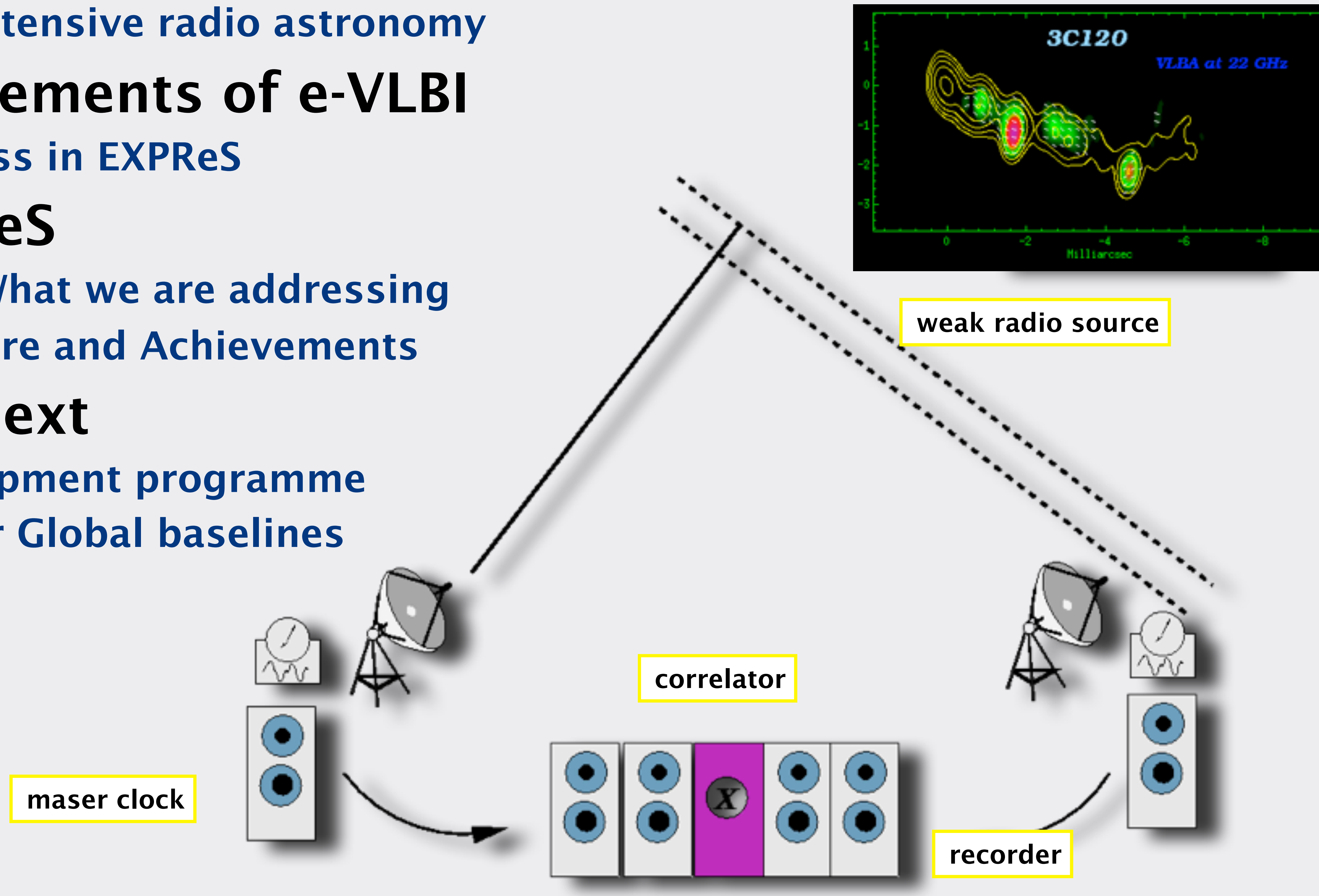
Connecting Radio Telescopes for Global VLBI

Huib van Langevelde
JIVE

Outline

- **Introduce concepts**
  - What is VLBI, how is it organized in Europe
  - Data intensive radio astronomy
- **Achievements of e-VLBI**
  - Progress in EXPReS
- **NEXPReS**
  - Why? What we are addressing
  - Structure and Achievements
- **What next**
  - Development programme
  - Call for Global baselines



Acronyms/Organisations involved

- VLBI: Very Long Baseline Interferometry
  - Radio telescopes thousands kilometres apart
- EVN: European VLBI Network
  - Consortium of (European) Telescopes
- JIVE: Joint Institute for VLBI in Europe
  - Funded by radio-astronomy institutes and research councils
    - NWO (NL), ASTRON (NL), STFC (UK), INAF (IT), ICN-IG (ES), OSO (SE), MPG (DE) CAS (CN), CNRS (FR), NRF (ZA)
  - Promote the use and advance of VLBI (for astronomy)
- EXPReS: FP6 project on establishing e-VLBI
  - Express Production Real-time e-VLBI Services
- NEXPRes: FP7 project building on e-VLBI
  - Novel Explorations Pushing Robust e-VLBI Services

Hartebeesthoek a very valued member of the EVN

- Now with 2 antennas on site
- North-south sensitivity on long baselines

South-Africa's NRF joined JIVE foundation on May 10

Recognizing a joint interest:

- VLBI with KAT7 and MeerKAT
- The potential of the AVN
- Human capacity building

Joint Institute for VLBI in Europe

- **Promote the use and advance of VLBI for astronomy**
  - Central correlation; User services; Network support; Innovation; EC liaison/ representation
- **Founded in 1993**
  - Base budget from partners in 9 countries:
  - Large number of external projects
  - Hosted by ASTRON, Dwingeloo NL
  - 34 employees
- **Just been reviewed**
  - Next 5-year funding cycle
  - In a newly build wing
- **Aiming to be an ERIC**
  - European Research Infrastrcucuture Consortium

The European VLBI Network

JOINT INSTITUTE FOR VLBI IN EUROPE

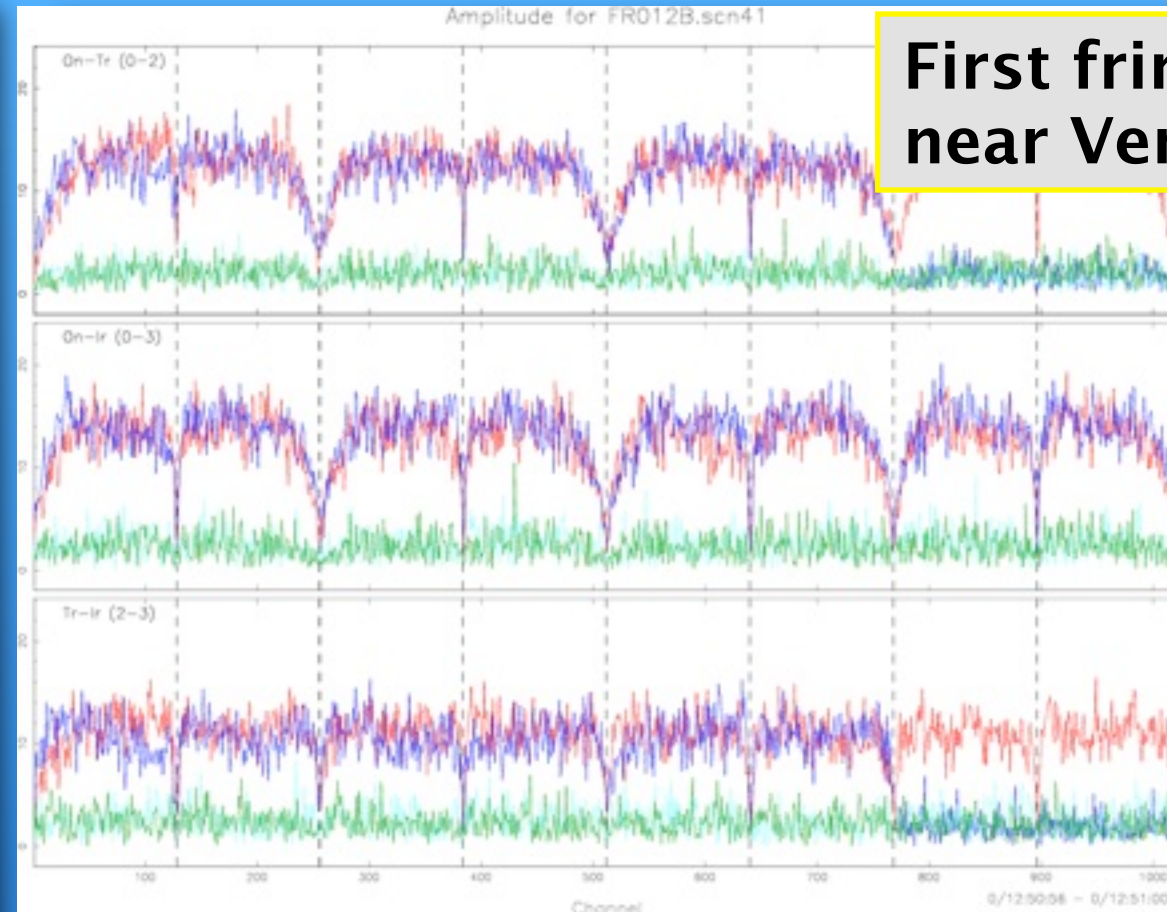
- Big telescopes in number of European countries
- 20+ possible antennas
    - Ef, Mc, On, Jb, Nt, Tr, Wb, Sh, Ur, Hh, Ar, Mh, Ys, Sv, Ro, Ku, My, Wz, Sm, Ny, Ka
  - Ran by up to 14 different organizations
  - And 12 more antennas for "Globals" with NRAO

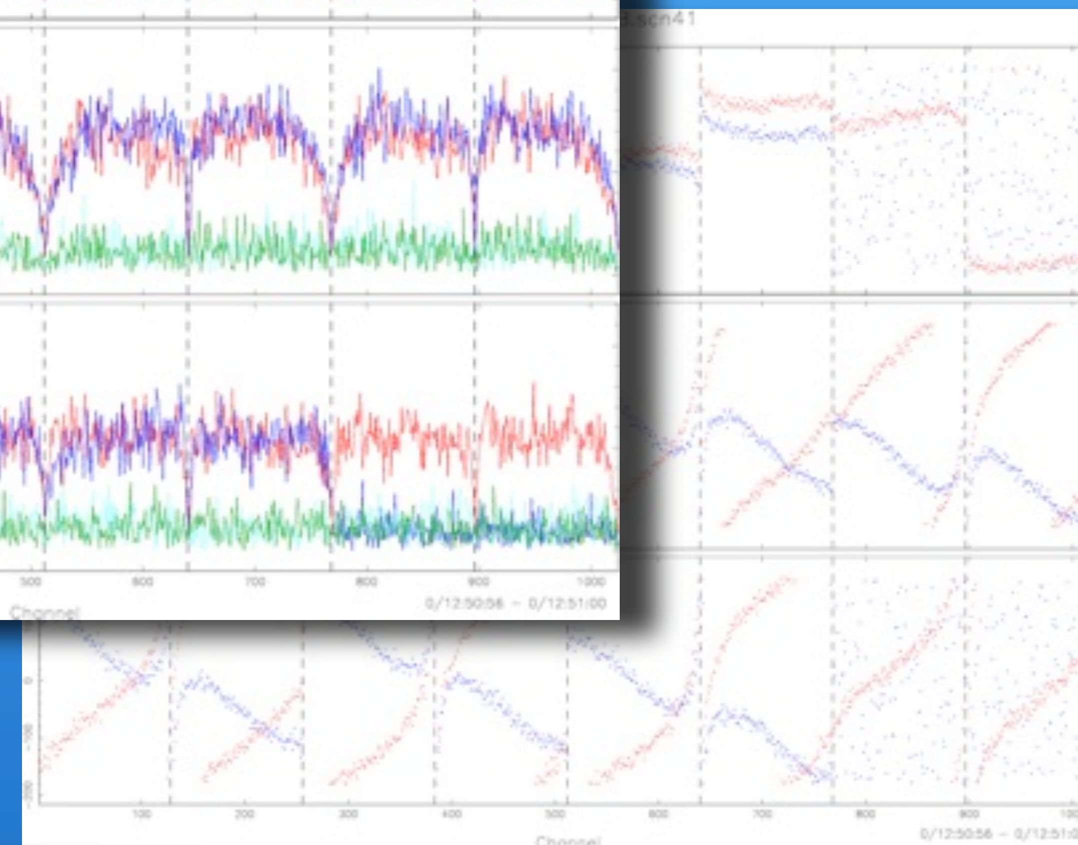
- Covering range of frequencies
  - Workhorse frequencies 18cm, 6cm,
  - Also available: SX, 5cm, 1.2cm
  - And at limited stations 90cm, 21cm, UHF, 50cm, 2cm, 0.7mm
- Reaching mas resolutions
  - From 15mas for 1.4 GHz EVN (can add MERLIN for brightness sensitivity)
  - To 1 mas at 5GHz with Asian, African or American baselines
- Sensitivity of 5µJy in 8hr at 1.4 GHz
  - Combination of Big Antennas and 1 Gbps bandwidth
  - Big antennas also vital for spectroscopy (mJy sensitivity)
- Operational approximately 60 days/year
  - 3 sessions augmented with e-VLBI once a month

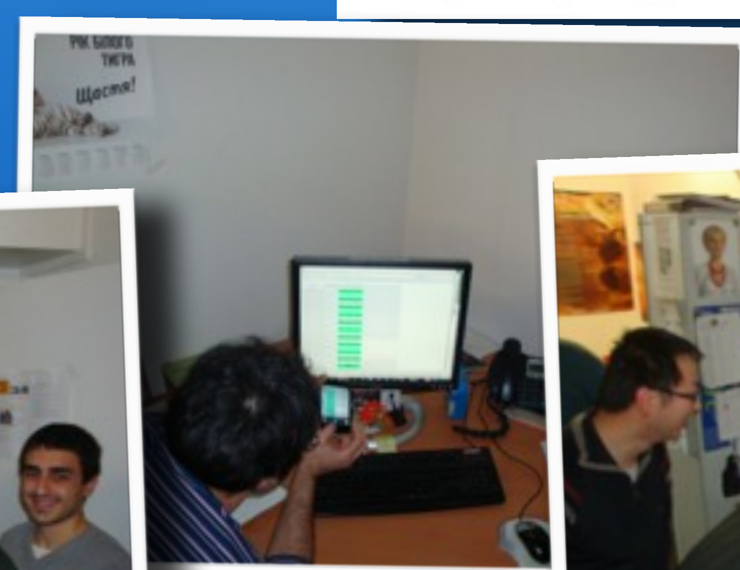

Jodrell Bank UK
Onsala SE
Metsahovi FI
Torun PL
Westerbork NL
Effelsberg DE
Medicina IT
Yebes ES
Noto IT
Arecibo
Svetloe
Irbene
Torun
Wettzell
Evpatoria

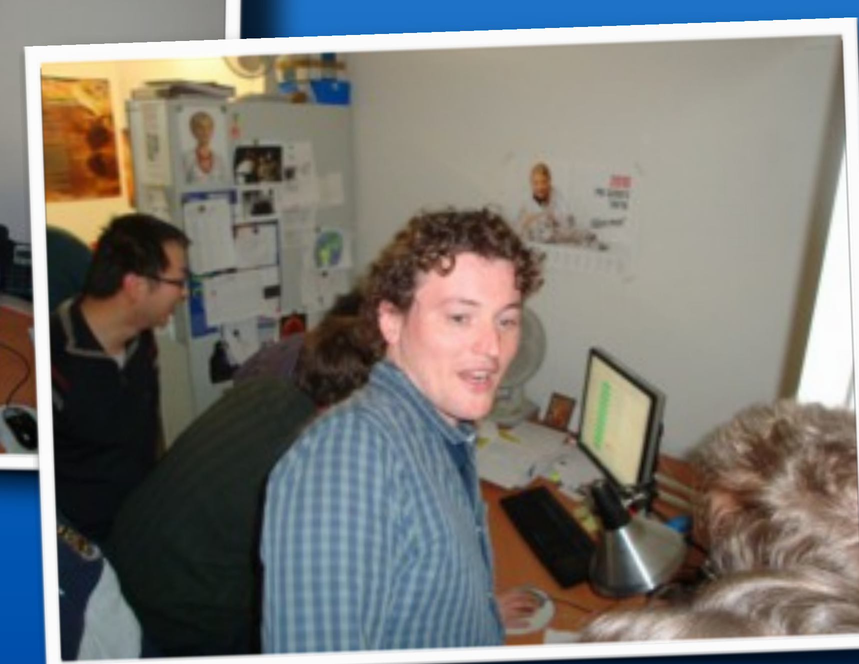

3 telescopes in Russia
Irbene LV
Sardinia 64m
Arecibo, Puerto Rico
Harte
4 telescopes in China

