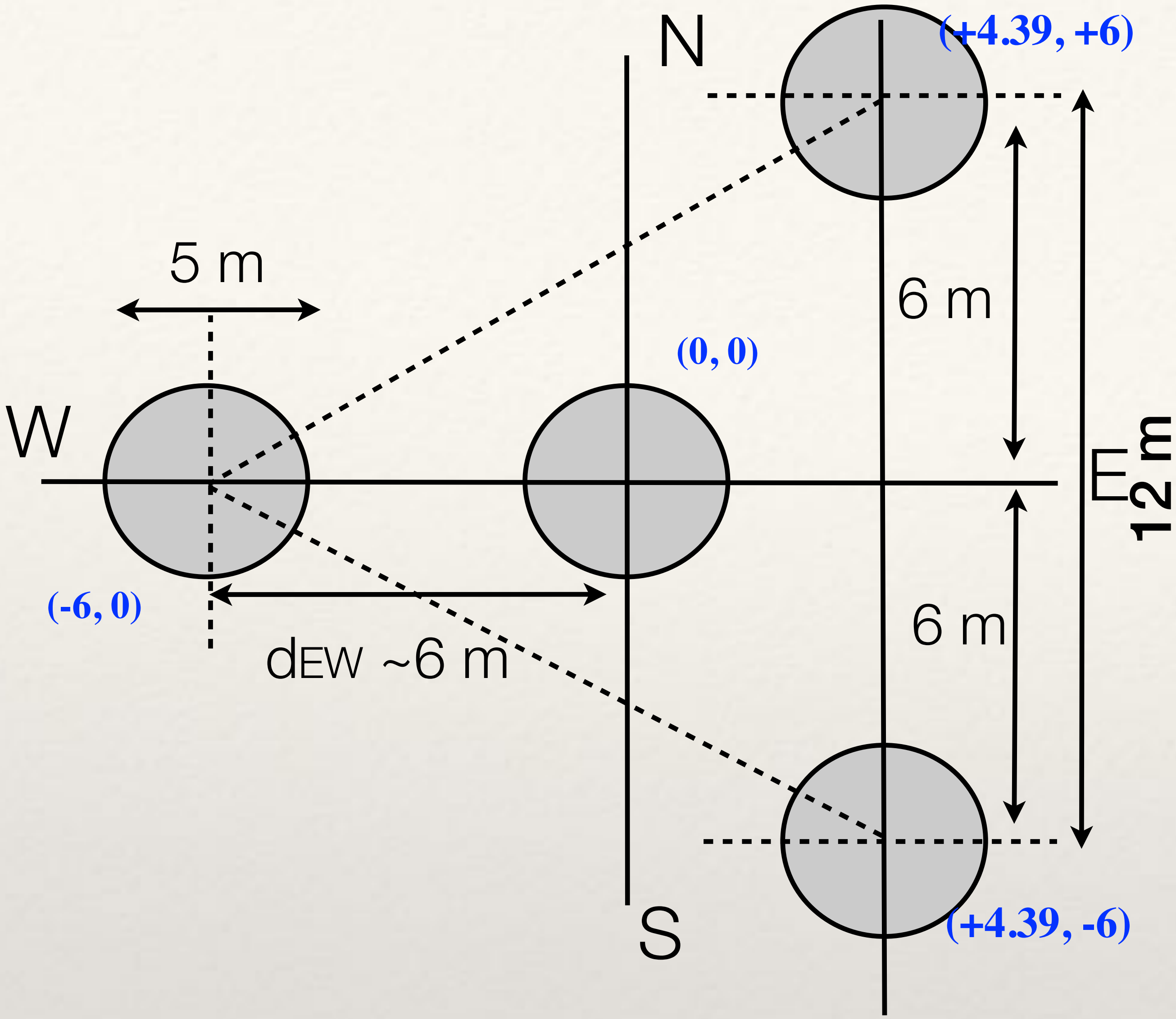
P. Hamès, M. Planchot, P. Deloye,
Services techniques et administratives de l'Observatoire,
GEPI/LESIA

Services techniques de l'IRFU

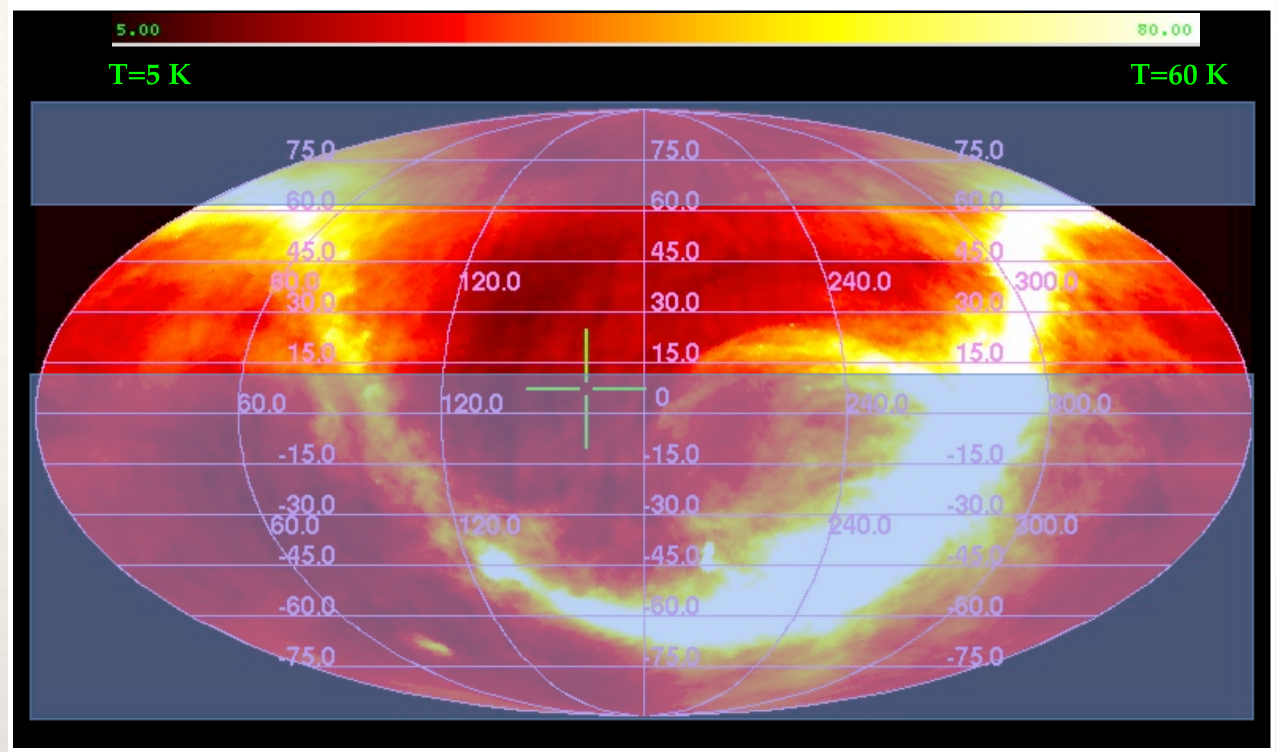
E. Delagnes, C. Flouzat, P. Starzynski

Montage: E. Amet, S. Blanc, J. Borsenberger, J.J. Bousquet, D. Coulmance, S. Gilleron, E. Gérard, S. Ouvrard, D. Polizzi, D. Proust, Y. Younes,