First fringes to Irbene, near Ventspils, Latvia





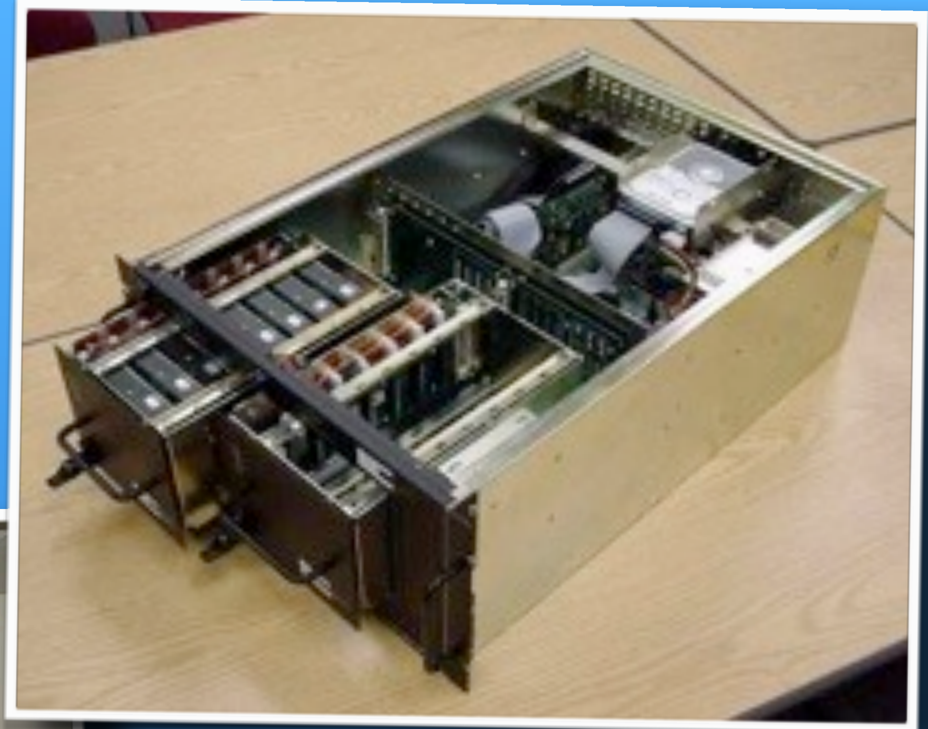




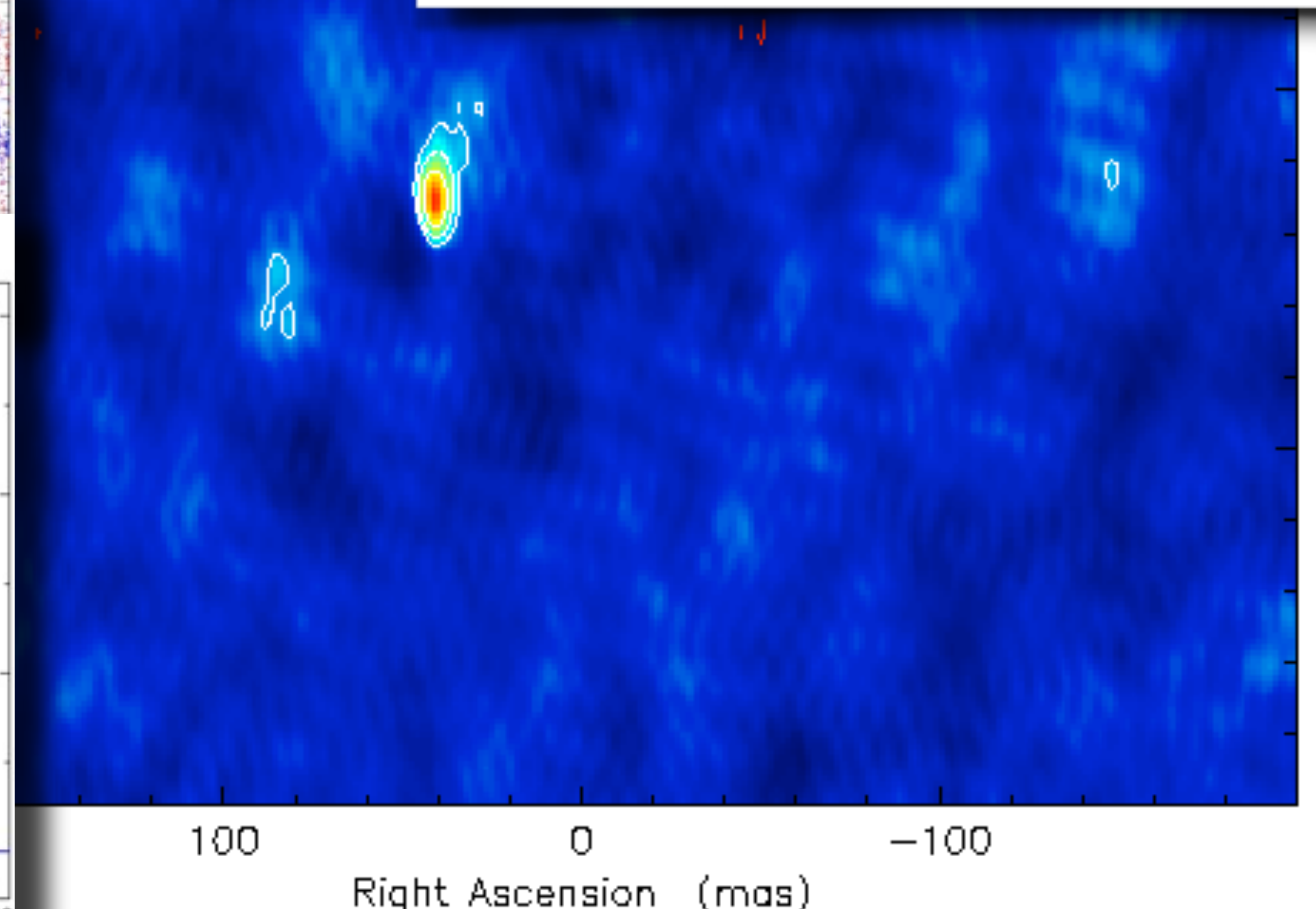
3 data deluges, really...

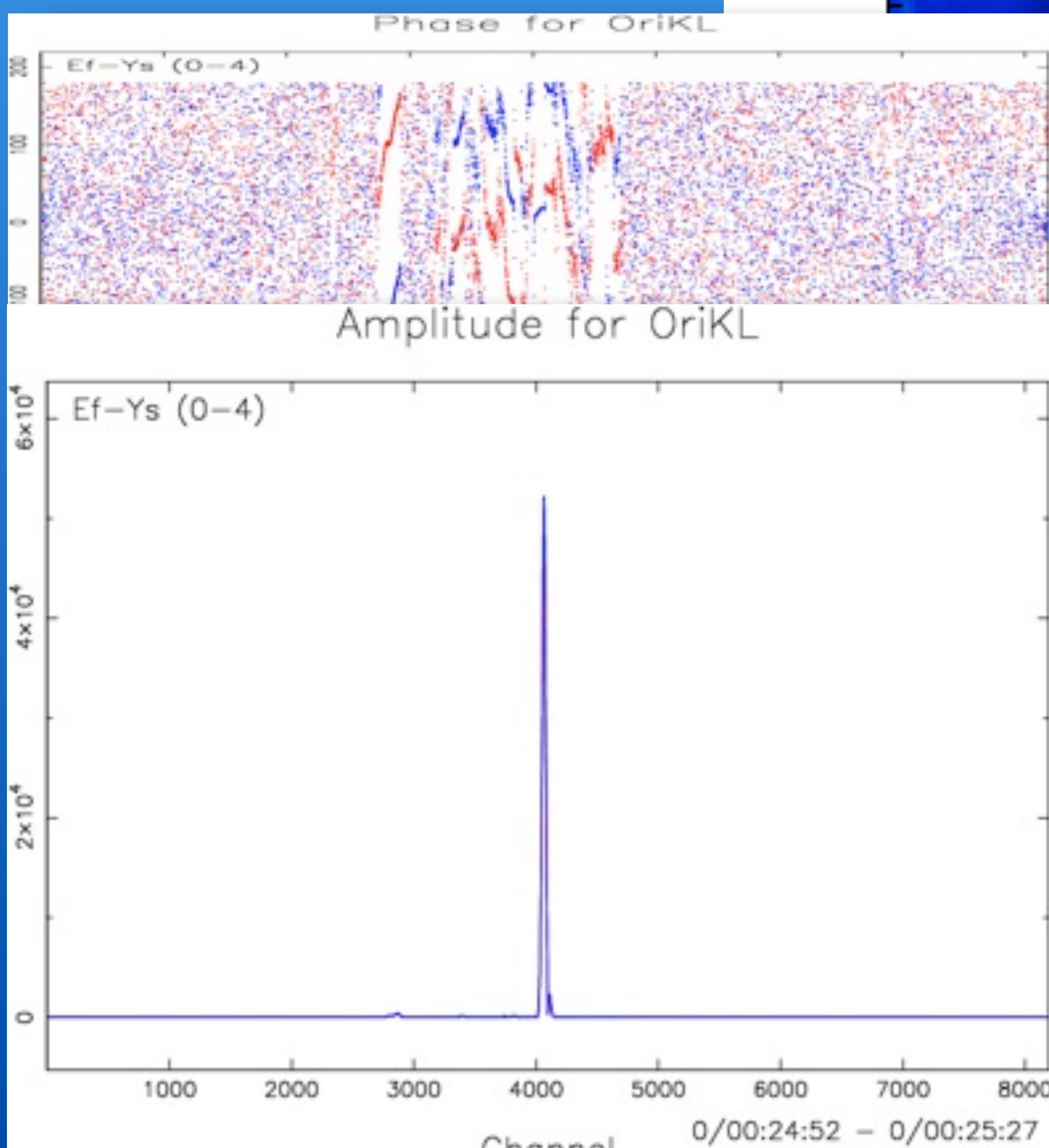
- **Bandwidth is sensitivity**
  - Bring as much frequency space to the correlator (but not archived)
    - But can live with 2 bit sampled data
  - Currently 128 Mbps - 1 Gbps from 6 - 20 telescopes
  - Future goal: 16 Gbps from 32 telescopes
    - Then SKA plans to have 1000 telescopes...
  - Typically run for 12h, using the earth rotation for imaging
- **Correlation is relatively simple operation**
    - But requires a very high precision geometric model
  - Few operations per incoming bit
  - But huge distribution problem
  - Quadratic: every telescope correlated against every other
  - Results are archived for future use
- **Imaging considerations span orders of magnitude**
  - High spectral resolution from spectrometric applications
  - High spectral and time resolution for wide field imaging
  - Iterative calibration procedures
  - Runs typically in the user domain (GB - TB data sets)
    - Limited by different aspects (user skills, software issues, data quality)
    - Sometimes computer resources

- Hardware correlator from 90s
- Went to disk in 21st century
  - Enormous boost in robustness
  - Correlator efficiency



- The EVN software correlator at JIVE (SFXC)
- 9 stations 1Gbps real-time
  - Pulsar gating
  - Space craft applications
  - Spectral polarimetry
  - Many field of views

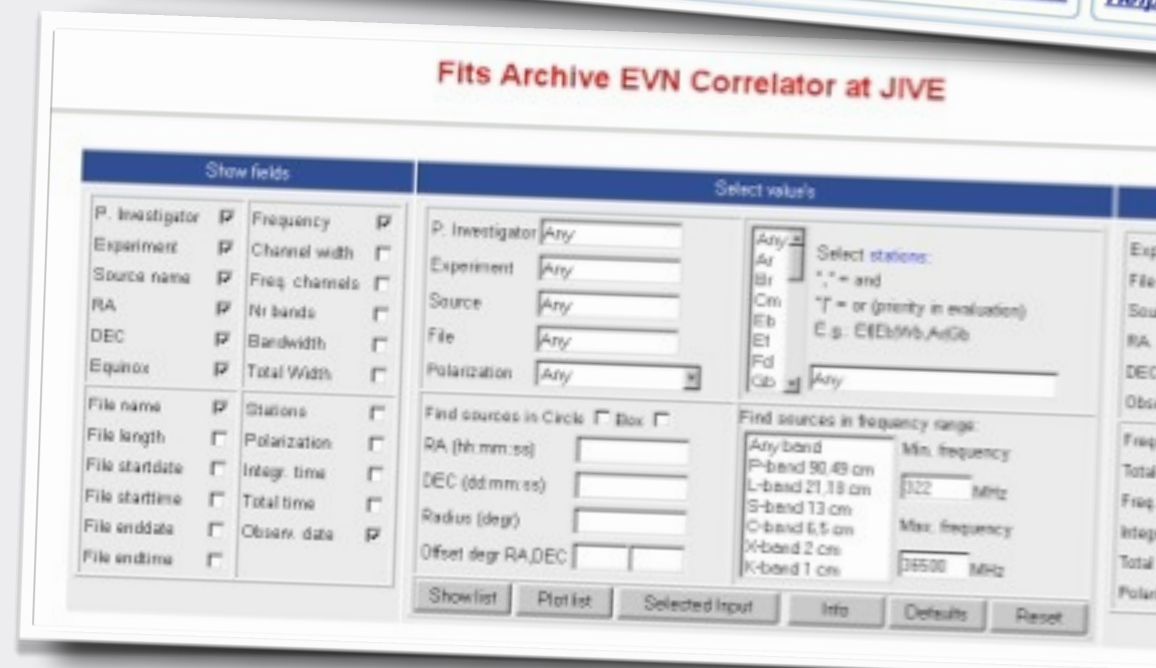




JIVE: Heart of the EVN

- VLBI requires central processor
  - Dedicated supercomputer
    - And data playback facilities
  - High precision digital equipment

- Plus all user interfaces
  - Proposal tool
  - EVN observation scheduling
  - Data product
  - Archive
- User support
  - Offer help in all stages
  - Preliminary processing
  - Visitor facilities
    - Currently being upgraded!
  - Point of contact various RadioNet funds
- Telescope support



Now turn to e-VLBI!