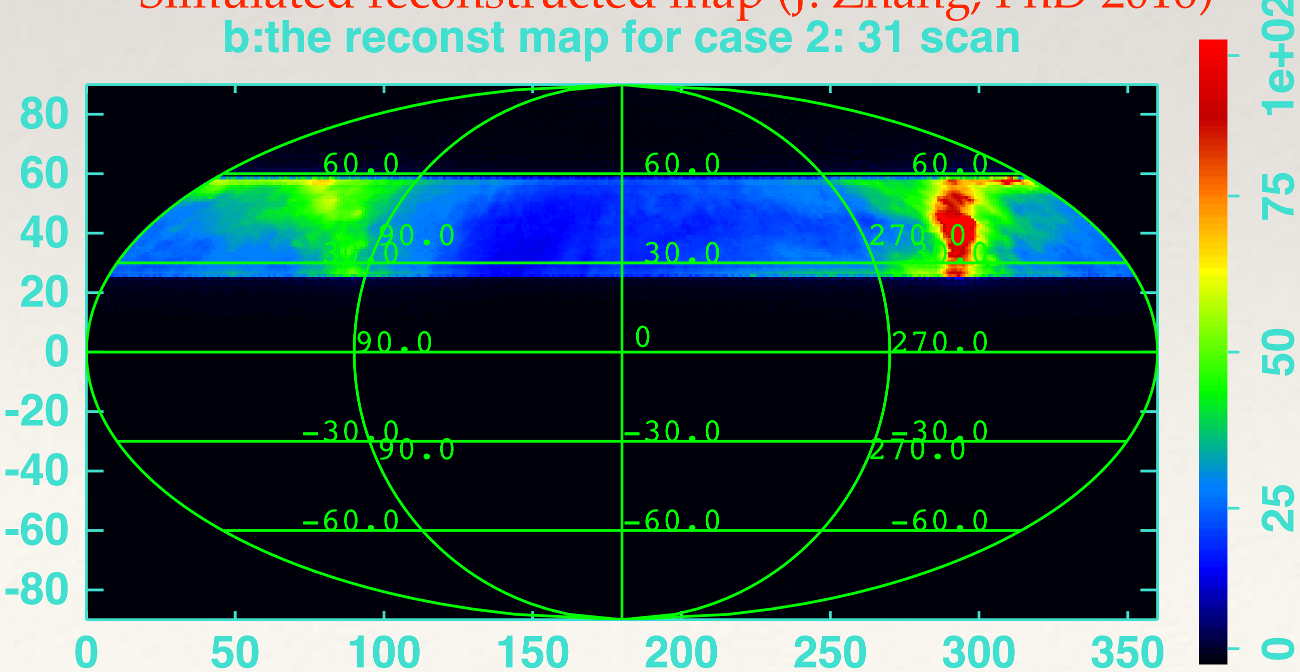
PAON4



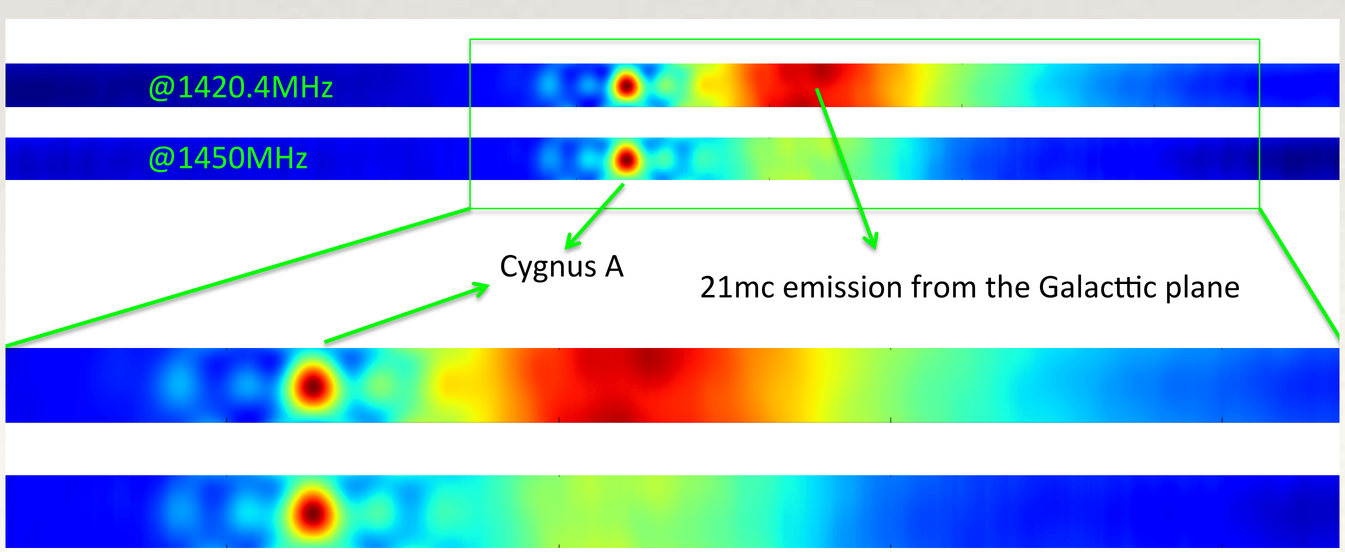
Synchrotron map @ 400 MHz - Eq. Coordinates (ra,dec)
PAON4 accessible sky region
38 S < Elevation < 15 N → 10 < δ < 60 at Nançay



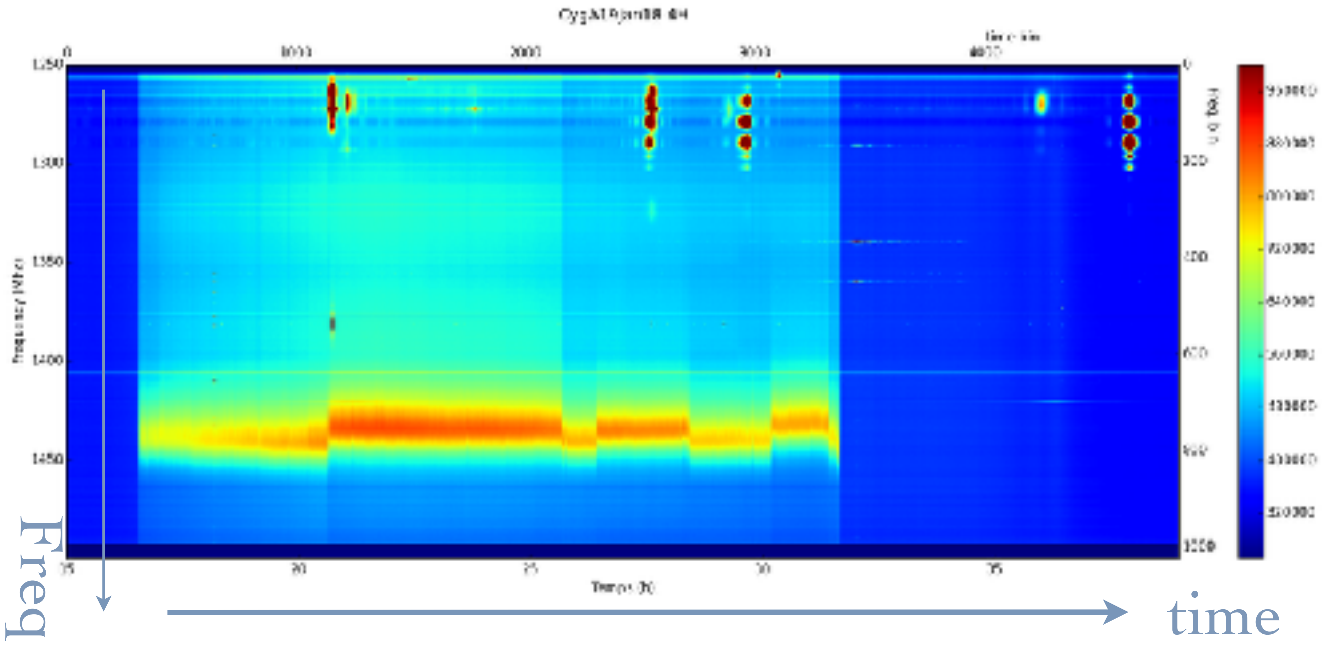
Simulated reconstructed map (J. Zhang, PhD 2016)

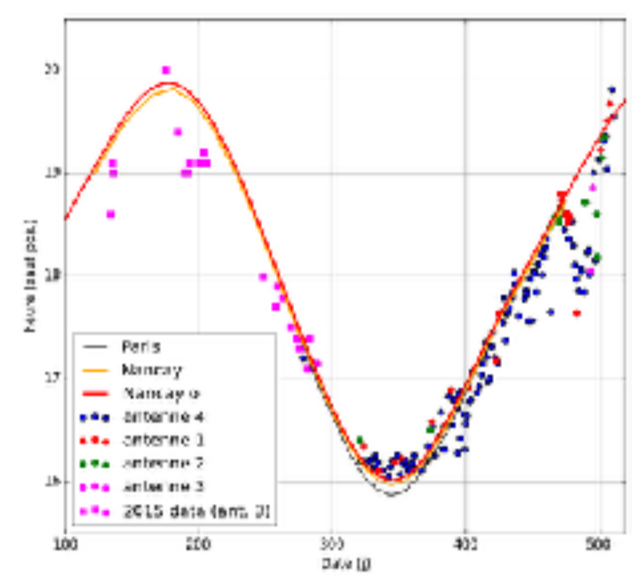


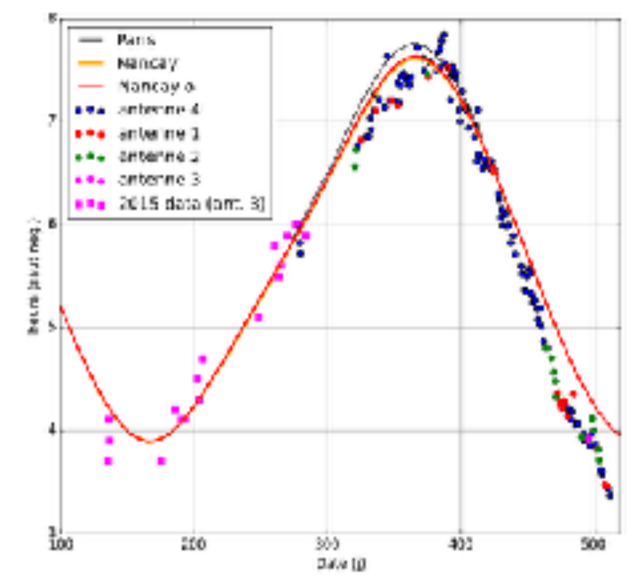
PAON4 reconstructed sky map, early 2015
(Q. Huang, PhD 2019)



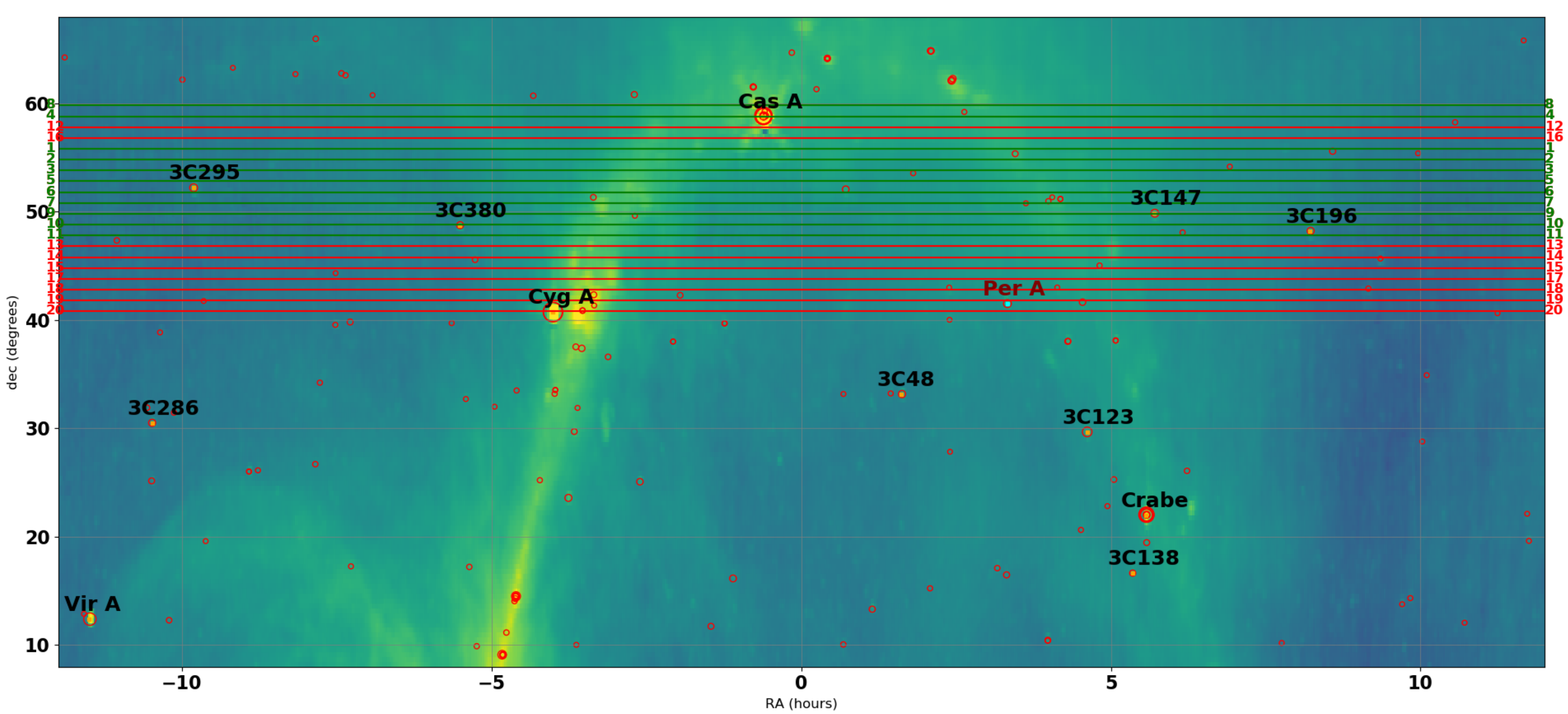
PAON4 : Perturbations due to a bird …

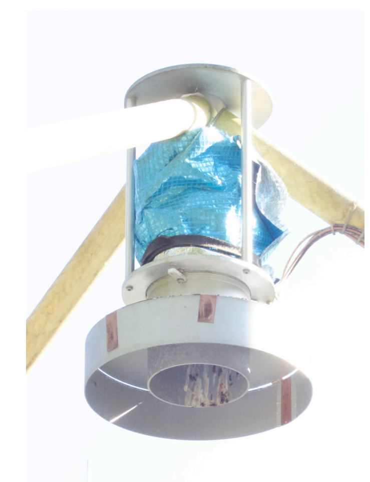






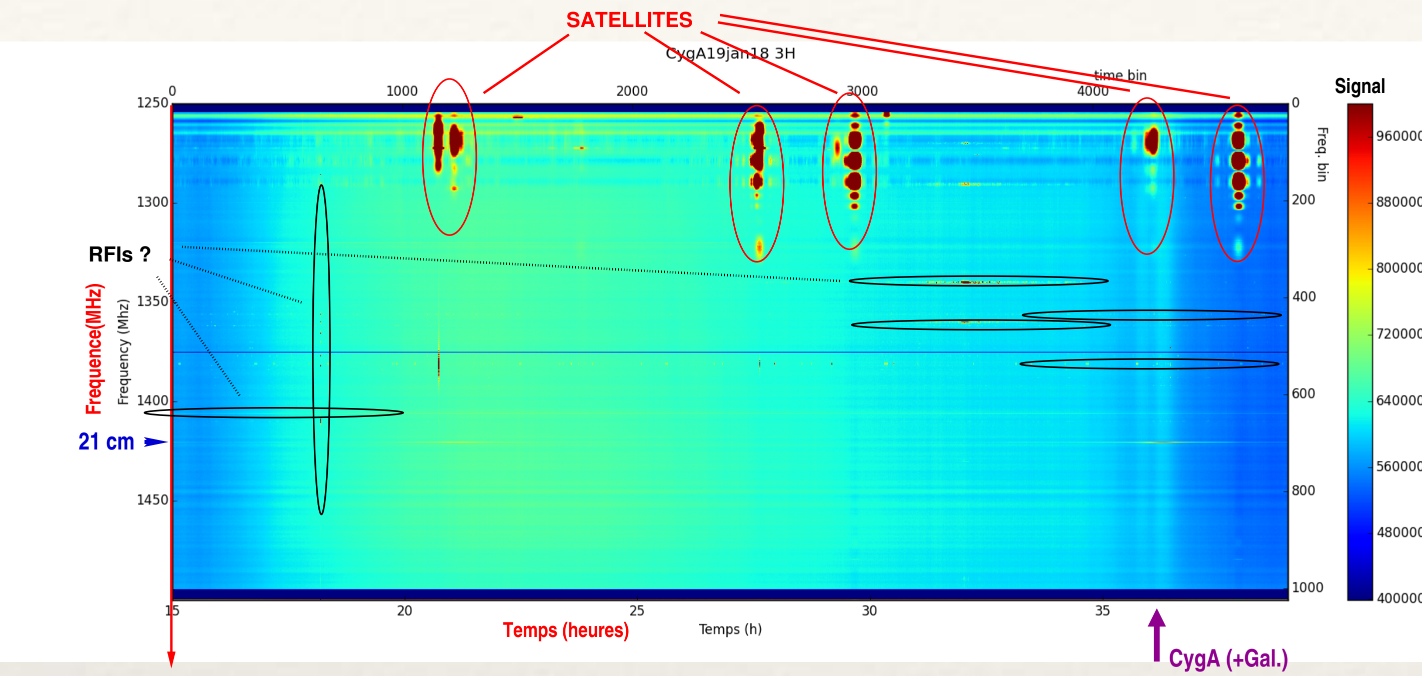
Nightly perturbations on one antenna (Winter/Spring 2017) -> bird in the feed !

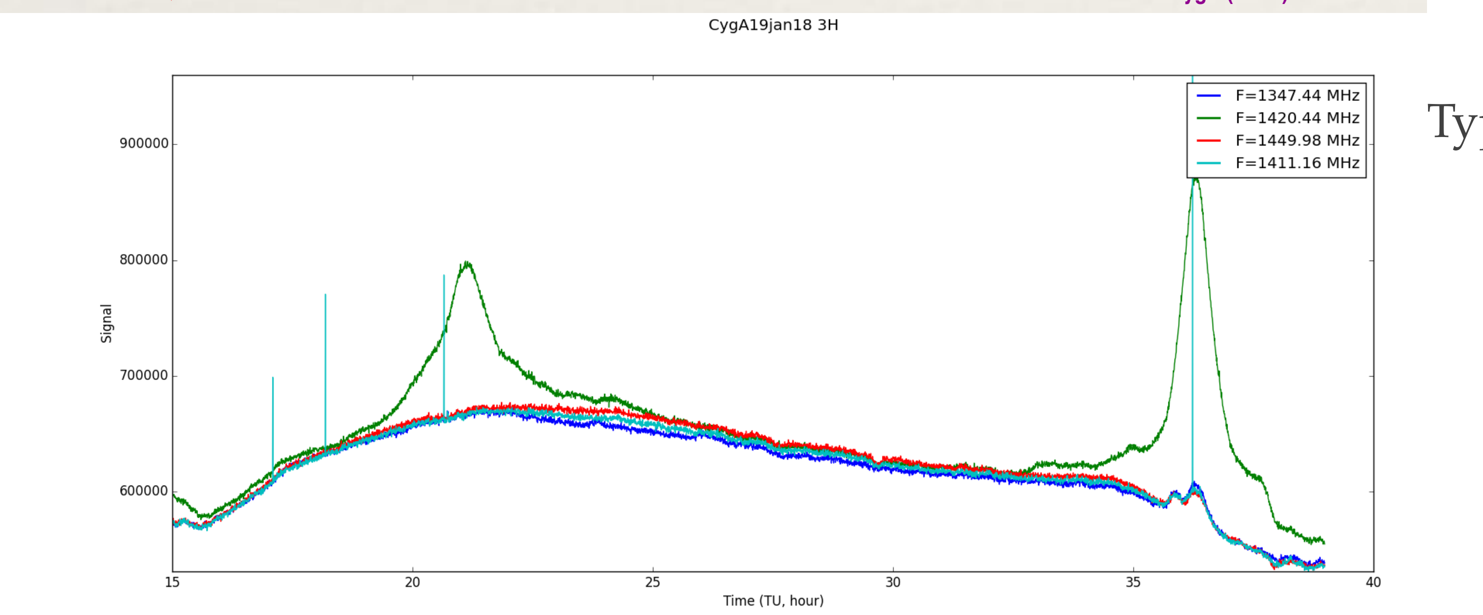


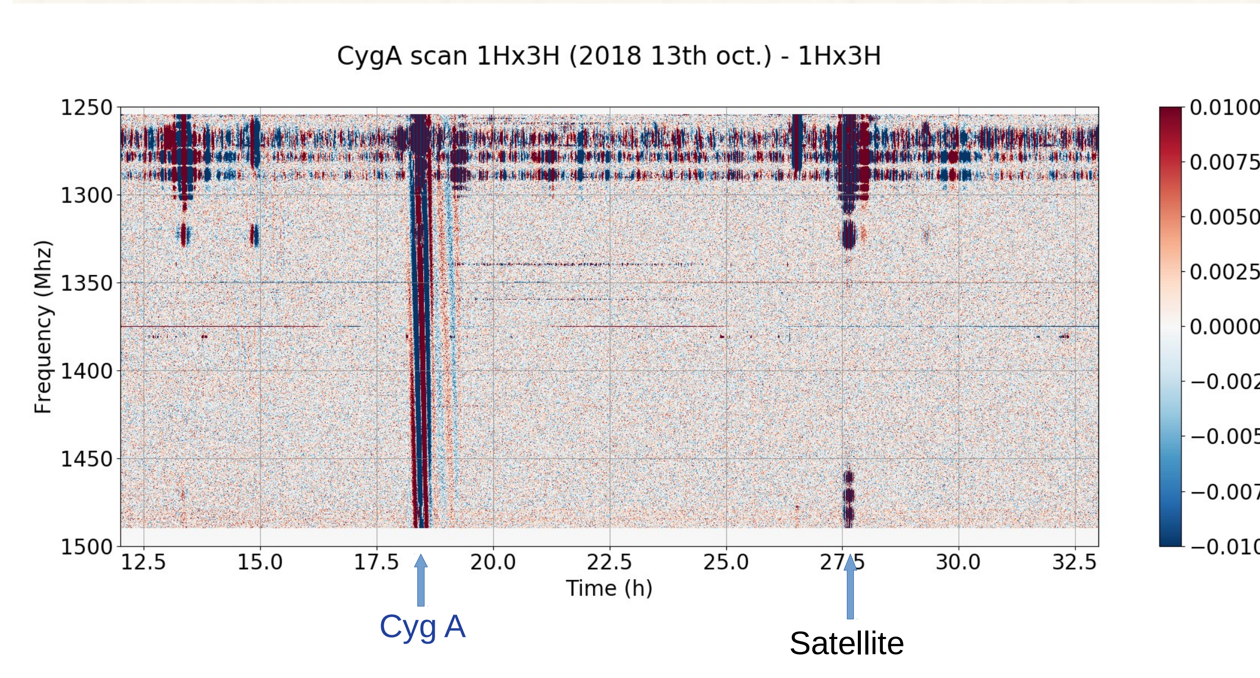


Observations : summer/Fall 2018 , 1250 - 1500 Mhz

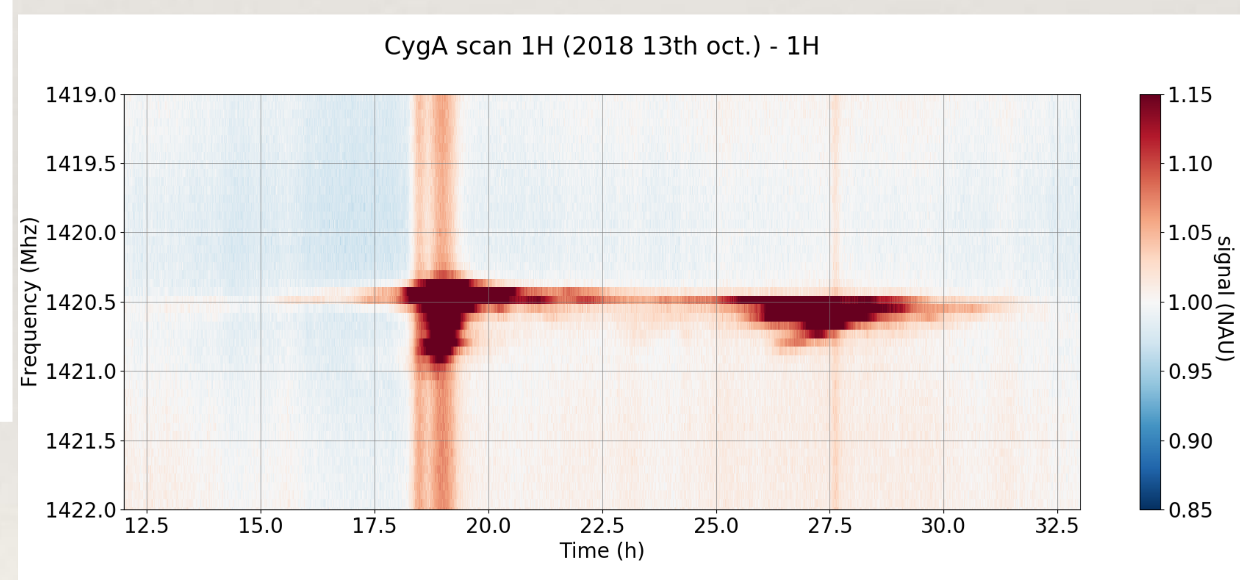
PAON4 : some results from 2018-2019 observations/analysis (I)