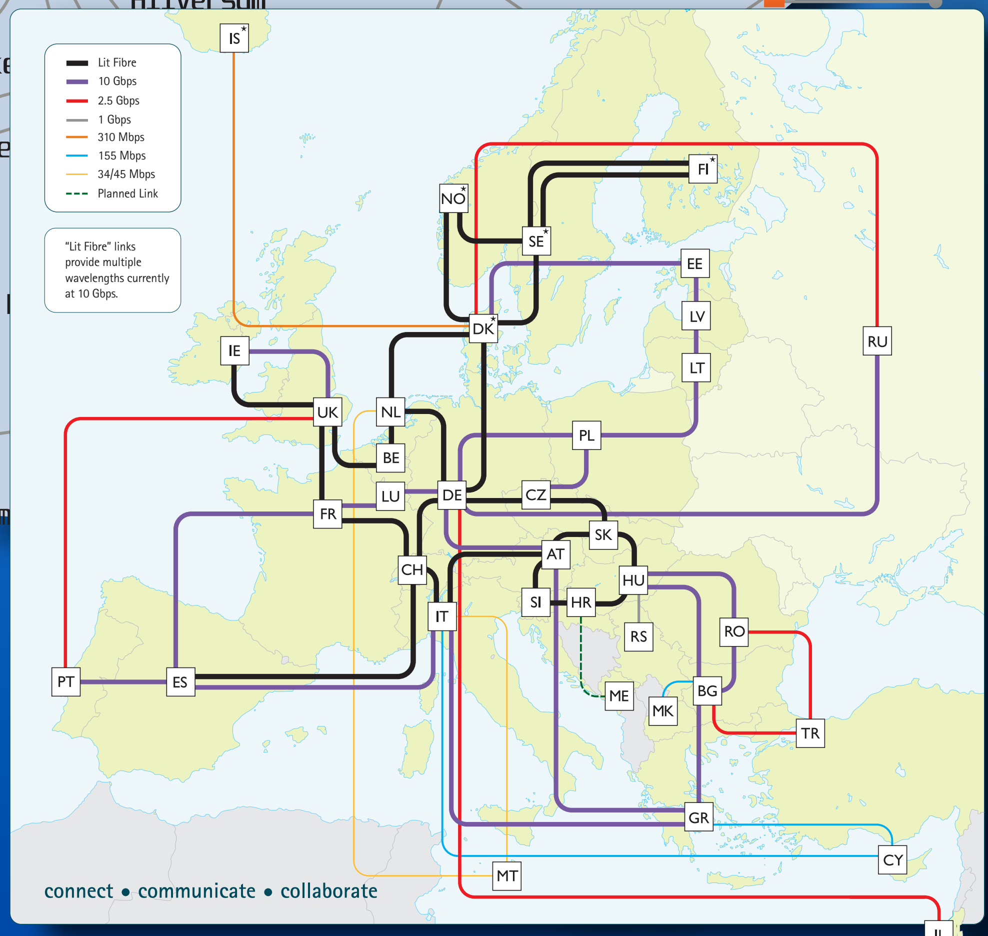
- PC based recording
  - Also allows Internet transmission
  - Upgrade EVN to e-EVN
    - Started with a pilot in 2004
- And was boosted with EXPReS
  - Retrofit correlator to work real-time
  - Help solve last mile problem at telescopes
  - Work closely with NRENs on robust connectivity
  - Push to 1024 Mb/s limit
  - Bring in the big telescopes
  - And start the revolution in radio-astronomy culture
- EC FP7 project
  - Radio-astronomy observatories
  - Some NRENs

EXPReS

Express Production Real-time e-VLBI Service

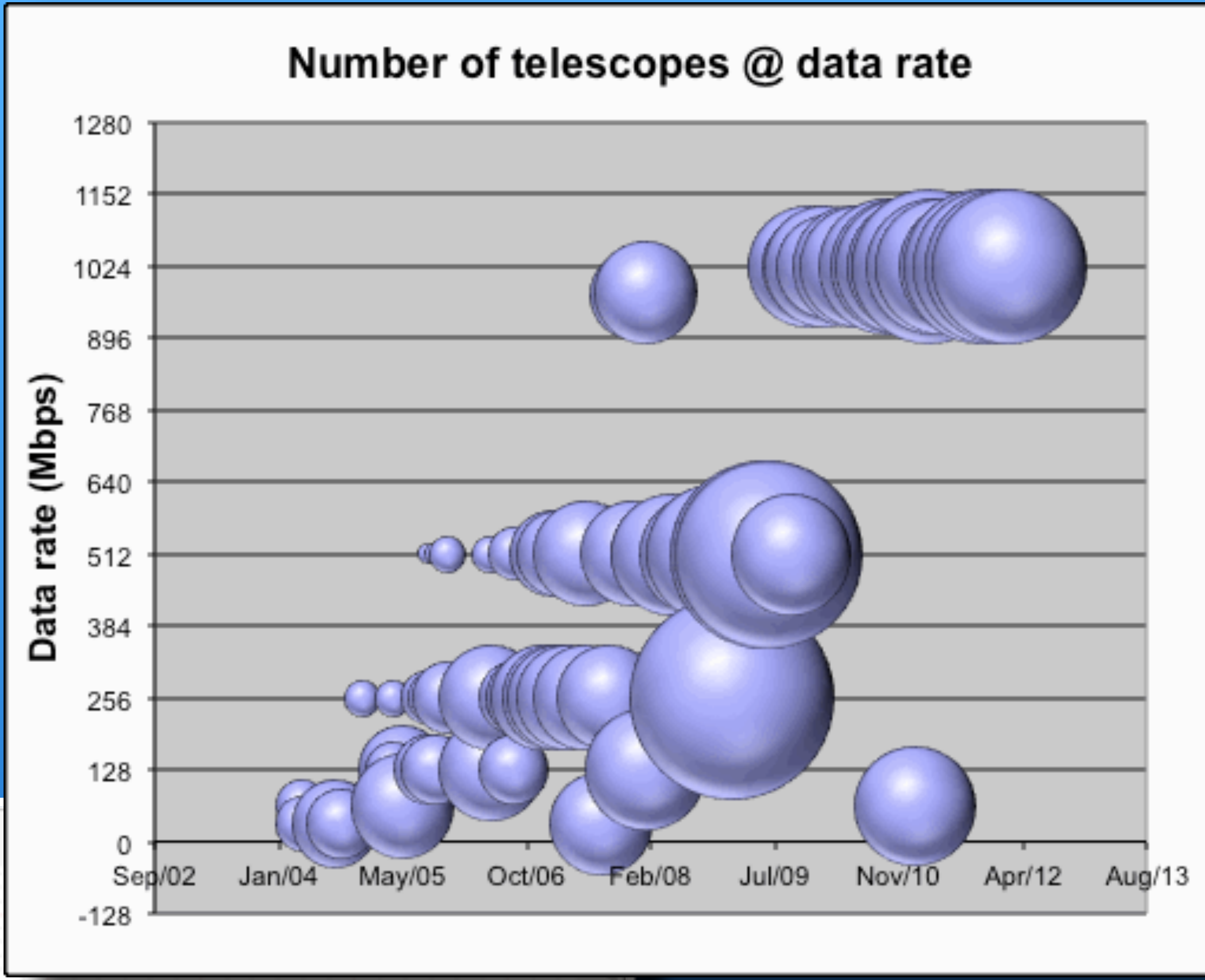
Friends all over the world ready to collaborate

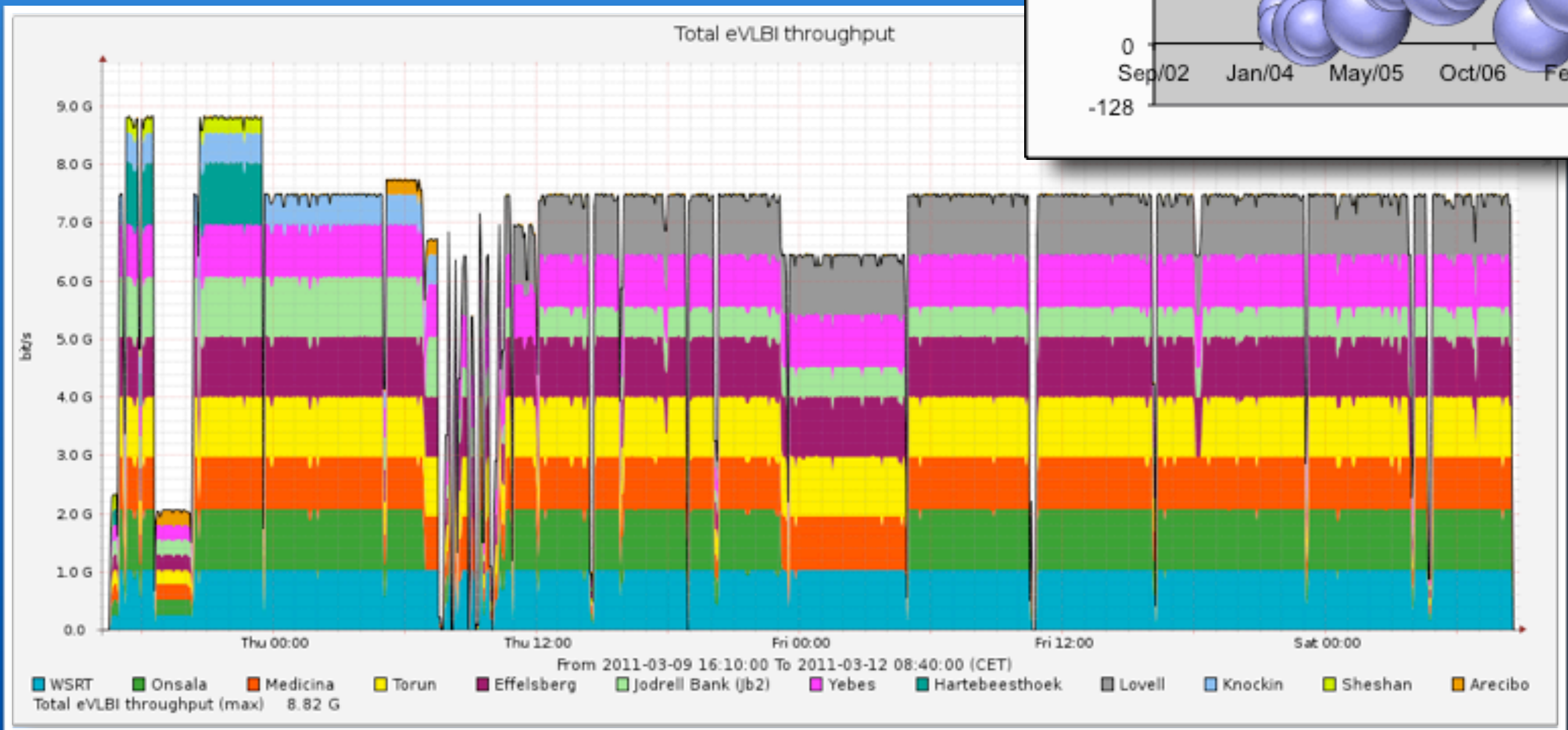
- **All come together on the Dutch SURFnet infrastructure**
- **Large bundle from Amsterdam to Dwingeloo**

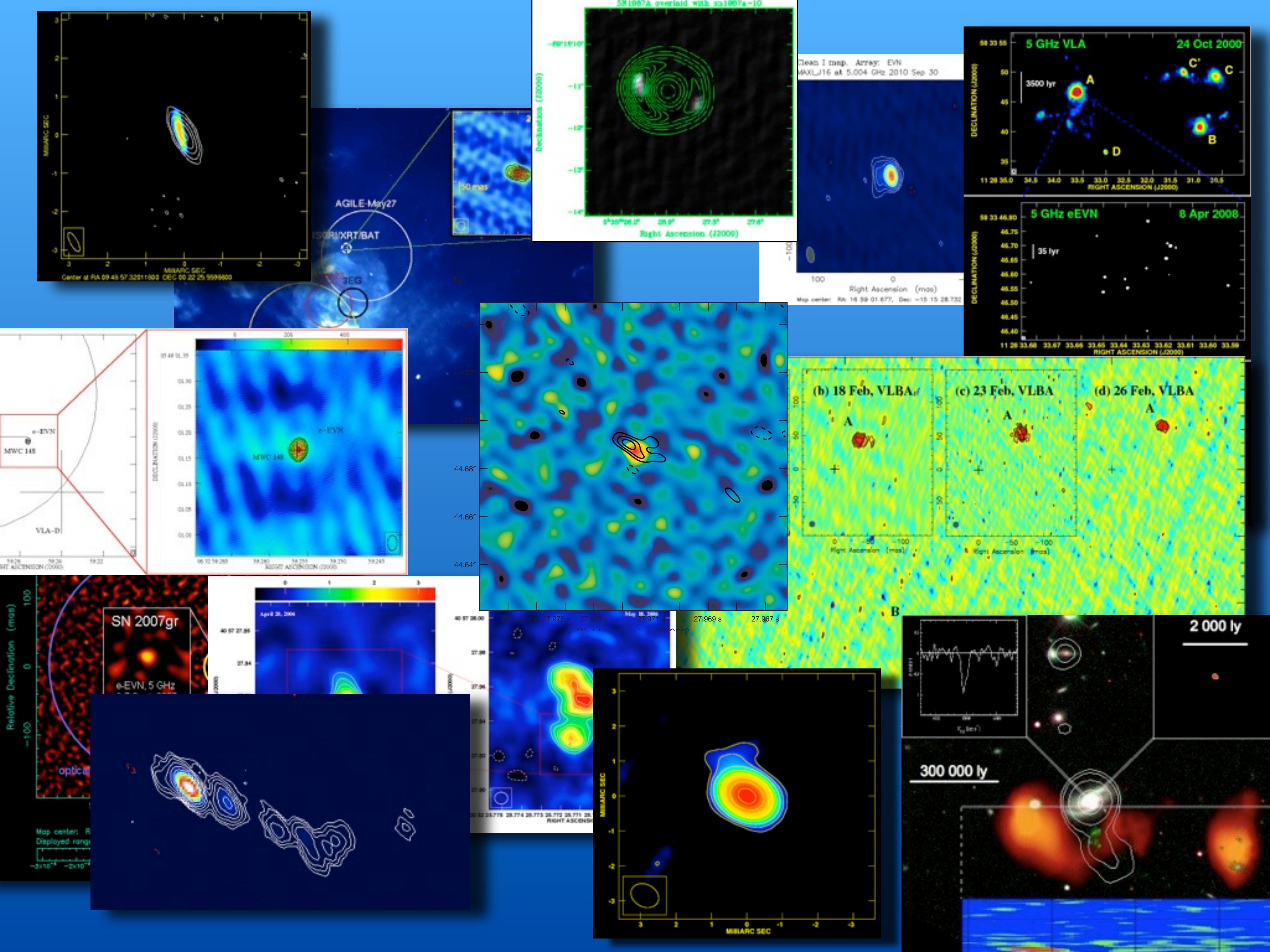


- **Establish connectivity through Europe on GÉANT**
- **or using cross-border NREN connects**
- **Often together with LOFAR**

- Operational facility
  - often dedicated light paths
  - Use optimized protocols
- Closed feedback loop makes e-VLBI more robust