Typical cross-correlation time-frequency map over ~24 hours

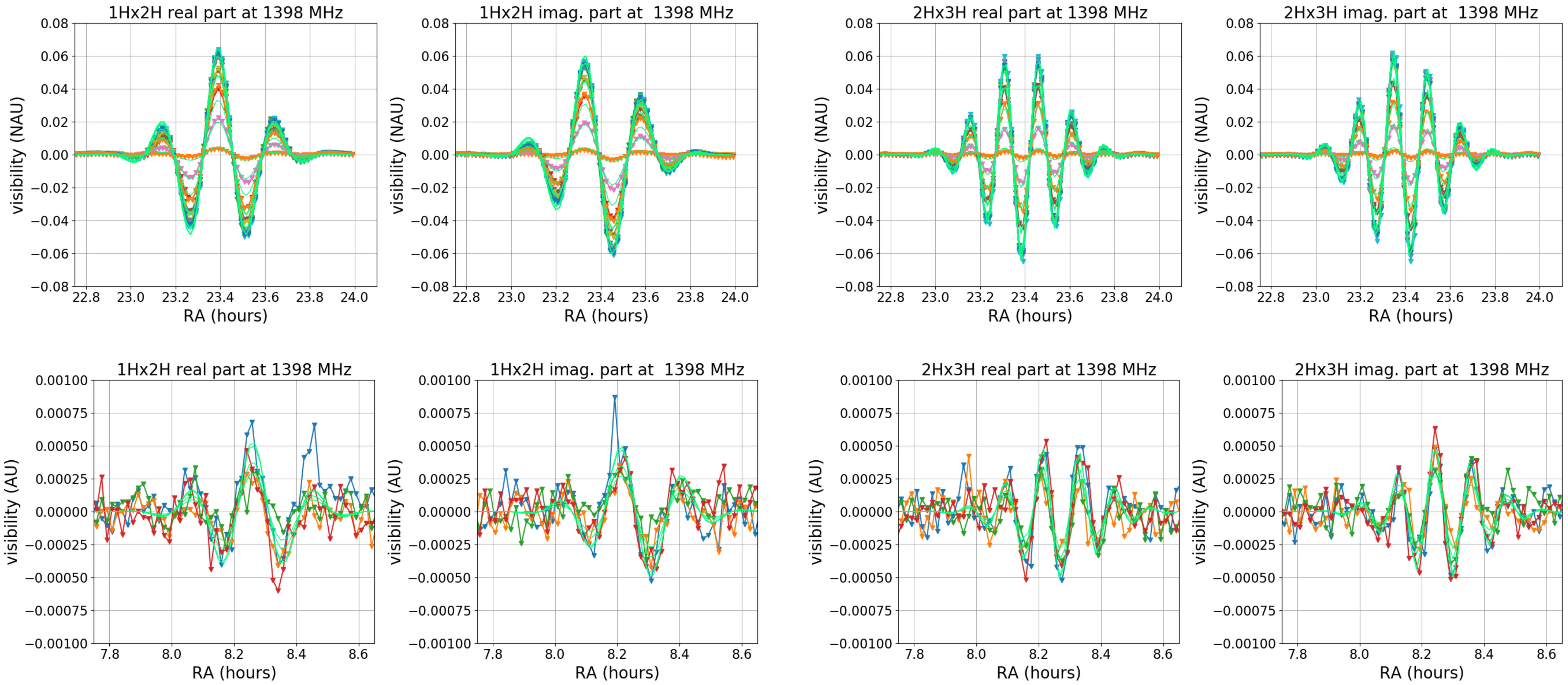


Typical auto-correlation time-frequency map (water-fall plots) over ~24 hours - Gain variation with Temperature corrected for using dedicated (or blind) channel - we achieve currently stability $\pm 3-5\%$

Galactic 21cm signal - zoom in frequency

R. Ansari et al, MNRAS 2020 , arXiv:1910.07956

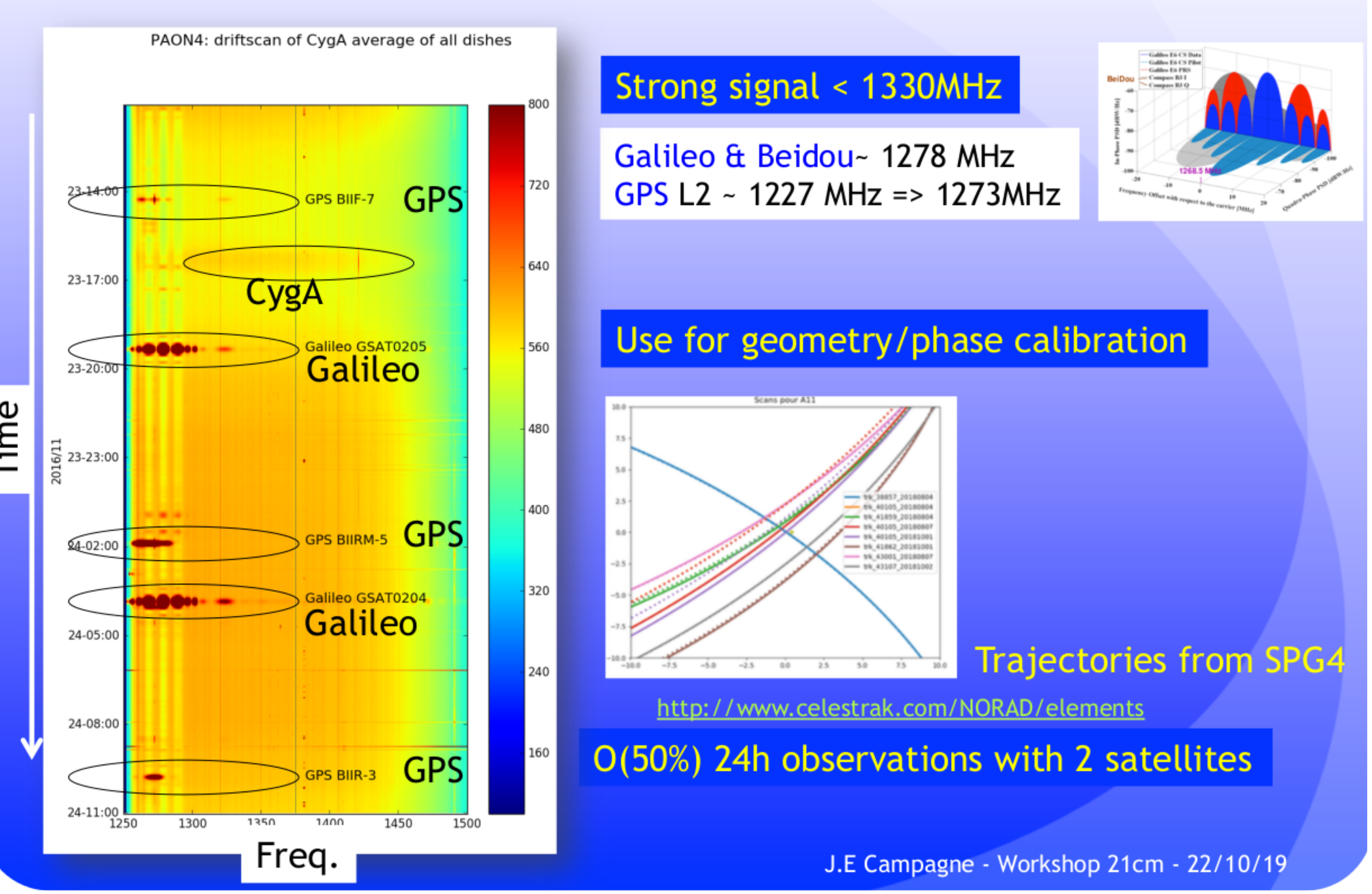
PAON4 : some results from 2018-2019 observations/analysis (II)



CasA transits (top) , 3C196 (bottom) - PAON4 observations (different declinations) - compared with expected signals
O. Perdereau, J.E. Campagne

R. Ansari et al, MNRAS 2020 , arXiv:1910.07956

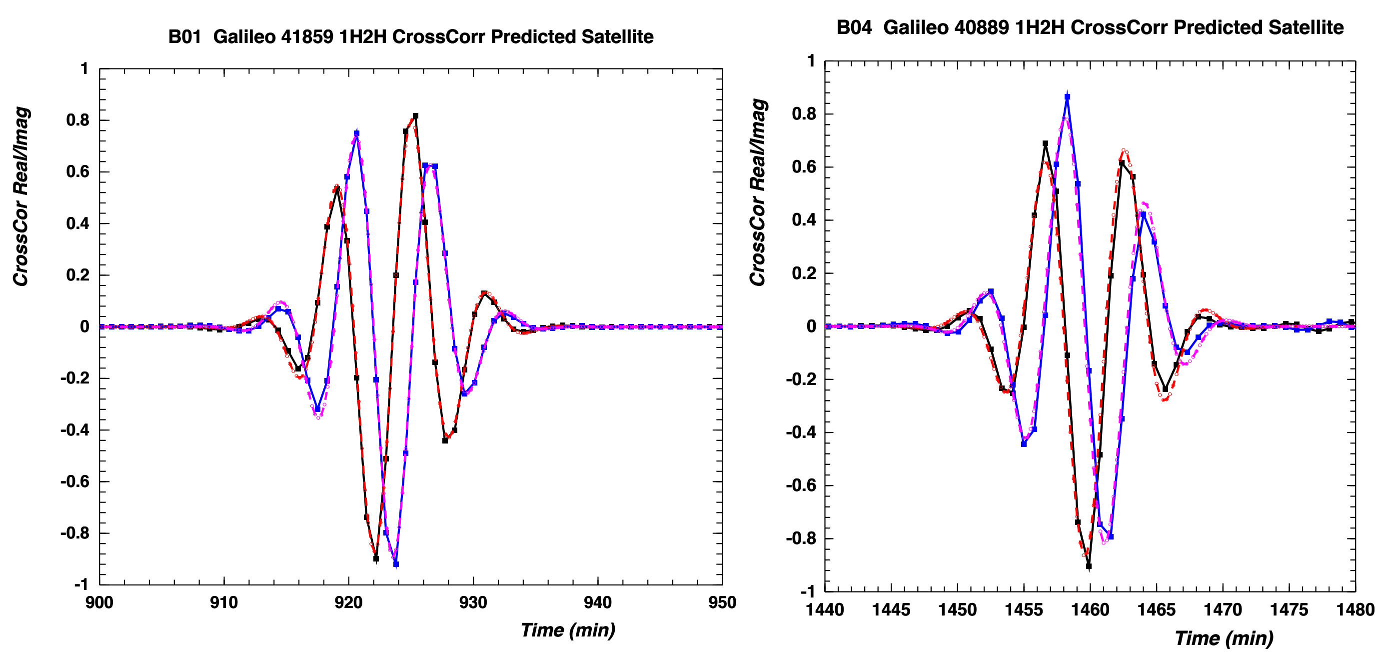
PAON4 calibration using GPS/Galileo satellites

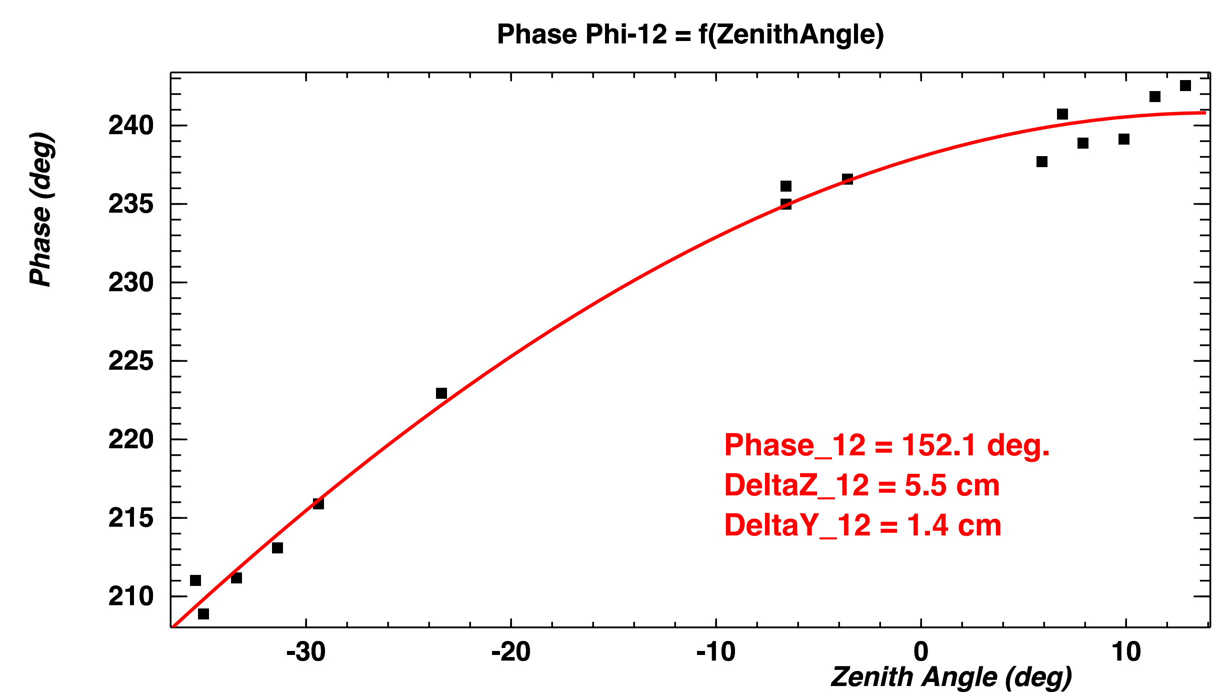


Using Galileo/GPS/Beidou satellite tracks , we were able to compute phase calibration, adjust the geometry (using tracks when observing at different declinations, over several months)

phase stability within +/- 3 deg after correcting for geometry

Satellite tracks : observed , expected -> phase and geometry calibration



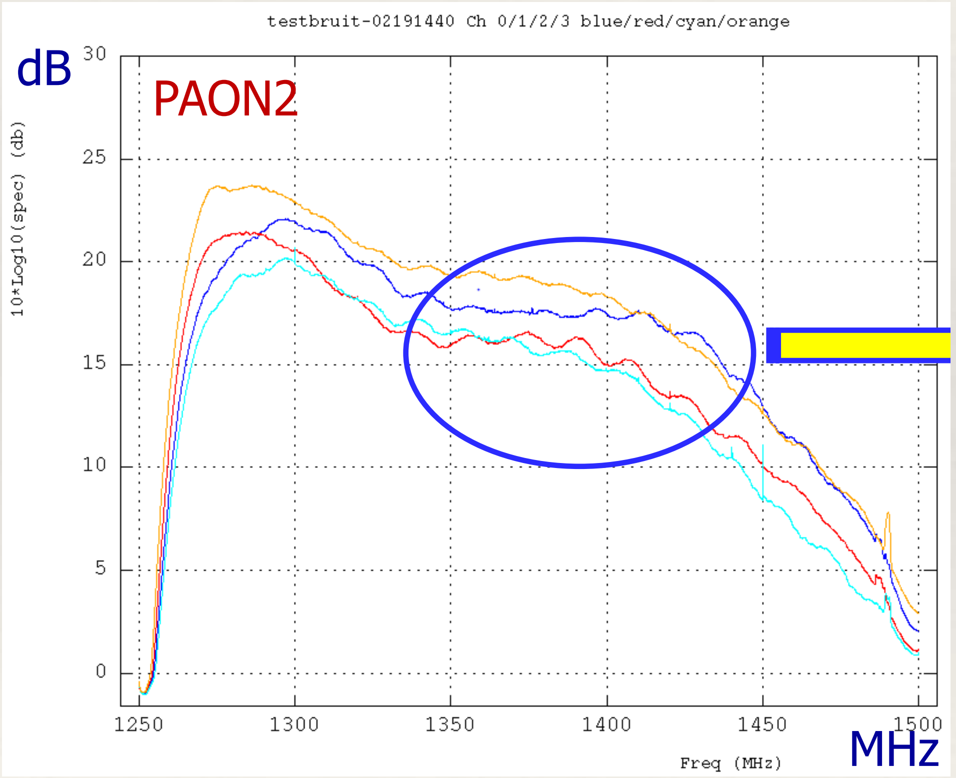


R. Ansari et al, MNRAS 2020 , arXiv:1910.07956

NEBuLA / IDROGEN

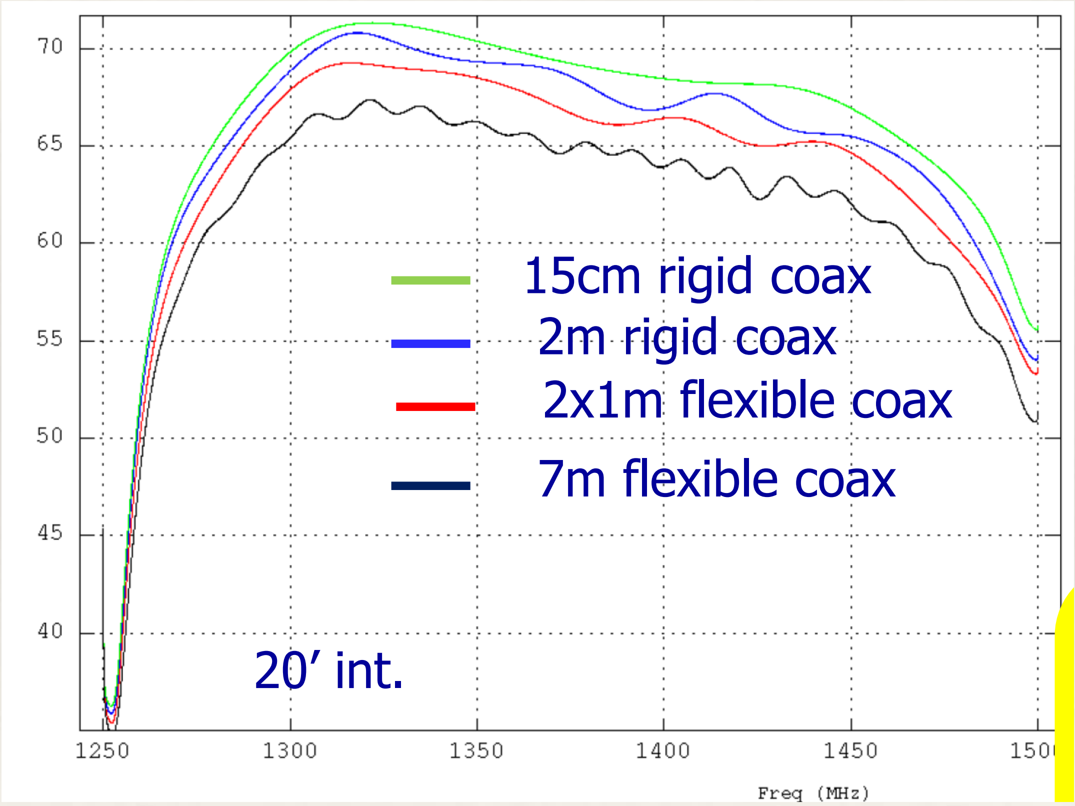
- Gain drifts with temperature
- wiggles in the band-pass due to standing waves (cables …) - seen also with HICluster

See also Tianlai standing wave paper, Jixia Li et al RAA (2020) arXiv:2007.11129



left: band pass wiggles, observed on PAON2, (2014)

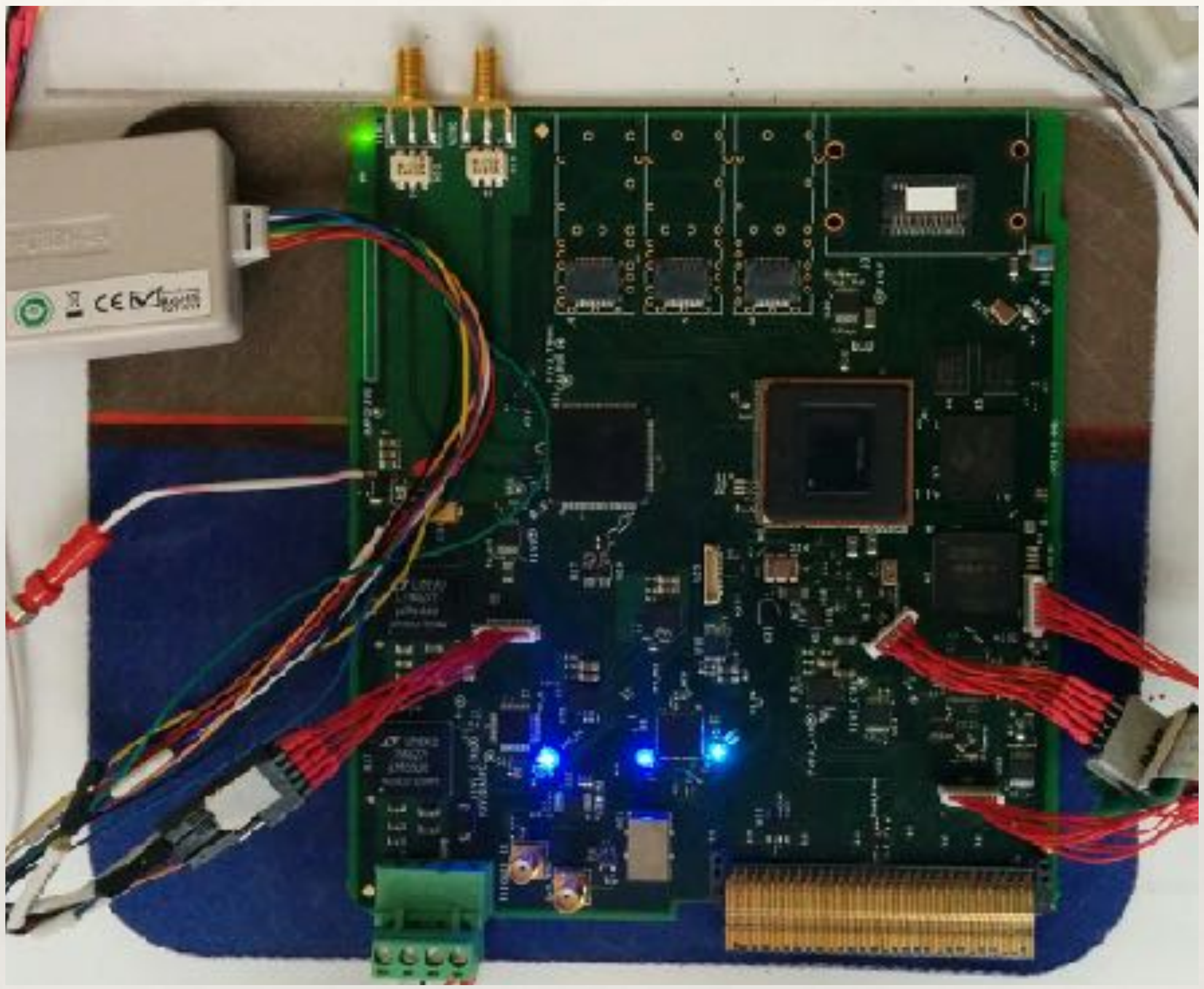
Measured in the lab, with different cable lengths