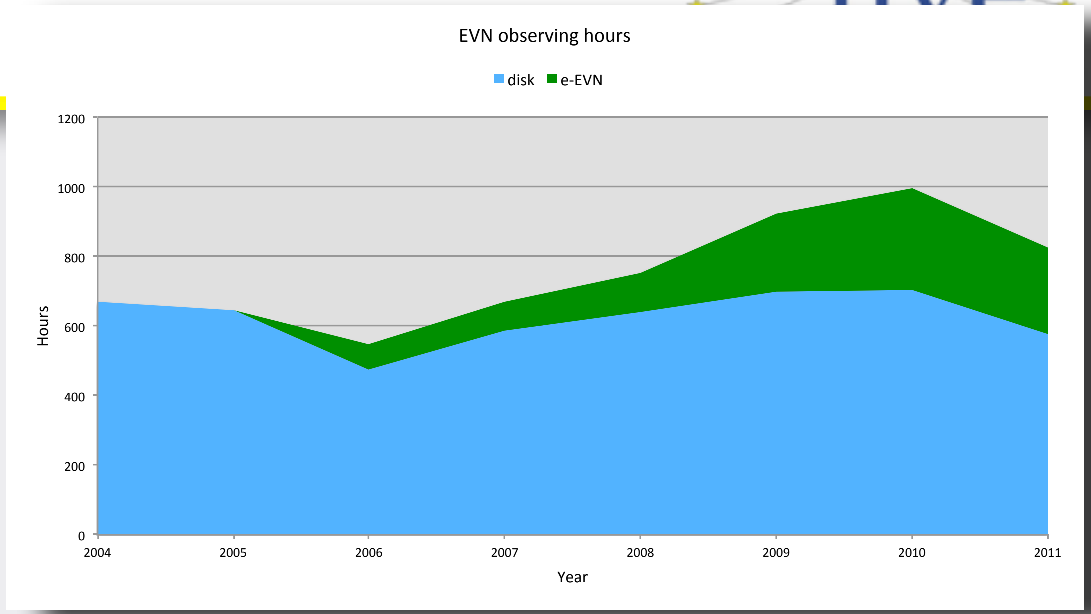






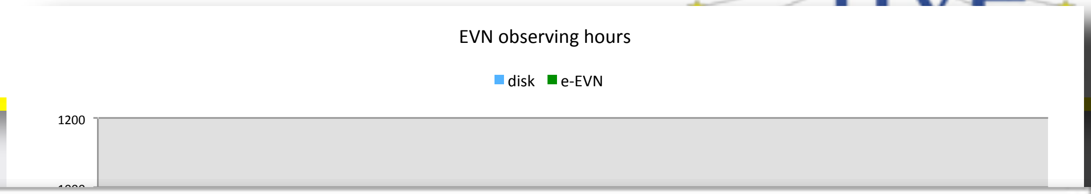
5 GHz VLA
24 Oct 2000
3500 lyr
5 GHz eEVN
8 Apr 2008
35 lyr
AGILE-May27
ISGRI/XRT/BAT
3EG
50 mas
Right Ascension (J2000)
Declination (J2000)
Clean I map. Array: EVN
Right Ascension (mas)
(b) 18 Feb, VLBA
(c) 23 Feb, VLBA
(d) 26 Feb, VLBA
A
B
C
C'
D
e-EVN
MWC 148
VLA-D
SN 2007gr
e-EVN, 5 GHz
Relative Declination (mas)
MILLIARC SEC
2 000 ly
300 000 ly

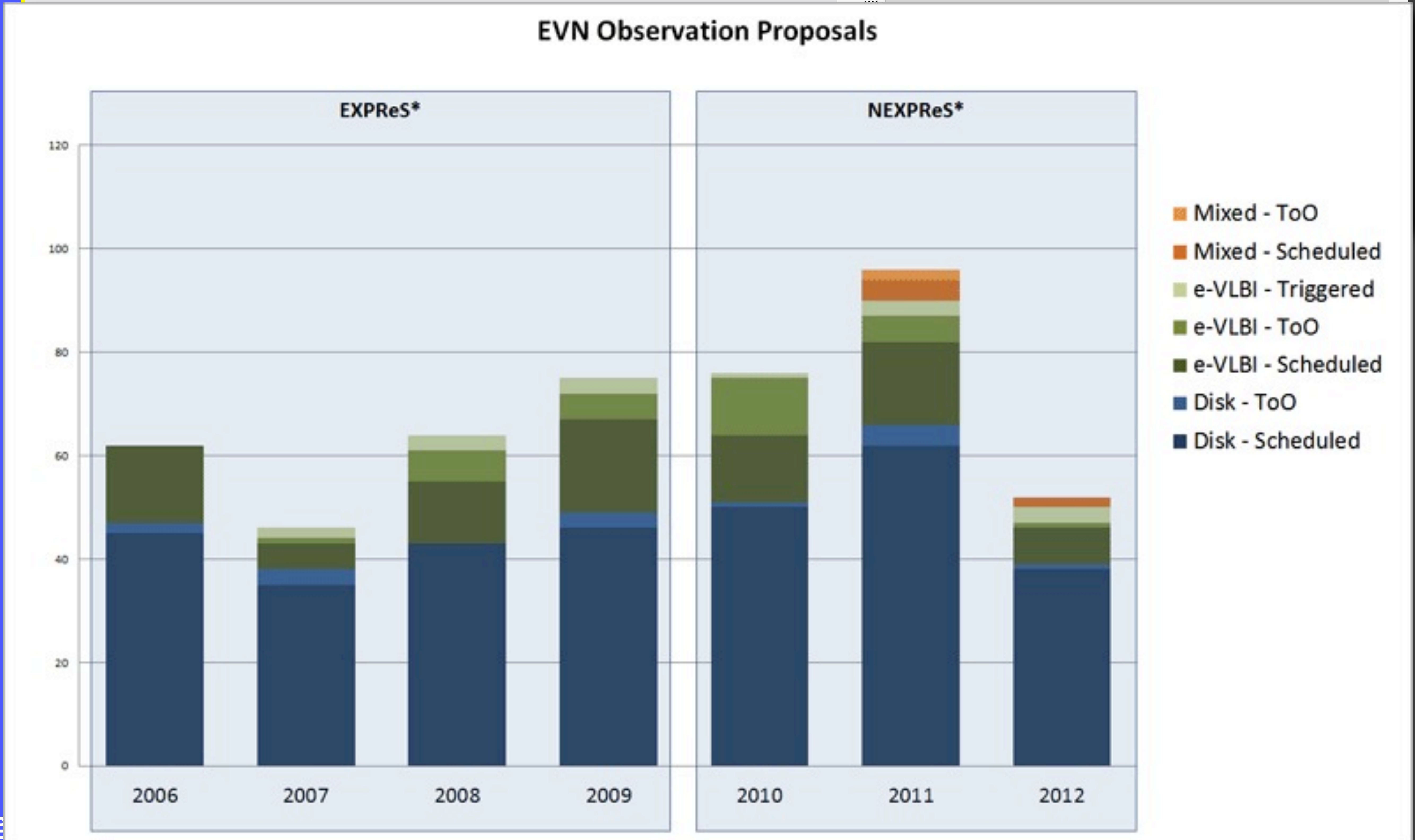
Observations



- Now an operational facility
  - Guaranteed 10 x 24h per year
    - And quite bit more in practice (>30%)
- Flexible ways to get into e-VLBI
  - Request e-VLBI for fast response
    - Can be approved by PC for existing sessions
  - Or for triggered proposals
    - To be submitted at regular proposal dates
    - Requires specific trigger criteria
  - Short requests <2hr
    - e.g. calibrator checks
  - Target of Opportunities
    - EVN agreed to have substantially more of these
  - Or just because you prefer to e-VLBI
  - Or just because the EVN prefers to do e-VLBI
    - Because of logistics or (disk) resources

Observations



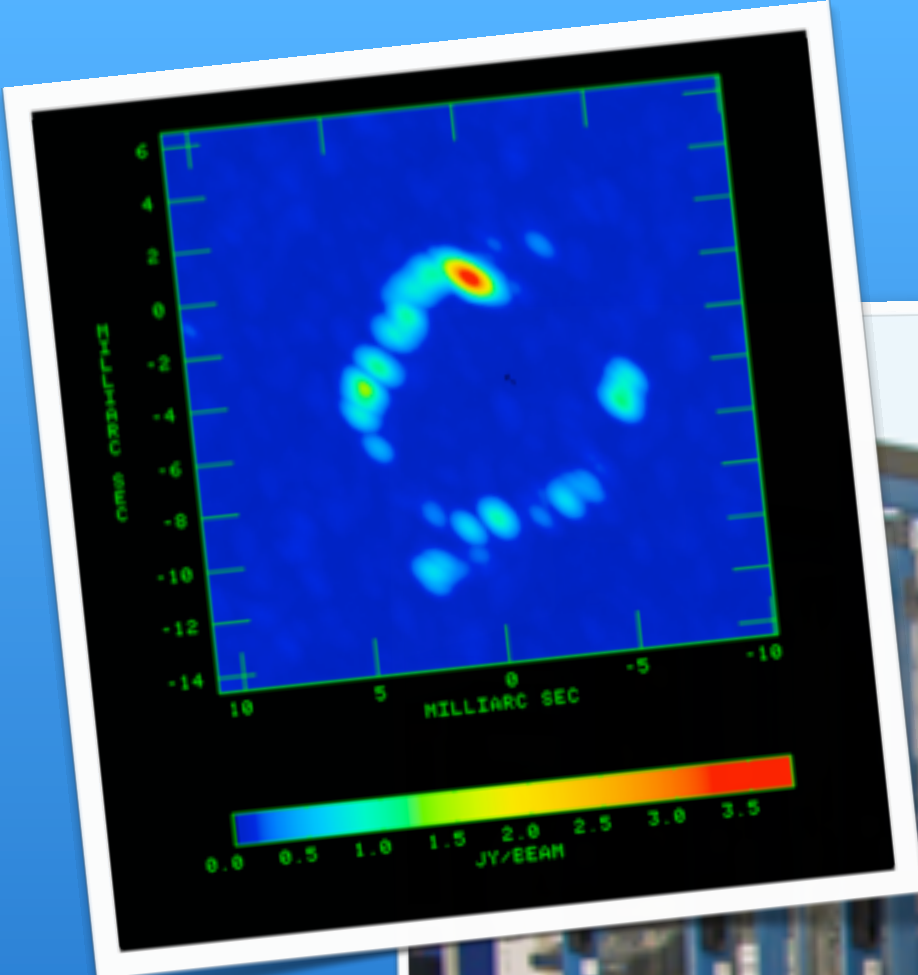


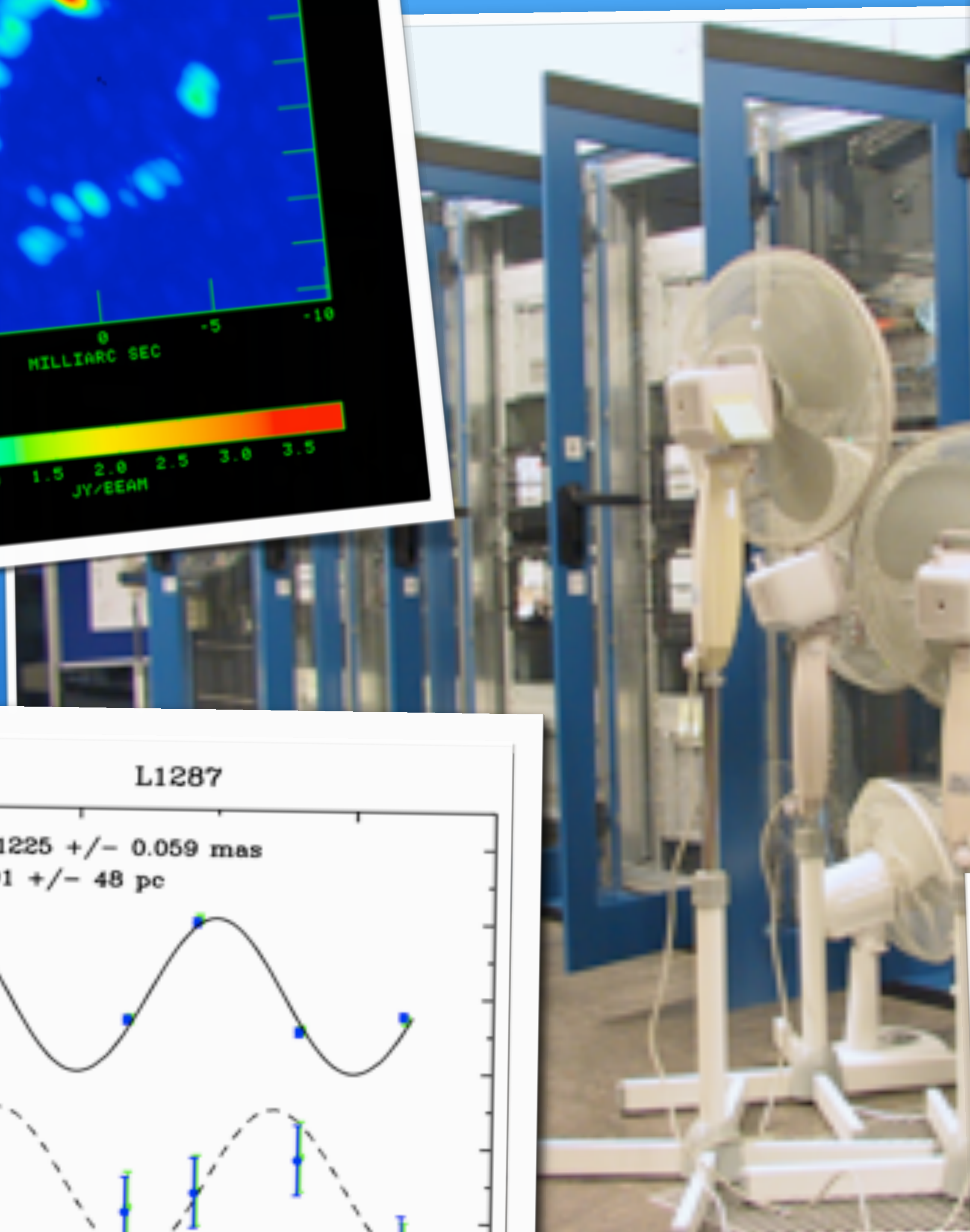
- Because of logistics or (disk) resources

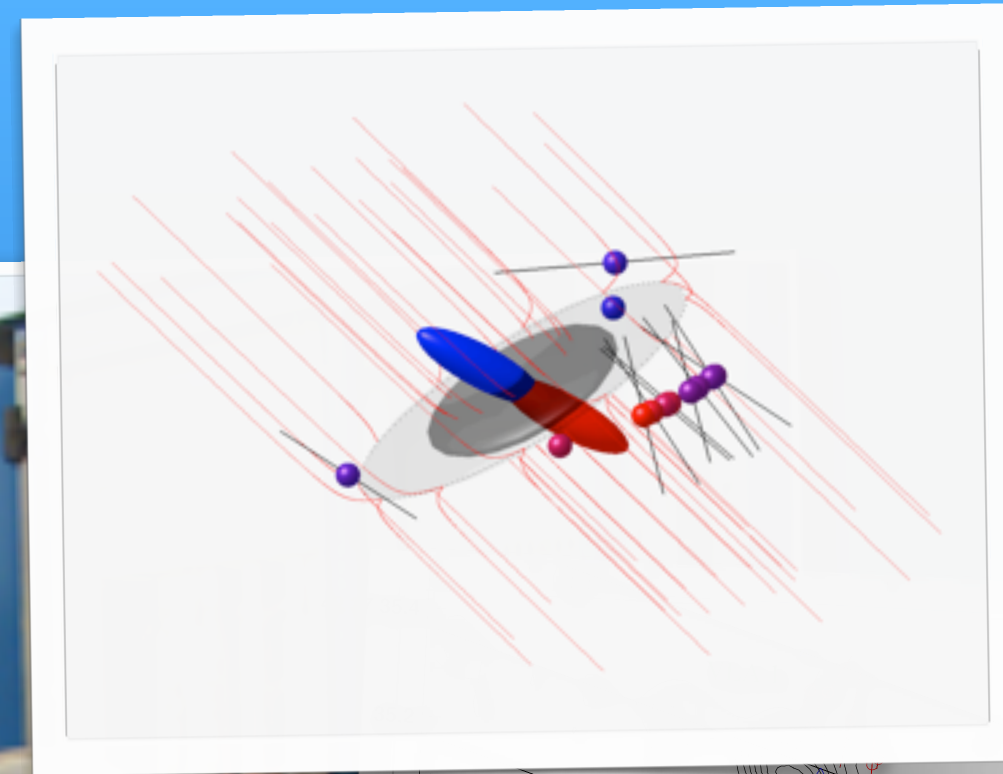
What we learned from EXPReS

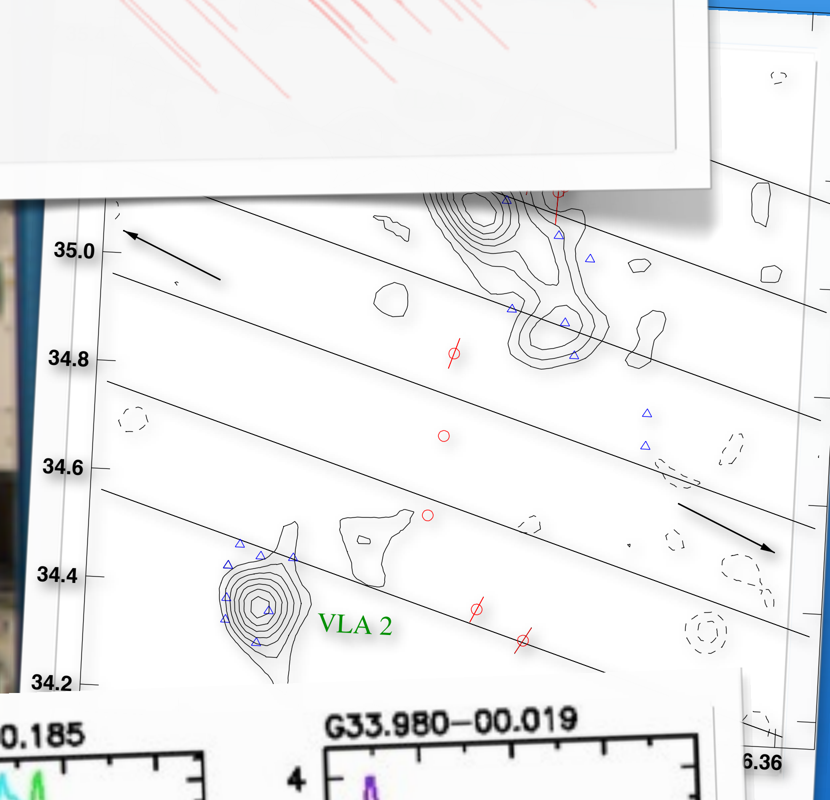
- **Besides building expertise and making new friends:**
  - Bandwidths of 1Gbps and above not a problem
  - e-VLBI is probably even more reliable
    - By closing the loop in real-time
  - It can be applicable to Global VLBI
    - Local connectivity often the more serious problem
  - It did produce new science
    - Moreover, users think it is exciting and convenient