- Development of a new digitiser board, to be placed as close as possible to the feed
- Shorten cable length, simplify the analog electronics (drop the LO,mixer-frequency shifter)
- Program **NEBuLA** initiated in 2014/2015, later became **IDROGEN**

From NEBuLA to DAQGEN/IDROGEN

D. Charlet (LAL) , C. Viou (Nançay)



NEBuLA board (v1) in 2016/2017
clock system, ADC, microcontroler,
White-Rabbit, xTCA interface tested OK

- Direct sampling after the LNA + filters (no mixer)
- Up to 500 MHz bandwidth
- designed to be put near the antennae
- optical data output & control / synchronisation
- White Rabbit technology for clock synchronisation through (optical) ethernet
- board configuration through the optical ethernet link
- data (waveform or frequency components) transferred through optical links (10G ethernet), possibly higher rates in the future

NEBuLA-v2 as the IDROGEN board within the
IN2P3 - DAQGEN project. new FPGA,
ADC as a mezzanine board
IDROGEN board developed by LAL & Nançay

White Rabbit clock synchronisation

The White Rabbit Project

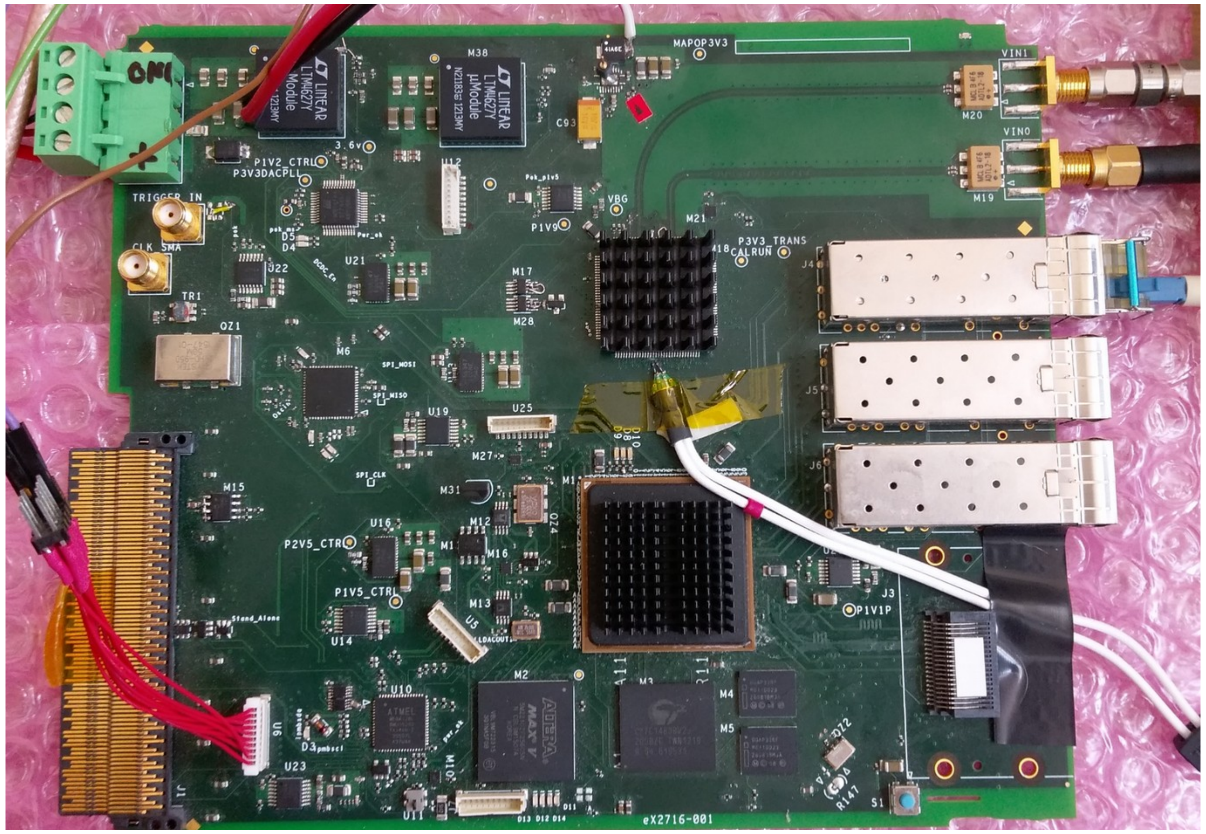
https://white-rabbit.web.cern.ch

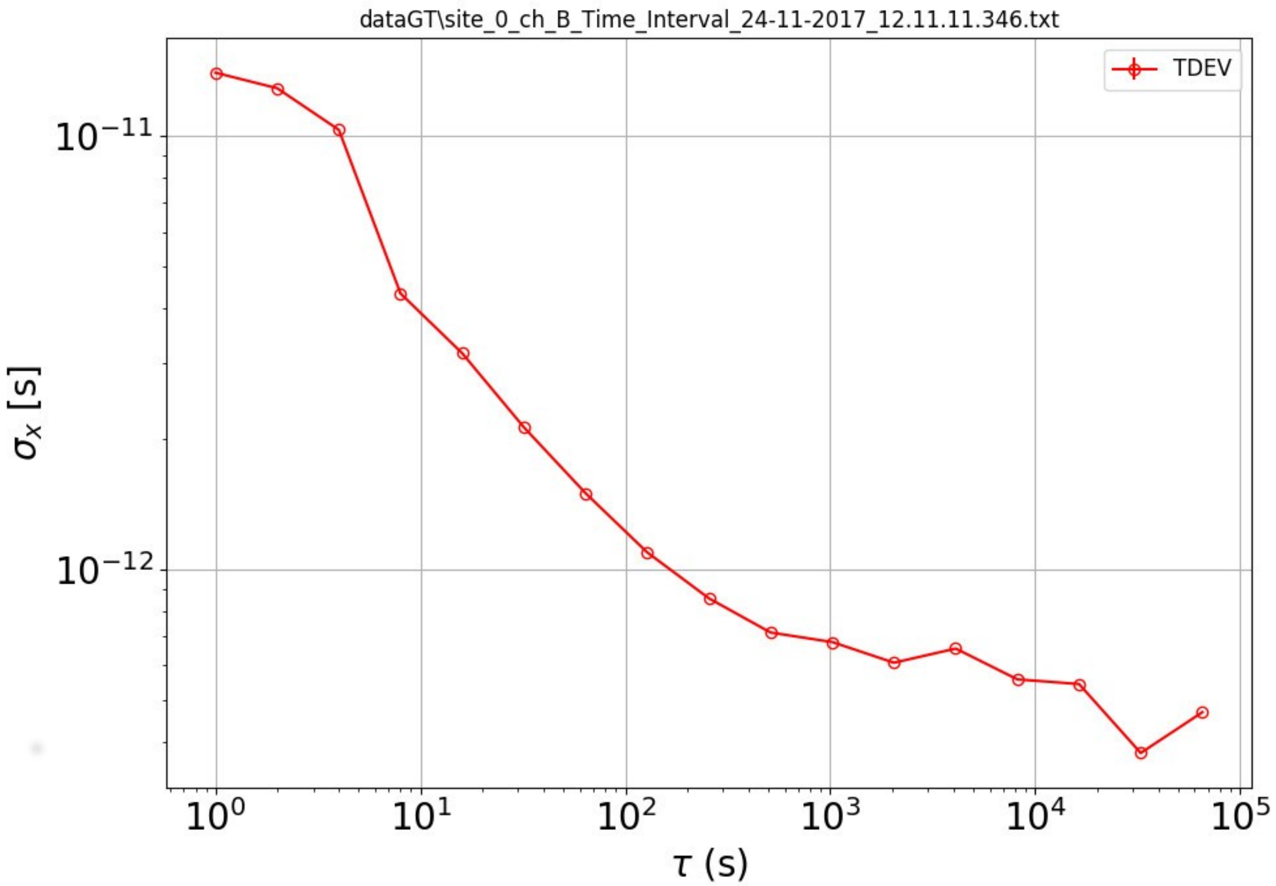
- sub-nanosecond accuracy and picoseconds precision of synchronization
- connecting thousands of nodes
- typical distances of 10 km between network elements
- Gigabit rate of data transfer
- fully open hardware, firmware and software
- commercial availability from many vendors

Lipinski et al (2011) https://white-rabbit.web.cern.ch/documents/index.html
White Rabbit: a PTP Application for Robust Sub-nanosecond Synchronization

Rizzi et al (2015) https://white-rabbit.web.cern.ch/documents/index.html
Enhanced synchronization accuracy in IEEE1588

IDROGEN : clock stability

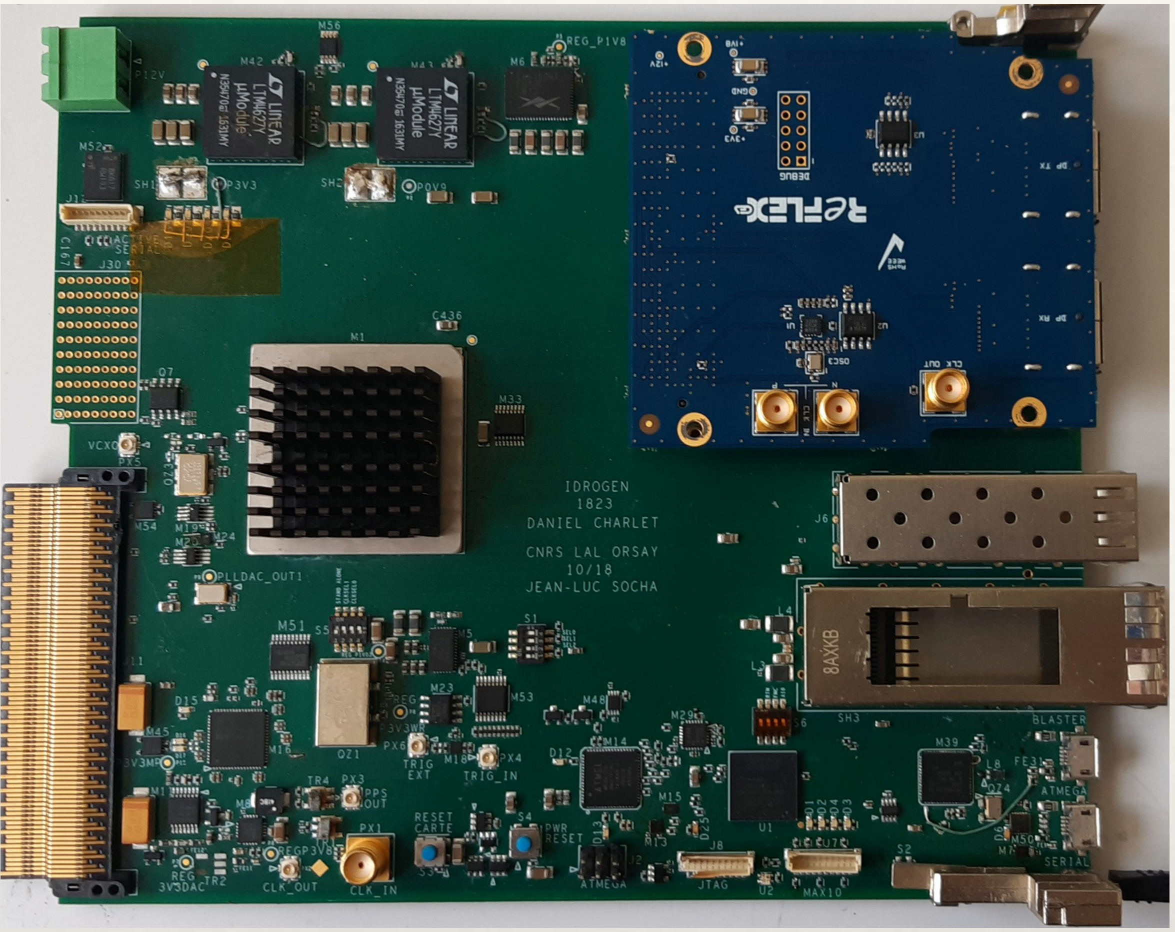




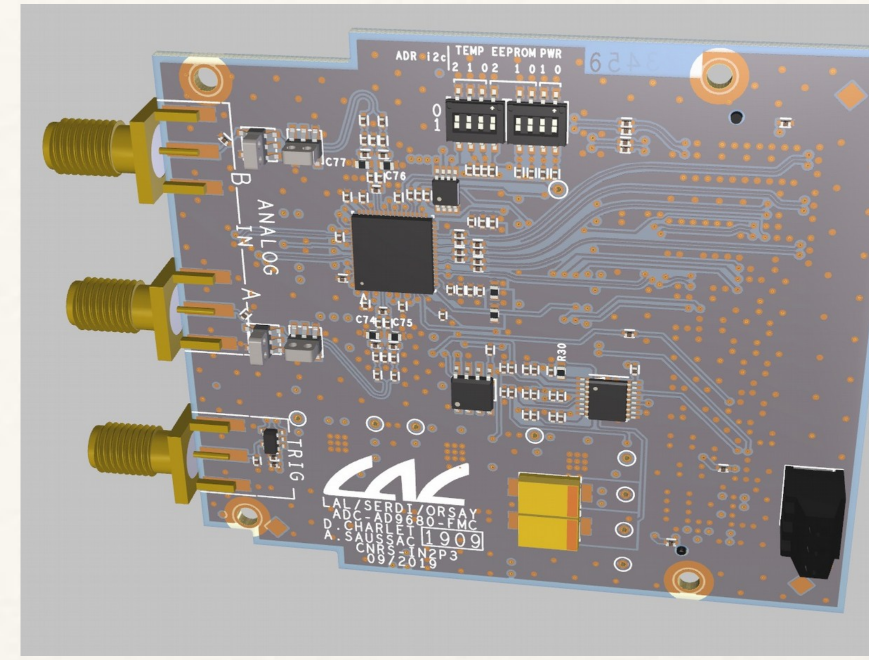
- Derived from Nebula board
  - White rabbit module
  - Power supply tree
- In collaboration with SYRTE
  - Observatoire de Paris
  - Time-Frequency laboratory
- 400 fs after 1000 s and 1 km fibre

First version of the IDROGEN board (v1) in 2017/2018

IDROGEN status (Aug. 2020)



IDROGEN board (v2) with commercial ADC (mezzanine) board -2019



Mezzanine ADC board designed and fabricated (2020), will be tested in fal

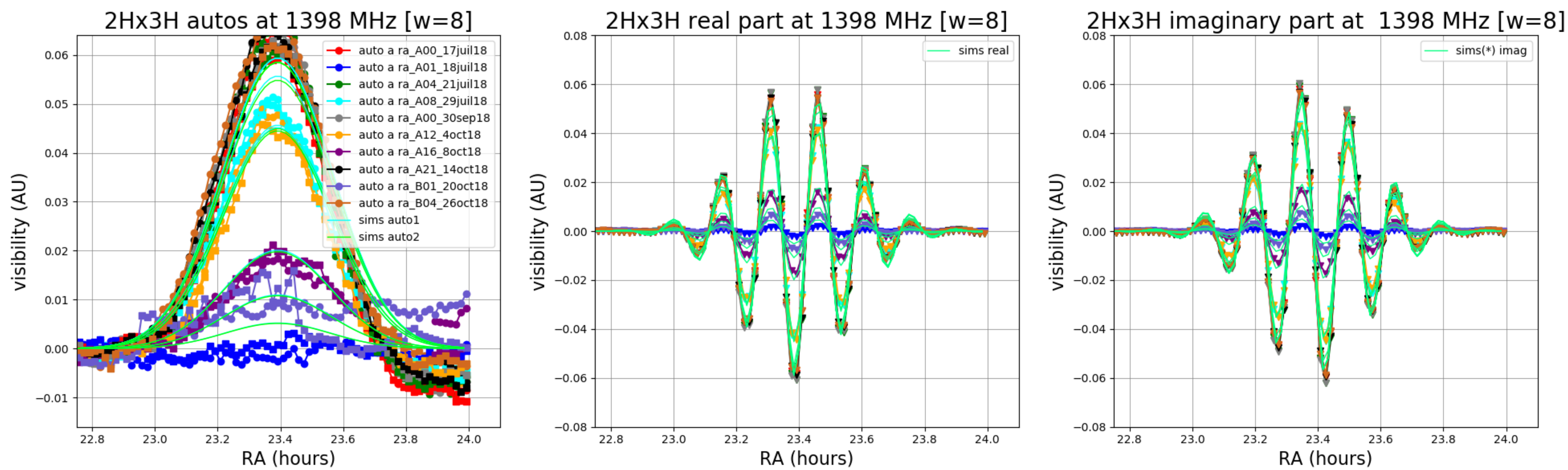
RF tight boxes/housing made for PAON4

- IDROGEN board v3 (v2.b) being produced for PAON4 and other users (IN2P3 labs)
- Firmware development continues
- IDROGEN softwares : acquisition and slow control (M. Taurigna, C. Cheikali)
- Expect deployment on PAON4 at the end of 2020
- A new version of the board, smaller size could be designed and produced by removing xTCA interface

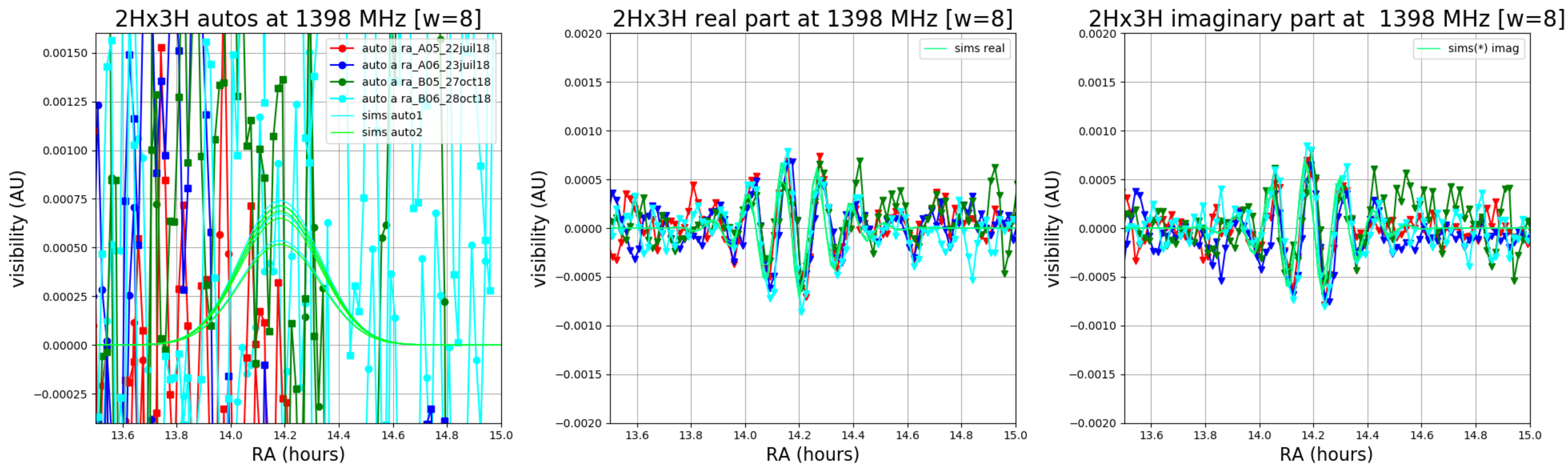
For technical details, see D. Charlet & C. Viou presentation at the 2019 Orsay workshop

Backup

PAON4 : some results from 2018-2019 observations/analysis (II)



CasA transit , comparison observations with simulated signals (instrument stability) , O. Perdereau, J.E. Campagne