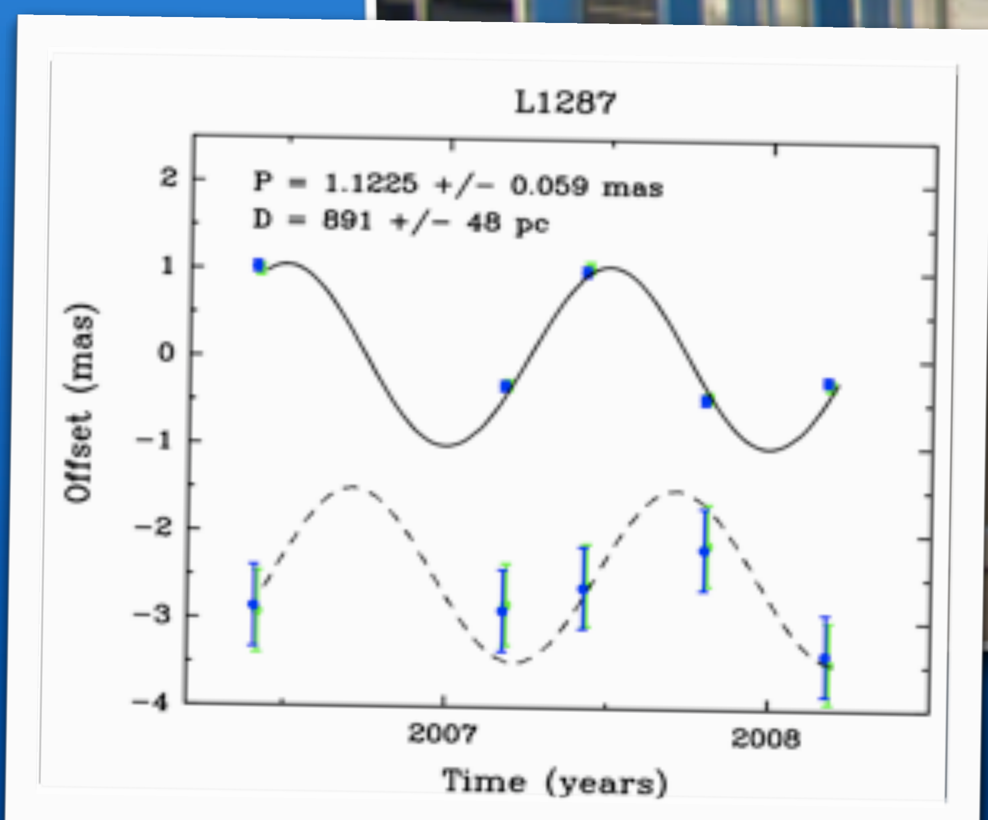
- **But some questions remain:**
  - Will it be cost effective?
  - Cannot accommodate all projects
    - Spectral line, mixed bandwidth
    - Multiple correlator centres
    - Some antennas in some experiments (Noto, Russian, Chinese)

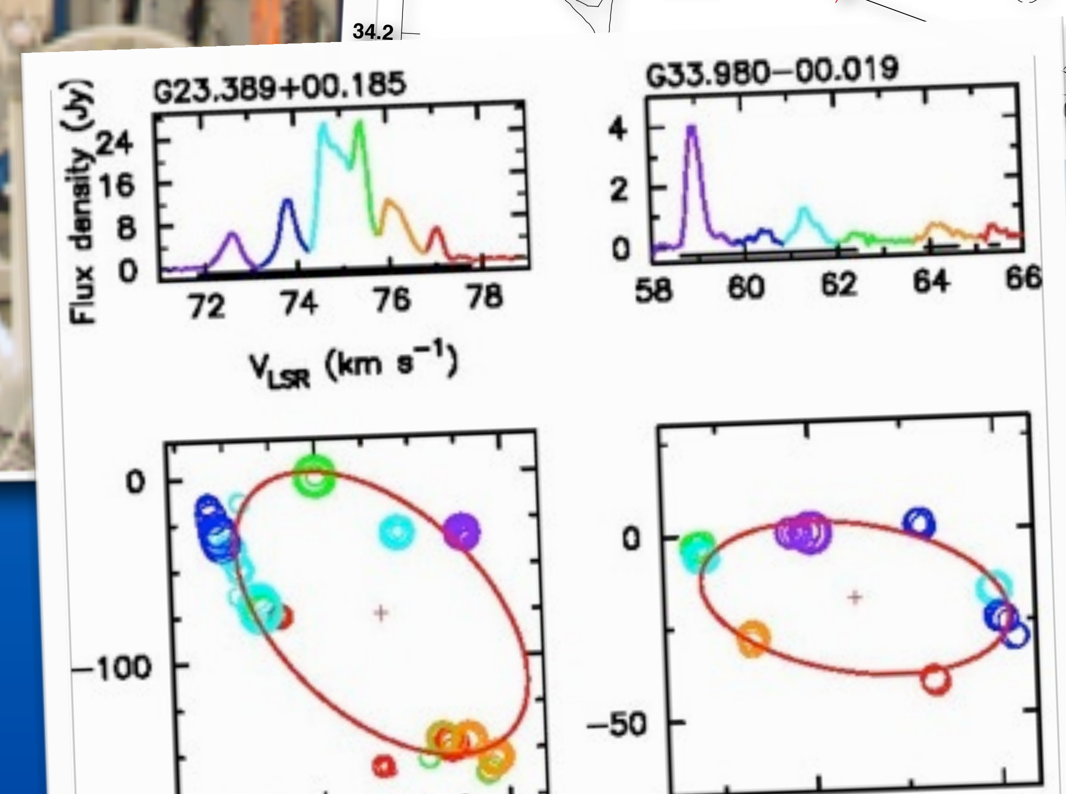

MILLIARC SEC
MILLIARC SEC
6 4 2 0 -2 -4 -6 -8 -10 -12 -14
10 5 0 -5 -10
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
JY/BEAM






DECLINATION (J2000)
35.0
34.8
34.6
34.4
34.2
VLA 2
6.36


L1287
P = 1.1225 +/− 0.059 mas
D = 891 +/− 48 pc
Offset (mas)
2 1 0 −1 −2 −3 −4
2007 2008
Time (years)


G23.389+00.185
G33.980−00.019
Flux density (Jy)
24 16 8 0
72 74 76 78
4 2 0
58 60 62 64 66
V_{LSR} (km s^{-1})
0
−100
0
−50

New project: NEXPReS

NEXPReS

Novel EXplorations Pushing Robust e-VLBI Services

- "owns" the e-VLBI operations and outreach
- Also some LOFAR transport and storage issues
- And link to SKA development

New project: NEXPReS

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New project: NEXPReS

NEXPReS
Novel EXplorations Pushing Robust e-VLBI Services

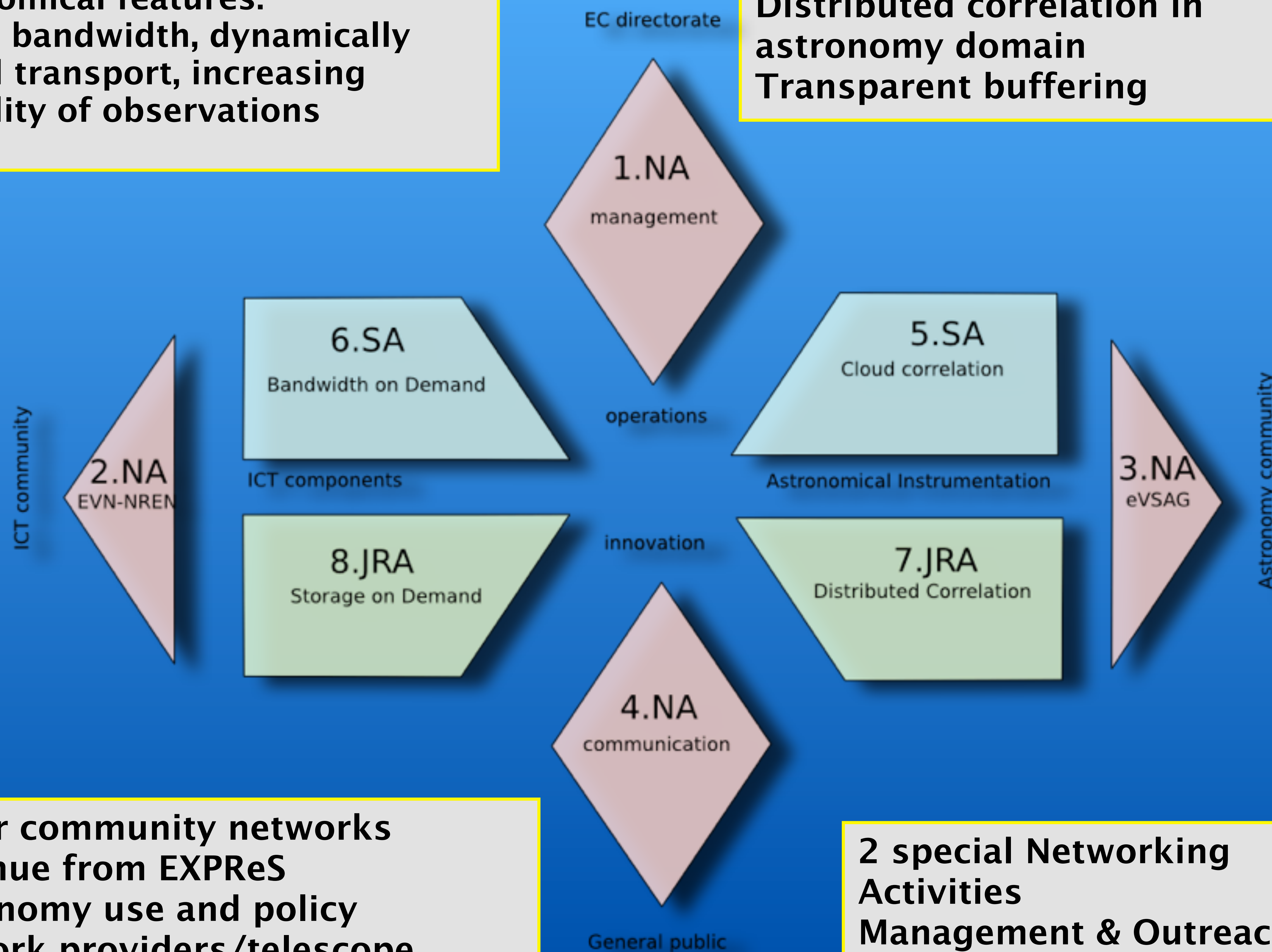
- Aims for
  - Correlate in real time what you can,
  - Correlate later what you need
- Allow multiple correlator passes
- Buffer for more reliable operations
  - addressed by simultaneous recording
- Be more sensible about resource allocation
  - Bandwidth on demand, limit physical shipping
- Reach for higher bandwidths (10 - 40 Gbps)
- But also:
  - Continue to connect more telescopes
  - NEXPReS maintains expertise
    - Collaborations with NRENs
  - ‘owns’ the e-VLBI operations and outreach
  - Also some LOFAR transport and storage issues
  - And link to SKA development

NEXPReS project info

- 15 partners
  - Of which 3 choose not receive funds from EC
  - Good mix from astronomy-networking-HPC communities
  - High level of partner-contributed effort
- Year 2 review this week
  - Think we are nice on schedule
  - But delivering user capabilities is a delicate process

2 Service Activities
focus on new operational astronomical features:
Higher bandwidth, dynamically cached transport, increasing flexibility of observations

2 Joint Research Activities aiming at innovating future operations
Distributed correlation in astronomy domain
Transparent buffering

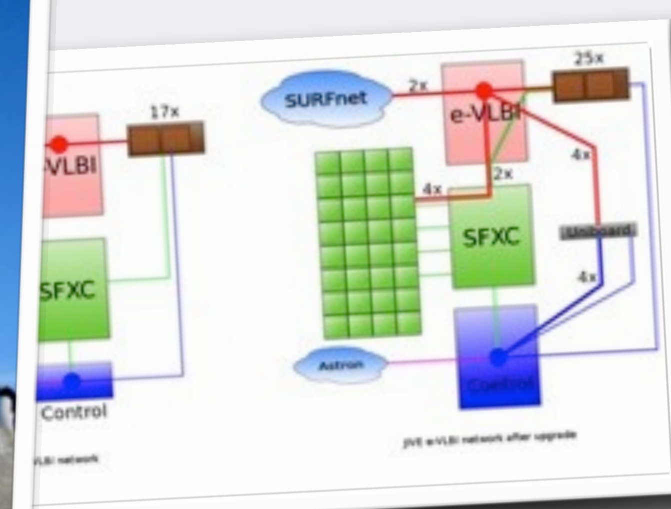


2 user community networks continue from EXPReS
Astronomy use and policy
Network providers/telescope operators