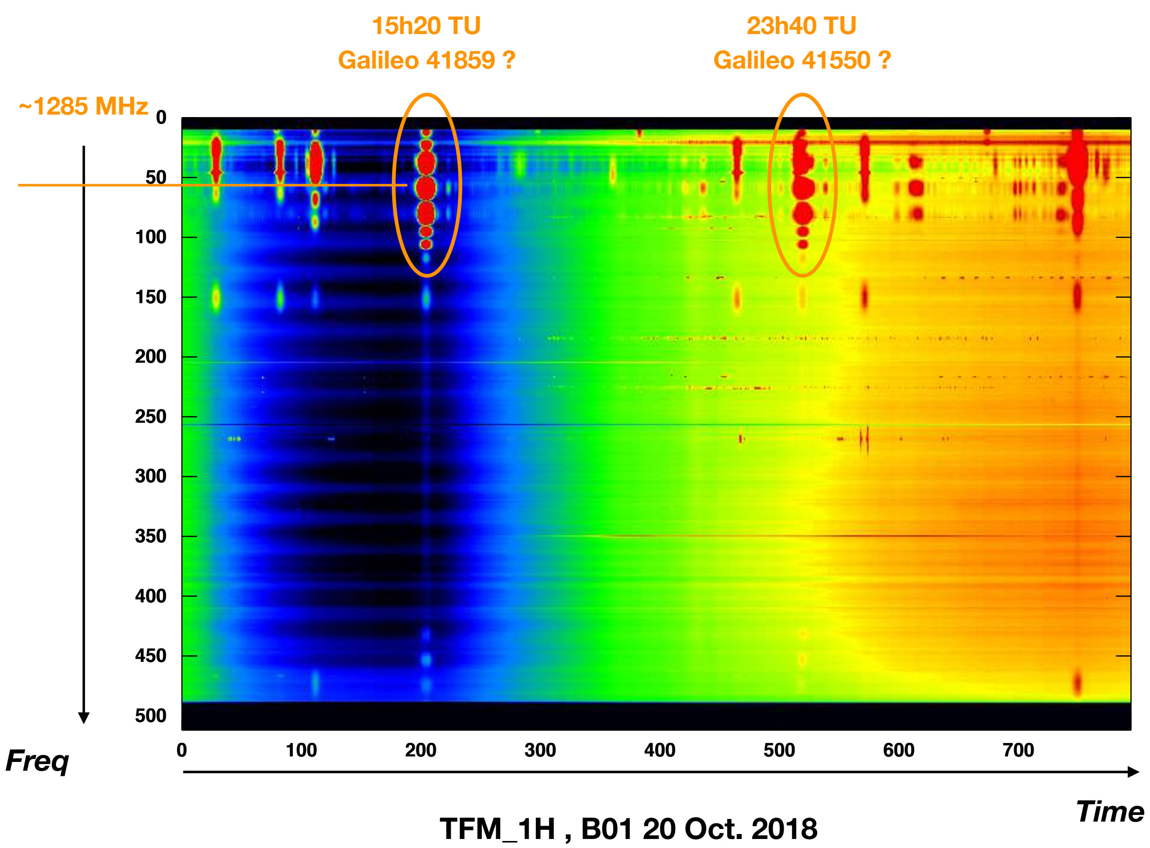


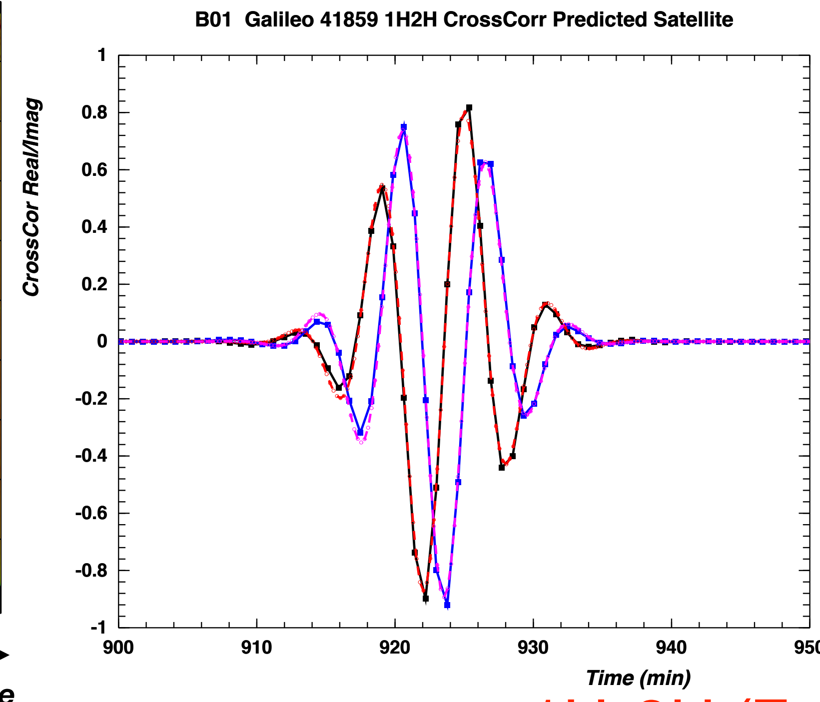
3C295 transit , comparison observations with simulated signals

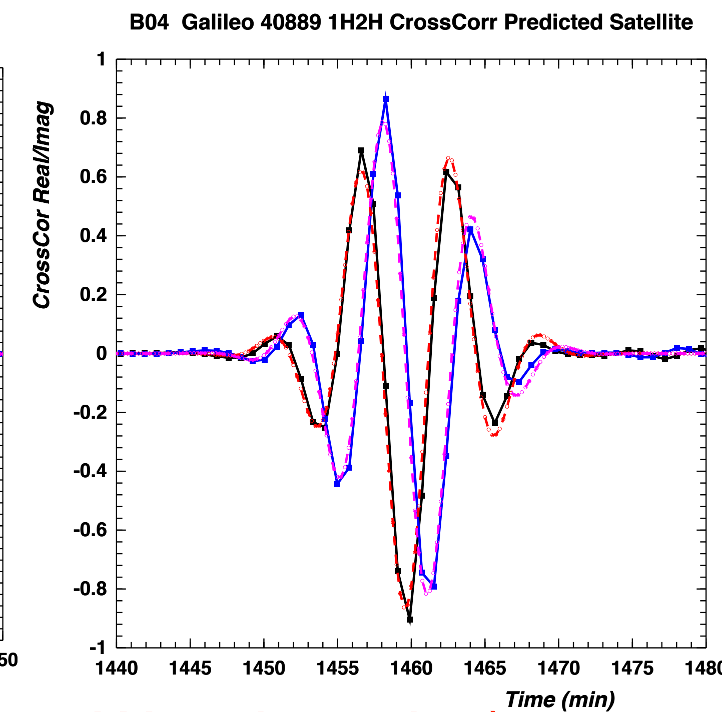
R. Ansari et al, MNRAS 2020 , arXiv:1910.07956

PAON4 : some results from 2018-2019 observations/analysis (III)

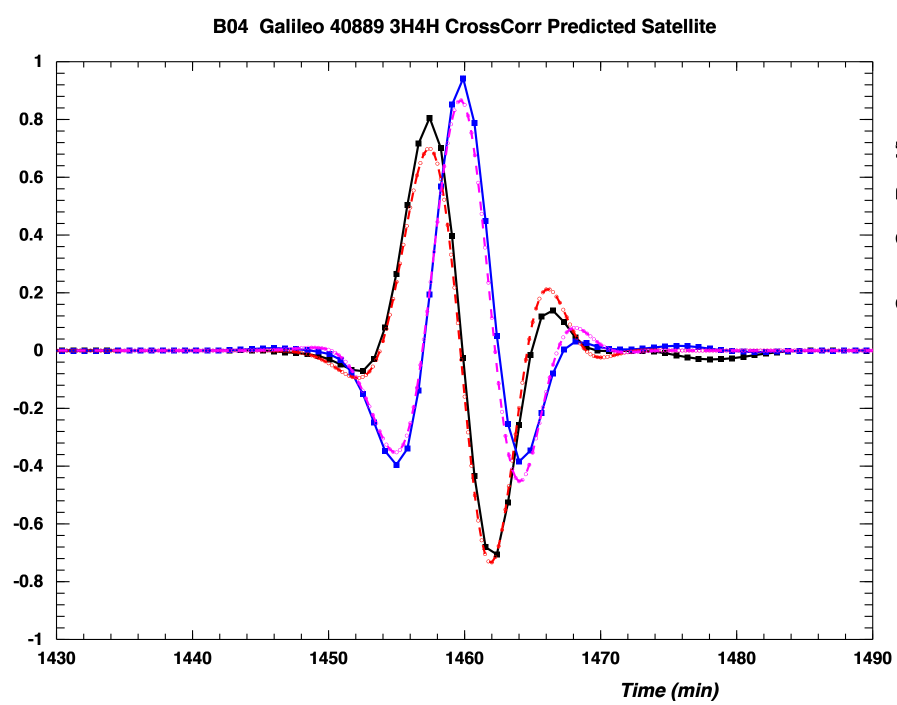
PAON4 : Using satellites (GPS, Galileo …) for phase & geometry determination

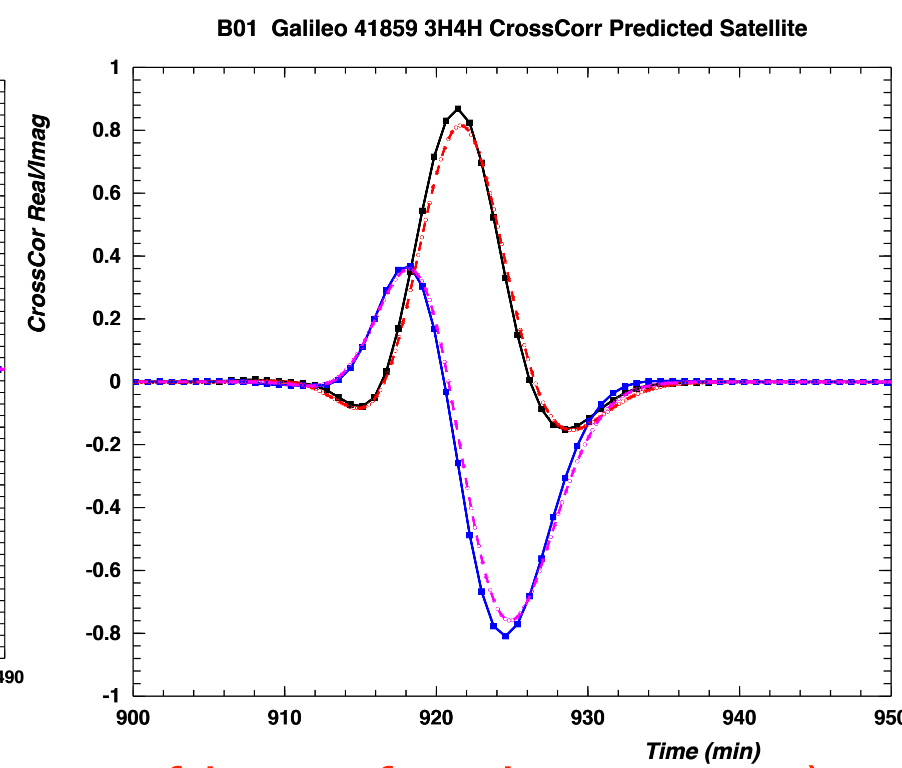






1H-2H (East-West baseline)





3H-4H (North-South baseline, no fringes for sky sources)