2 special Networking Activities
Management & Outreach
Essential for success

Cloud correlation

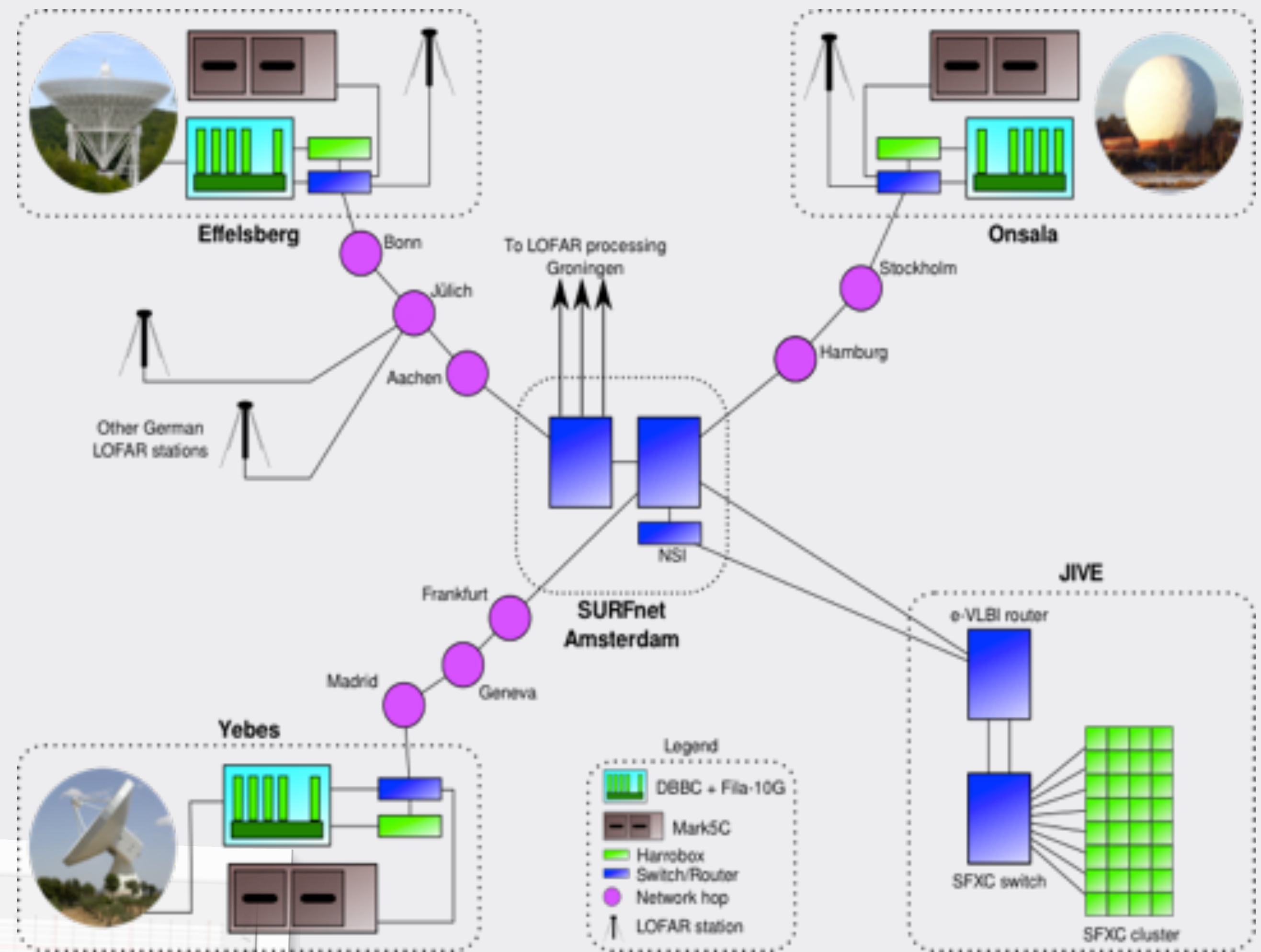
- **Infrastructure**
  - Overhaul of local network
  - Flexibly connecting playback
  - Fibres & correlators
- **Control code**
  - Allowing mixed rate operations
  - Making various playback units flexibly usable
  - Uniting correlator interfaces
  - Remote operations
- **Transparent buffering**
  - Working on JIVE Mk5 control code
  - For use in the field
  - And at the correlator



huib 17/9/12

Lots of progress

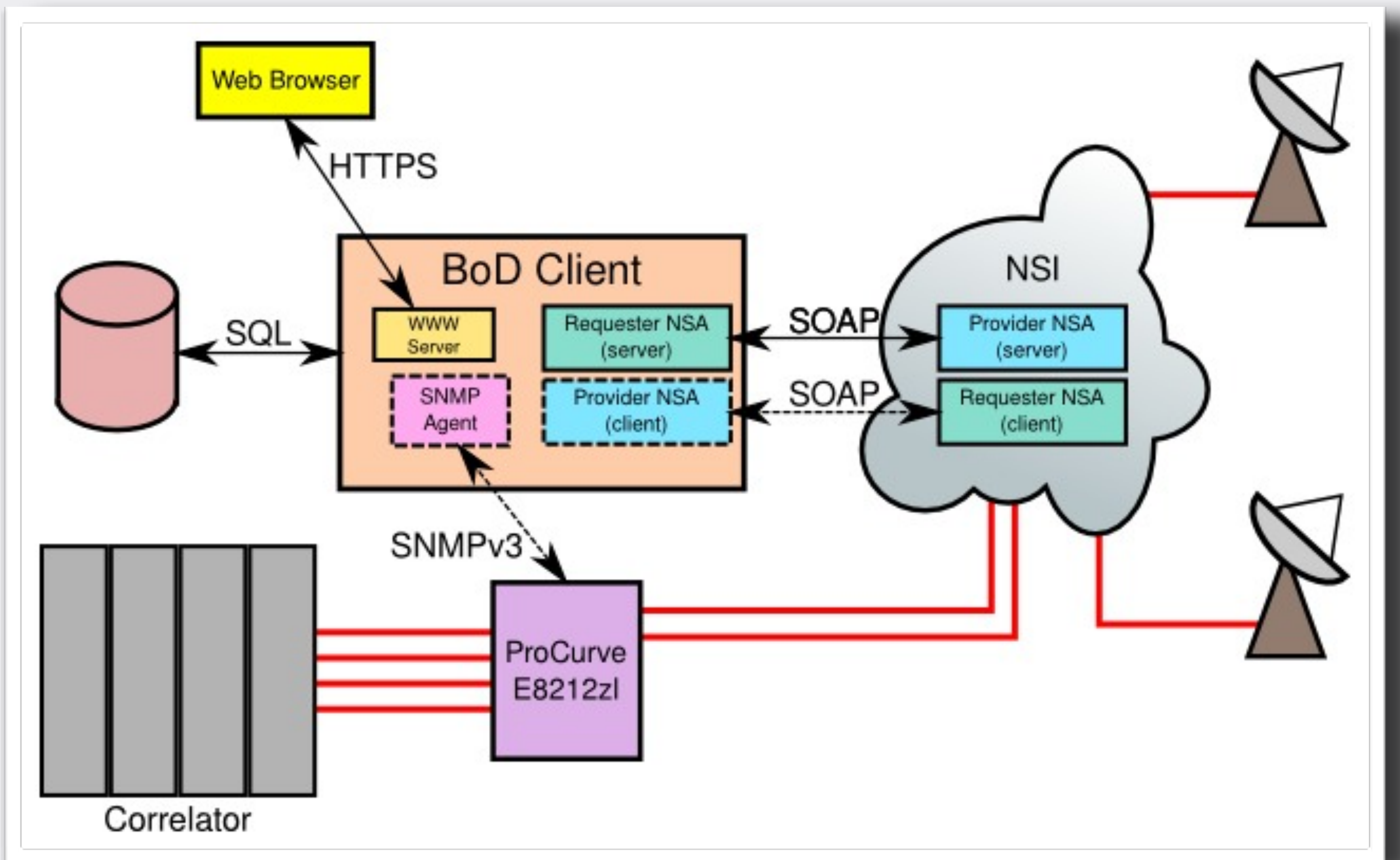
- Mostly rewriting code
  - for new hardware
  - and new use modes
- Testing in 4Gbps setup
  - Mostly successful
  - Except for the correlation



Bandwidth on demand

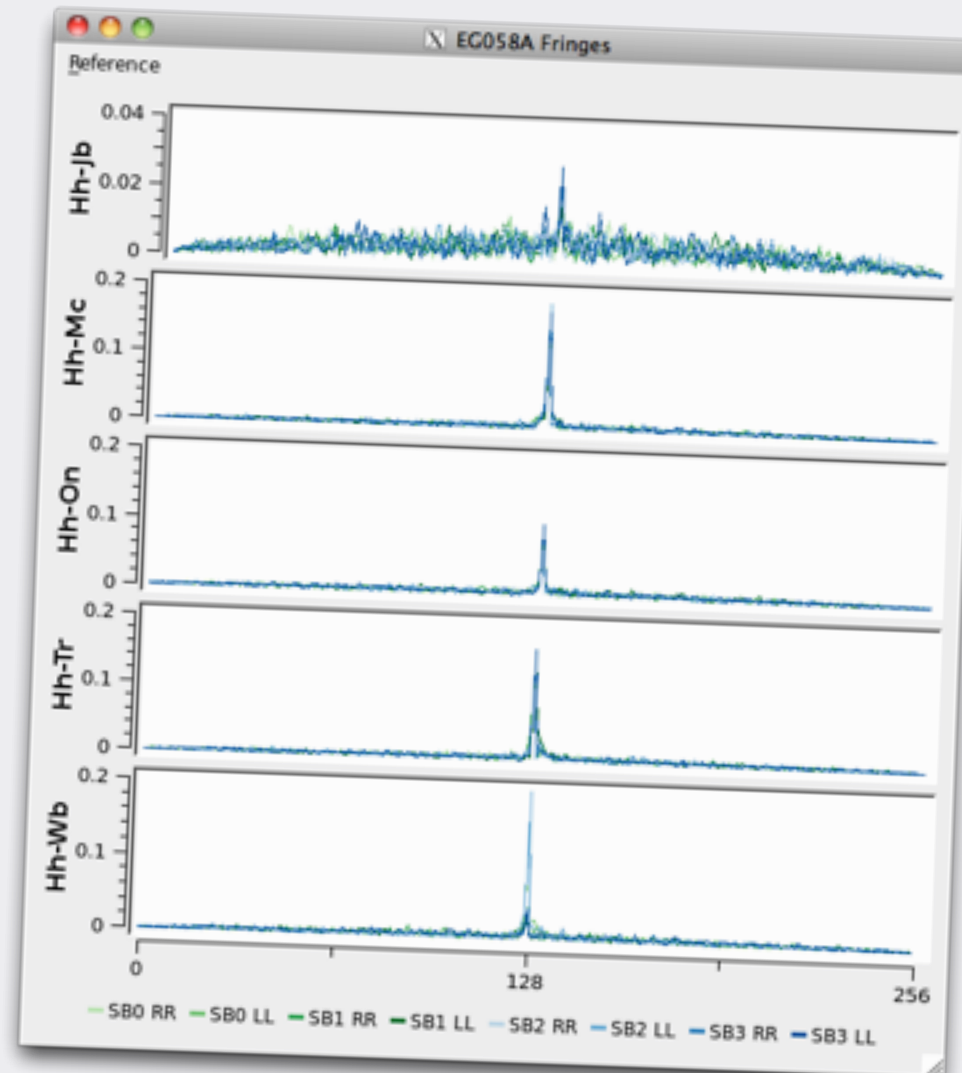
- Need to reserve dedicated connections
  - Across many domains
- Work on using flexible assignments NSI
  - Enabling 4 Gbps
  - Also for LOFAR archive

In parallel session



Distributed correlation

- **Enhance the software correlator**
  - **New functionality**
    - **Space craft modes**
    - **Multiple field centers**
    - **Pulsar timing beam**
  - **Latest interface definition**
  - **Make ready for e-VLBI**
  -
- **Push for distributed correlation**
    - **But moving away from Grid**
    - **Looking at resources in own domain**
  - **Can be effective way to construct correlator**
  - **Interest for round-the-clock VLBI**
    - **Ready for triggers**
- **Load balancing over multiple clusters**



First e-VLBI fringes at 512 Mbit/s Text

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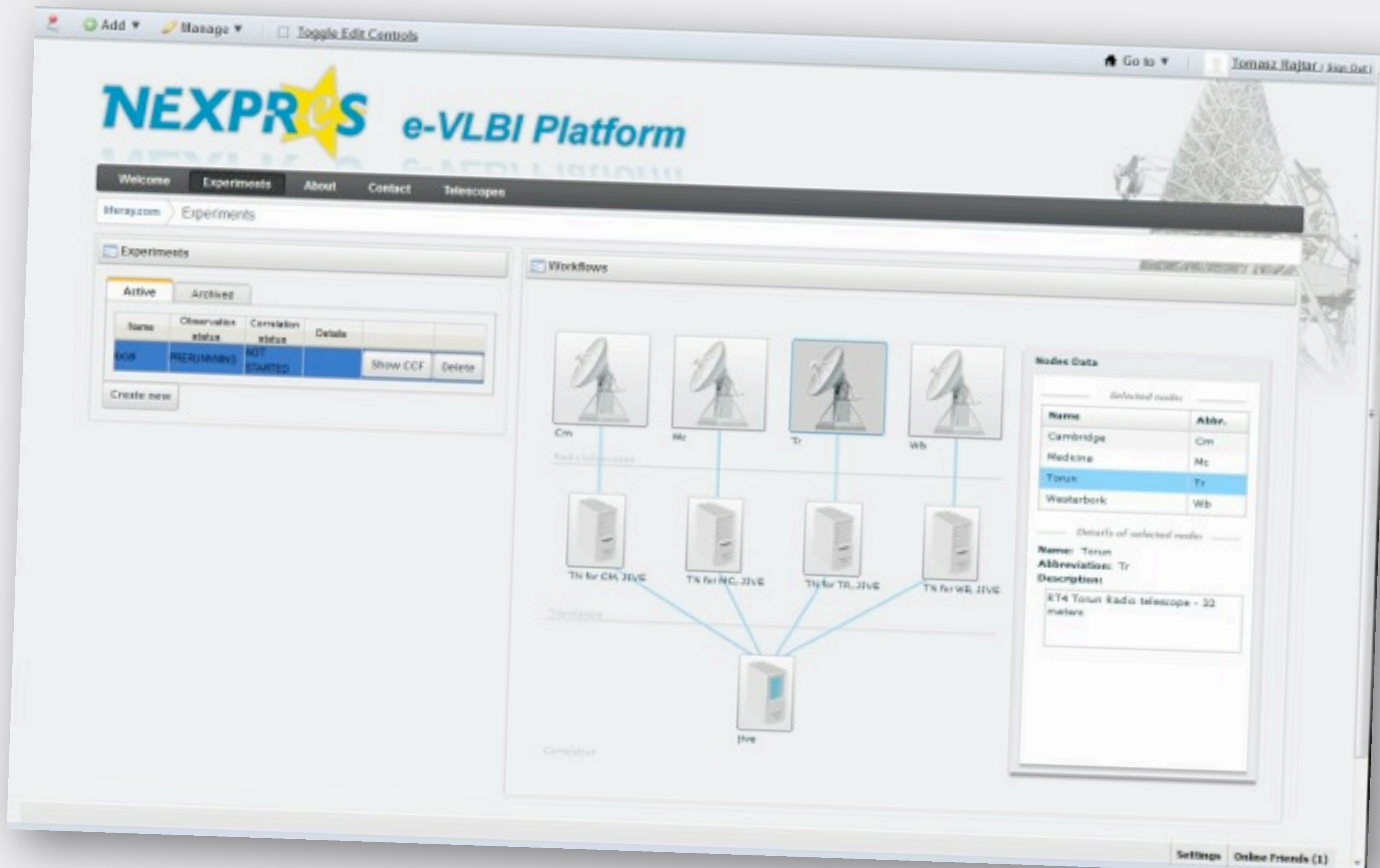
Web deployable correlator

- Graphic workflow managers
- Dynamic scheduling
  - Automated response to external triggers?



FlexBuff

- **Problem: high bandwidth storage**
  - Feeding into the caching demands of VLBI
    - Multiple 4Gbps streams
    - Read & write simultaneous
  - But also at massive (distributed) archives
  - Must be Linux based and off-the-shelve

- **Prototype hardware delivered**
- **And software suite**
  - Writing larges blocks

Network activities

- Management
  - Doing all the nasty stuff
  - Including dealings with EC
    - On finances for example

Charles Yun

- EVN-NREN
  - Interactions with Networking experts
  - Had first meeting in Aveiro, Pl

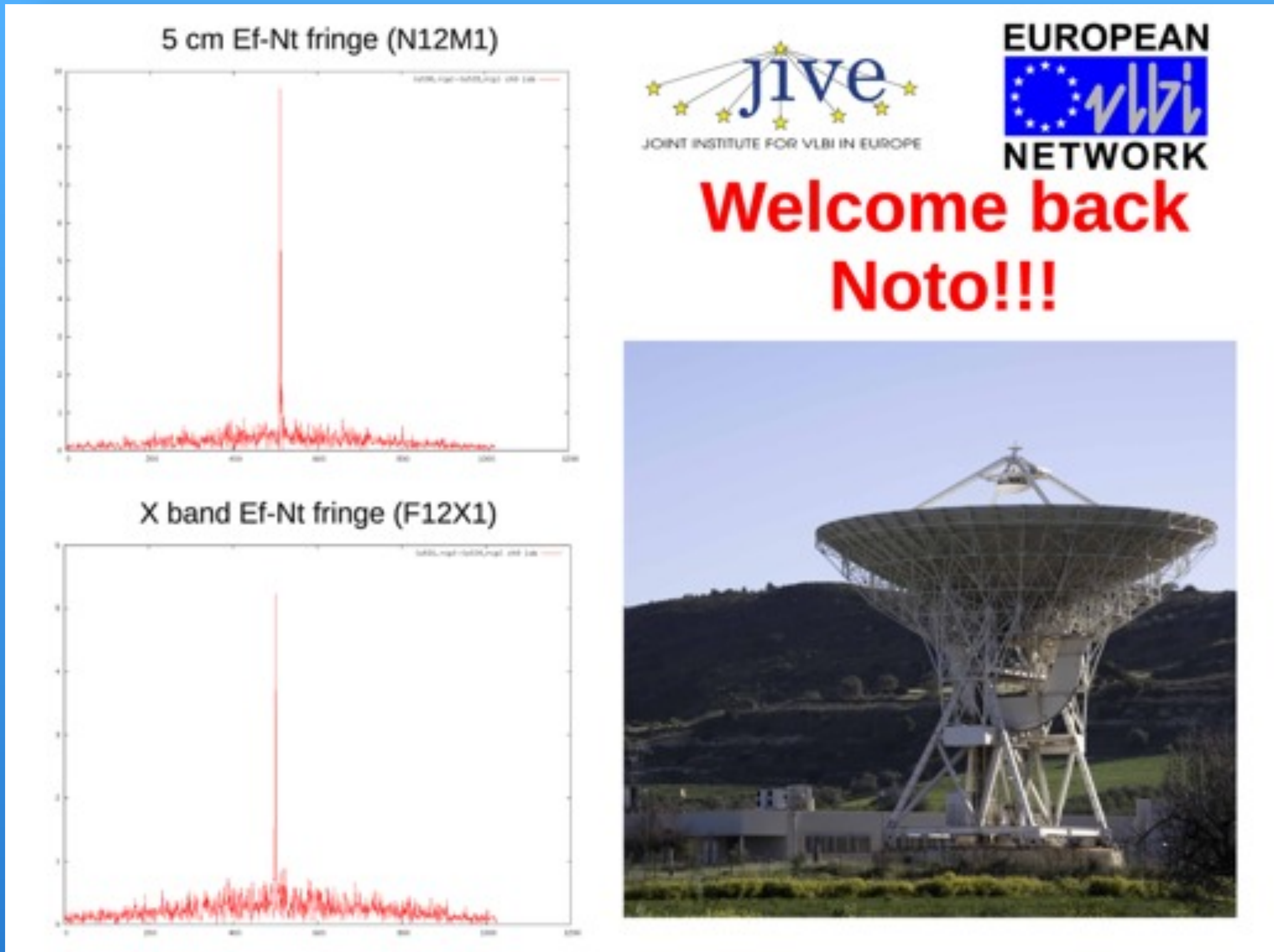
Richard Hughes-Jones

- EVSAG
  - e-VLBI Science Advisory Group
  - On policies and operational issues
    - Overlaps with EVN-PC
  - Meeting in Madrid last week

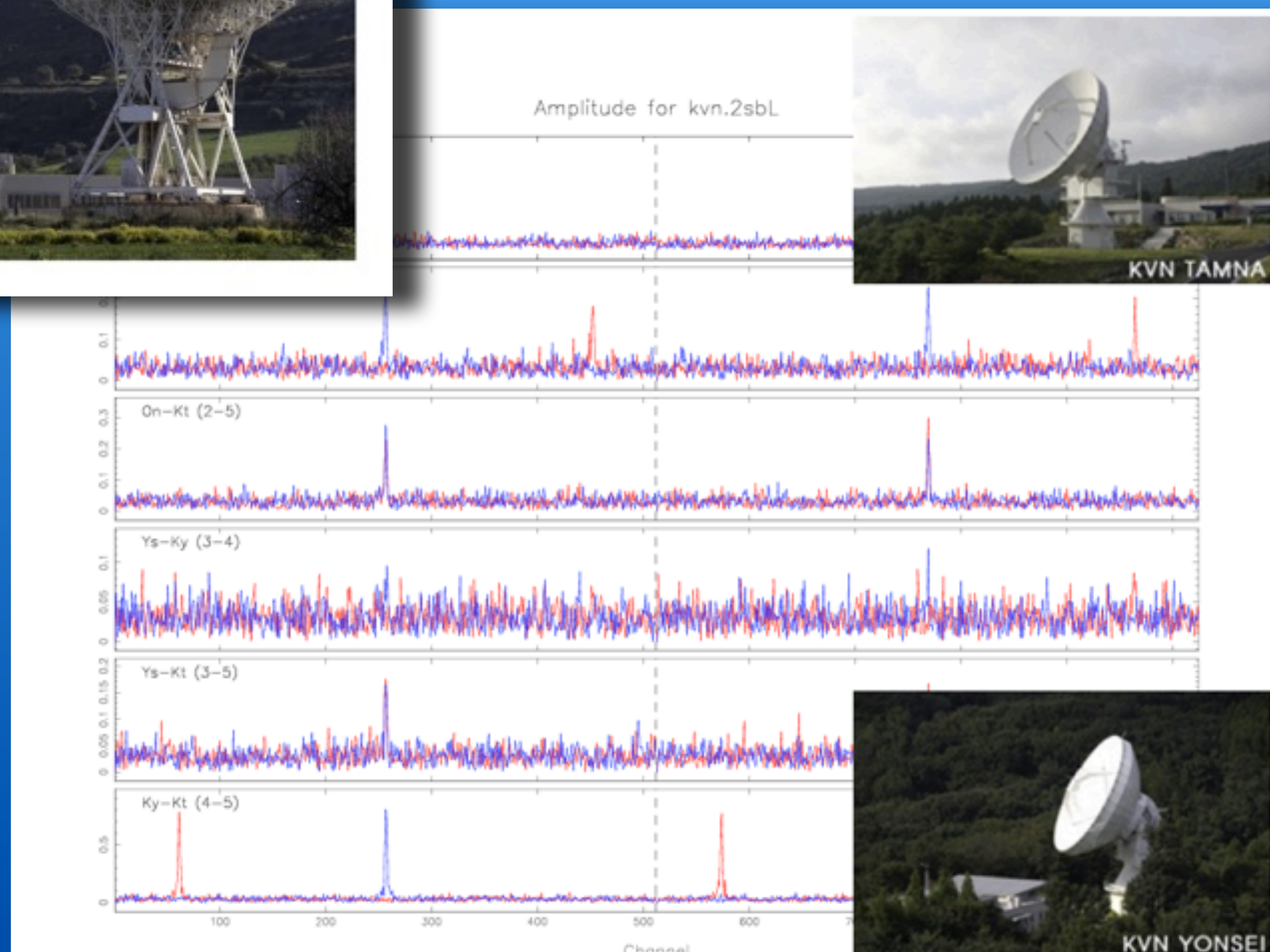
Paco Colomer

- Outreach & Dissemination
  - Maintains internal information
  - And external outreach material
    - Display booth
    - e-VLBI/JIVE film

Kristine Yun



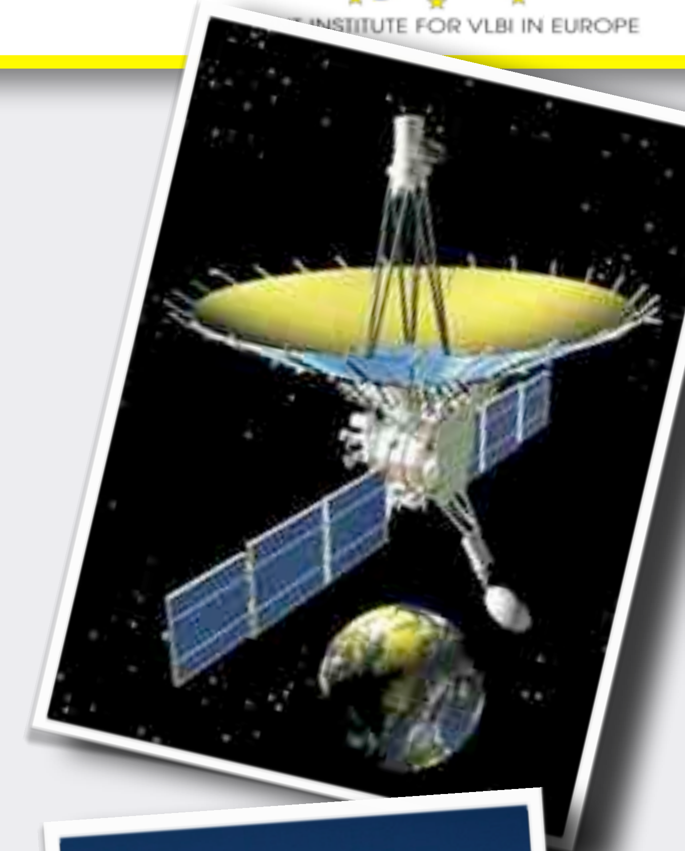
Noto, Sicily, antenna repaired and now on-line

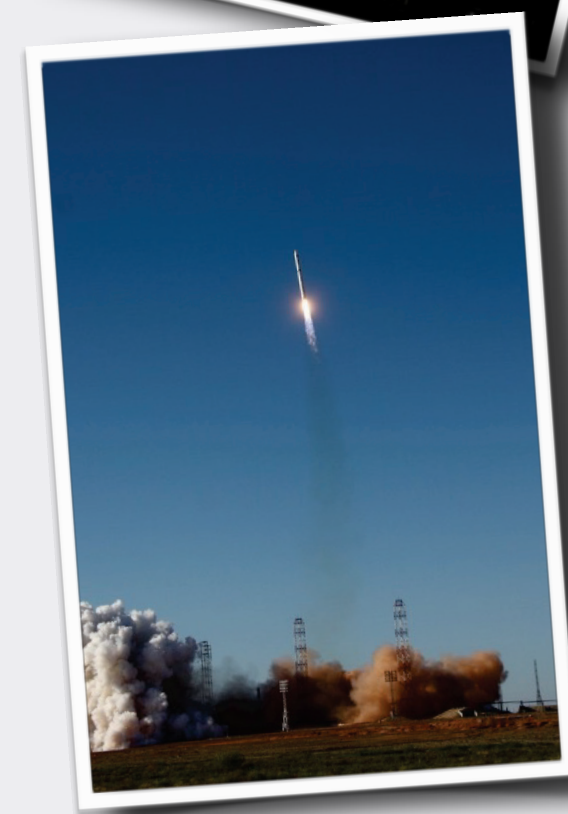


Successful tests done with Korea

NEXPReS impact on EVN

- Continuity in development programme
  - Essential in keeping local expertise
  - Vital for keeping in touch with NRENs
  - Continued effort in outreach/dissemination
- NEXPReS upgrades e-VLBI
  - Upgrades of equipment
  - Notably Mk5Cs at JIVE
- Step towards all EVN in e-VLBI
- Raise level of availability
  - Culture change on-going
  - New requests for (new) observing types
    - RadioAstron telescope in orbit
    - Observations of spacecraft (planetary/fundamental)
    - Monitor programmes/astrometry/joint observations
    - Triggers set by other observatories (link with LOFAR)
- Must offer new services
  - Offer tailored arrays? More e-VLBI days





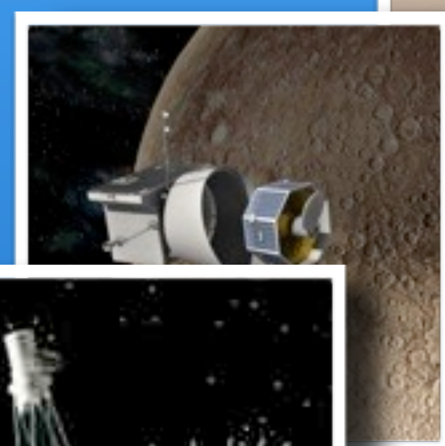
VLBI for Space applications...

JUICE-Laplace

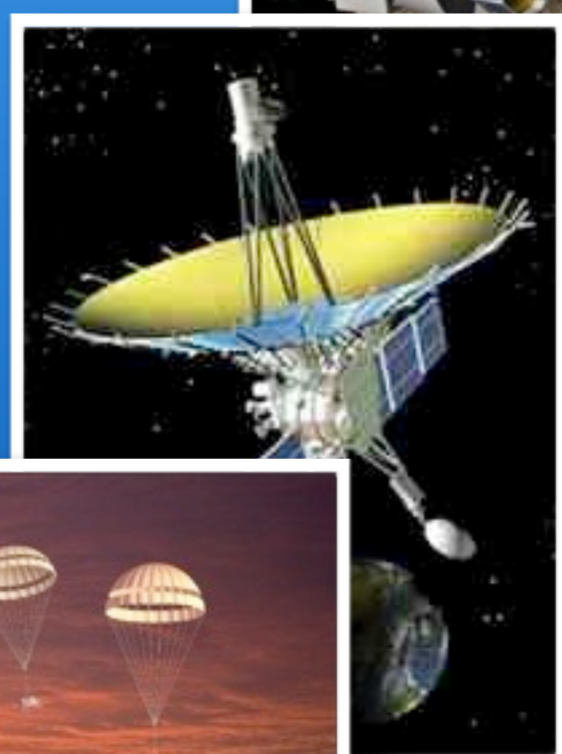
MarcoPolo-R?

ExoMars

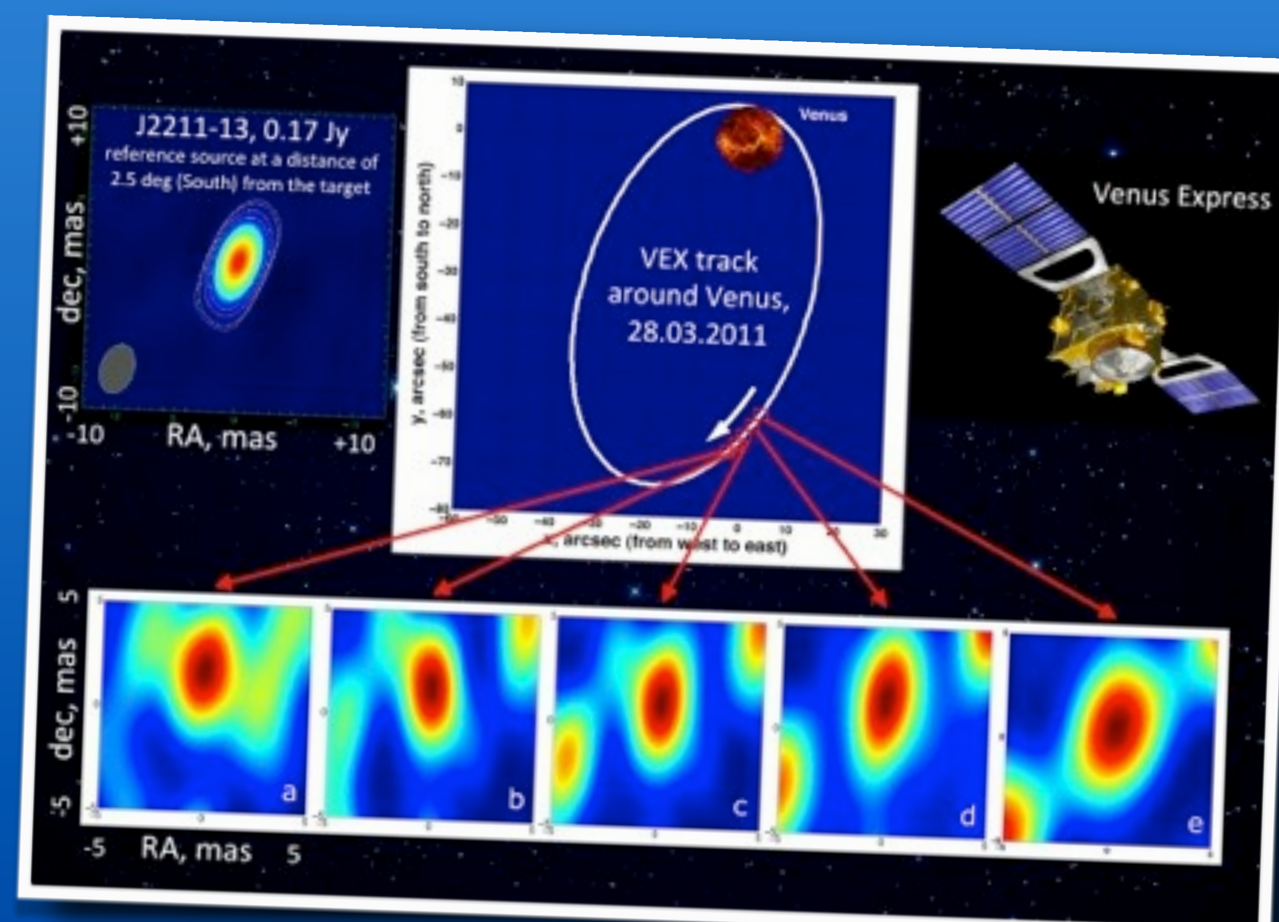
BepiColombo



RadioAstron



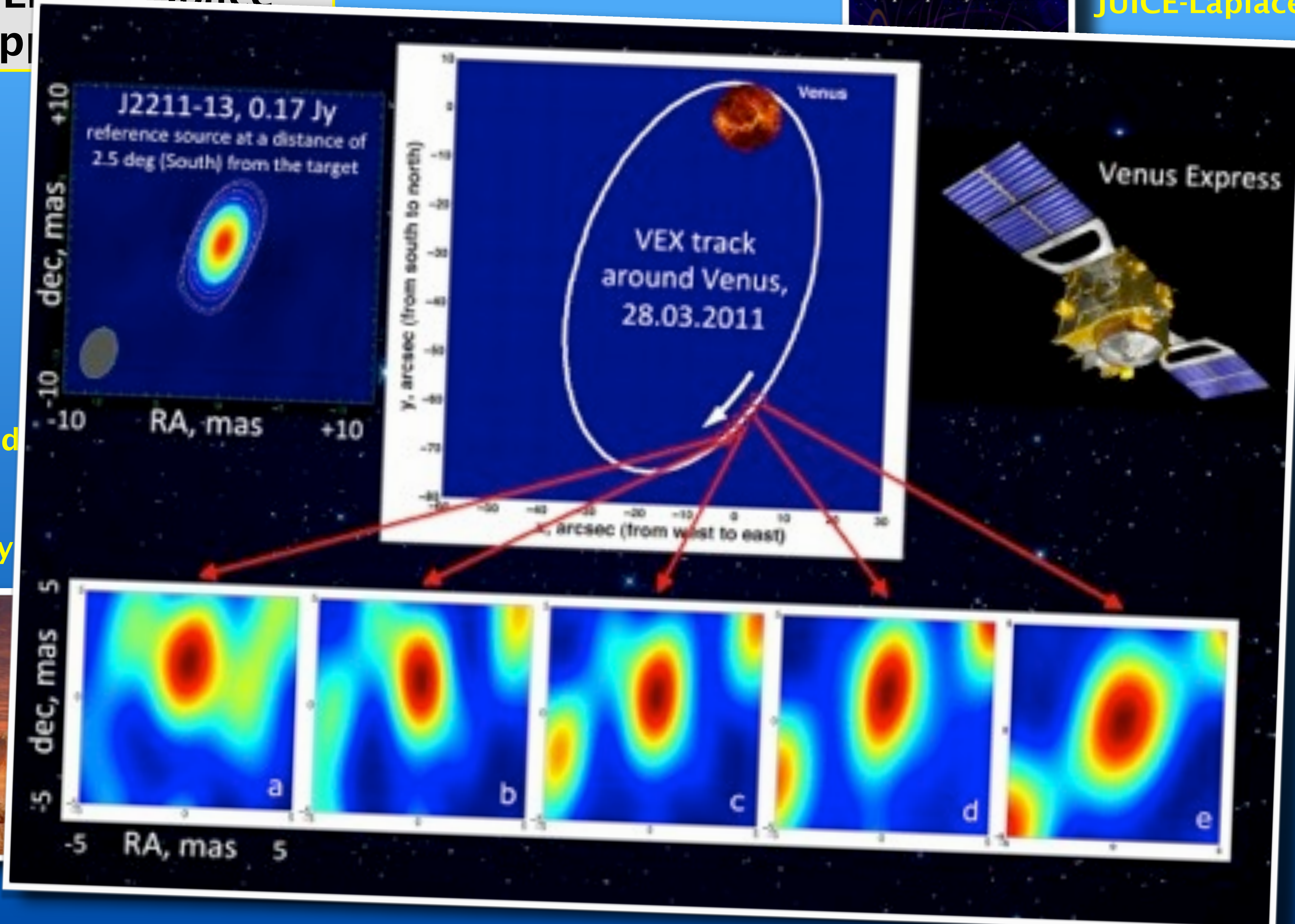
Huygens



VLBI for Space
ap

Europa Jupiter System Mission

JUICE-Laplace



Rad

Huy

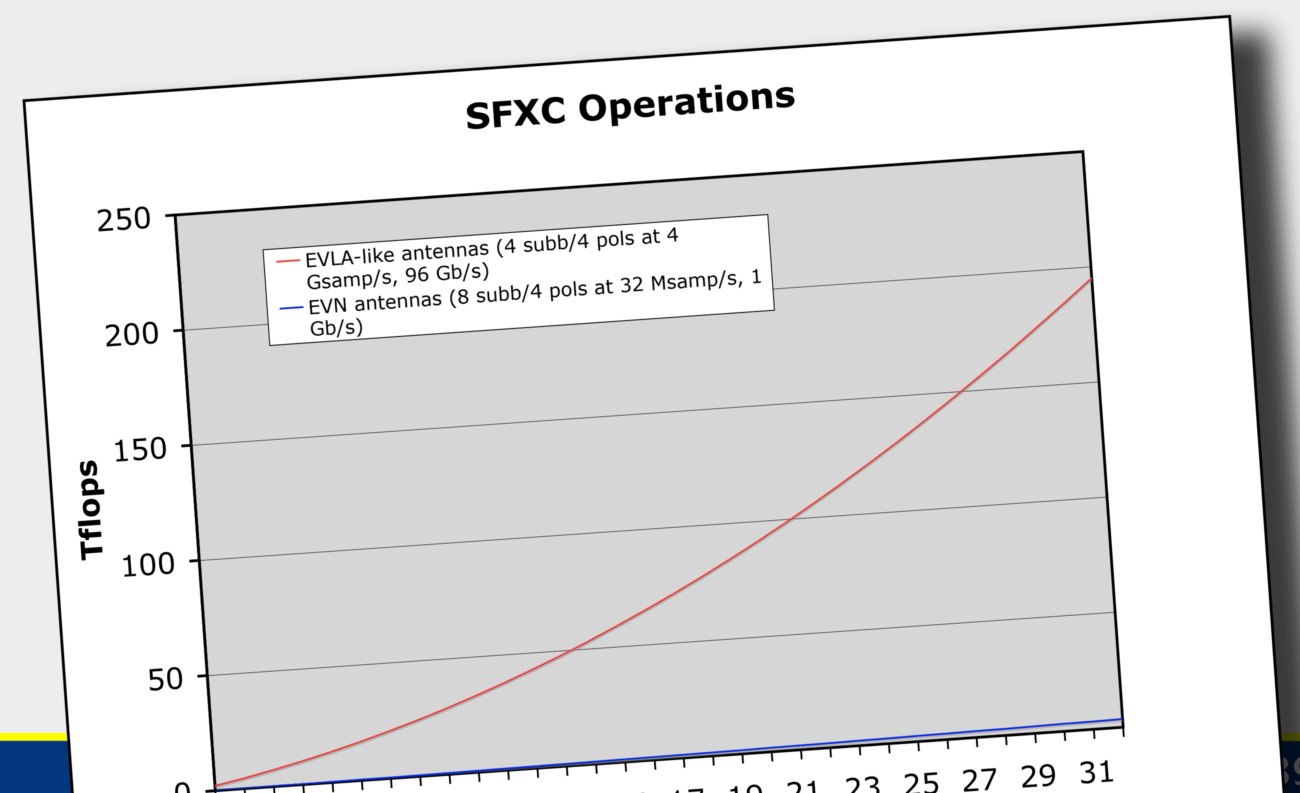
Next? More VLBI!

- **Increasing data rate will not stop any time soon:**
  - New stations: Africa, Goonhilly, Madeira, Brasil....
  - Joint observations with e-MERLIN
  - Joint observations with ALMA

- **Need for better sensitivity, more digital bandwidth**
  - with more bit sampling against interference
  - Science synergy with new survey instruments

Next correlator

- **Current EVN MarkIV**
  - 16 telescopes, 8 sub-bands (128 MHz), 4 pols
  - 1 Gb/s, or 512 Msamples/s for 2-bit sampling, per telescope
  - ~40 Tops
- **Current SFXC: 256 cores, 2 racks, 9.5 kW**
  - Can keep up with 9 stations
- **Next generation correlator: 100 fold more capacity**
  - 32 stations, 16 Gbps, high resolution
  - On software: 131072 cores, 1024 racks, 4.9 MW
  - UniBoard as 4GHz next generation correlator: 64 boards, 25.6 kW



Needed: next generation correlator

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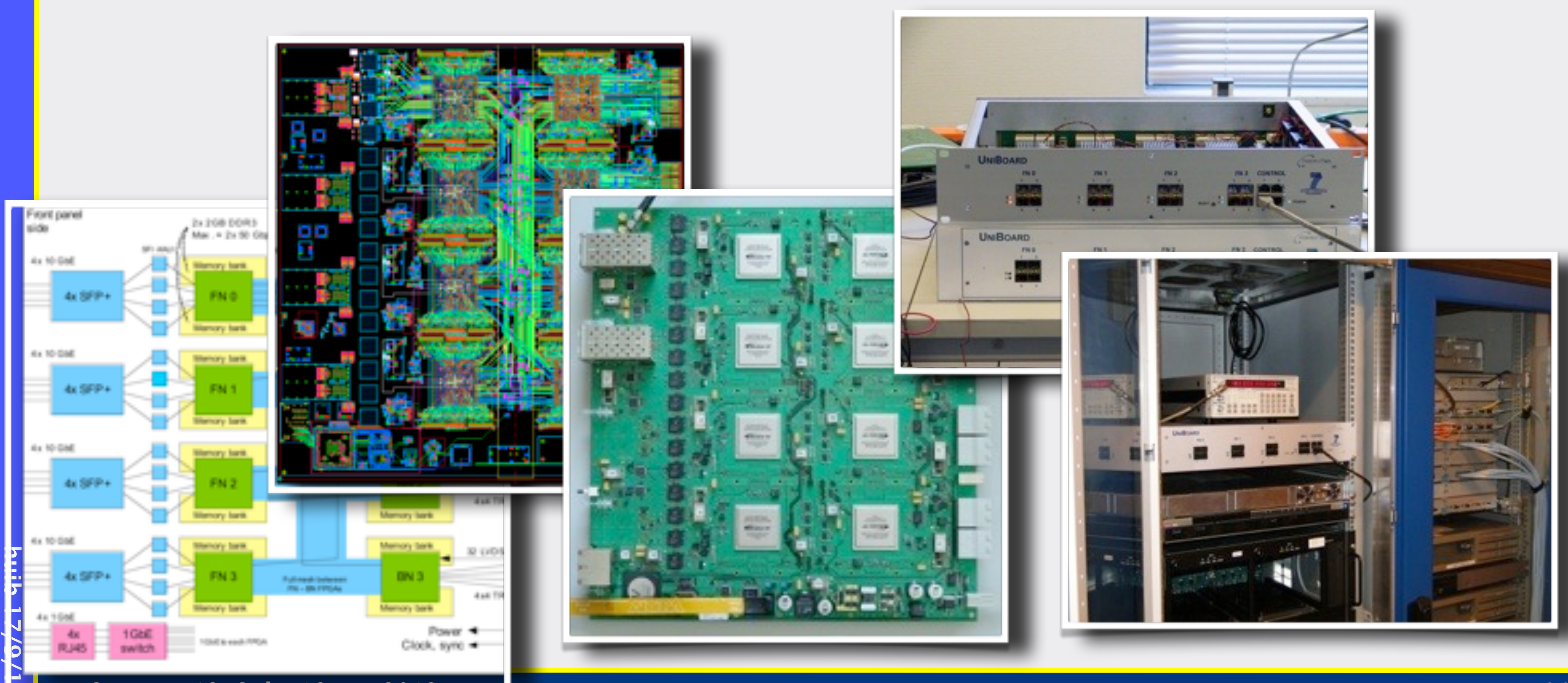
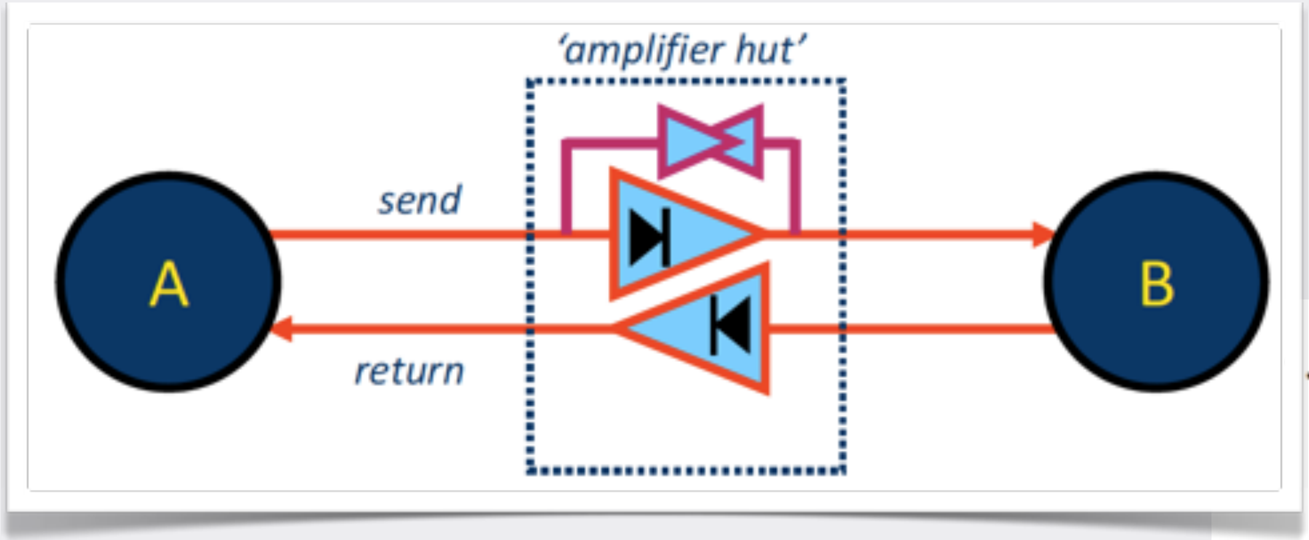
- Aiming for 32 station 10+ Gbps FPGA correlator
  - Flexibility of software correlator
  - Power consumption should be much better
  - Started in RadioNet::UniBoard, next step in RadioNet3
- Feeding into the SKA programme
  - As well as being used for EVN, LOFAR, WSRT, Effelsberg



Ambition: clock distribution

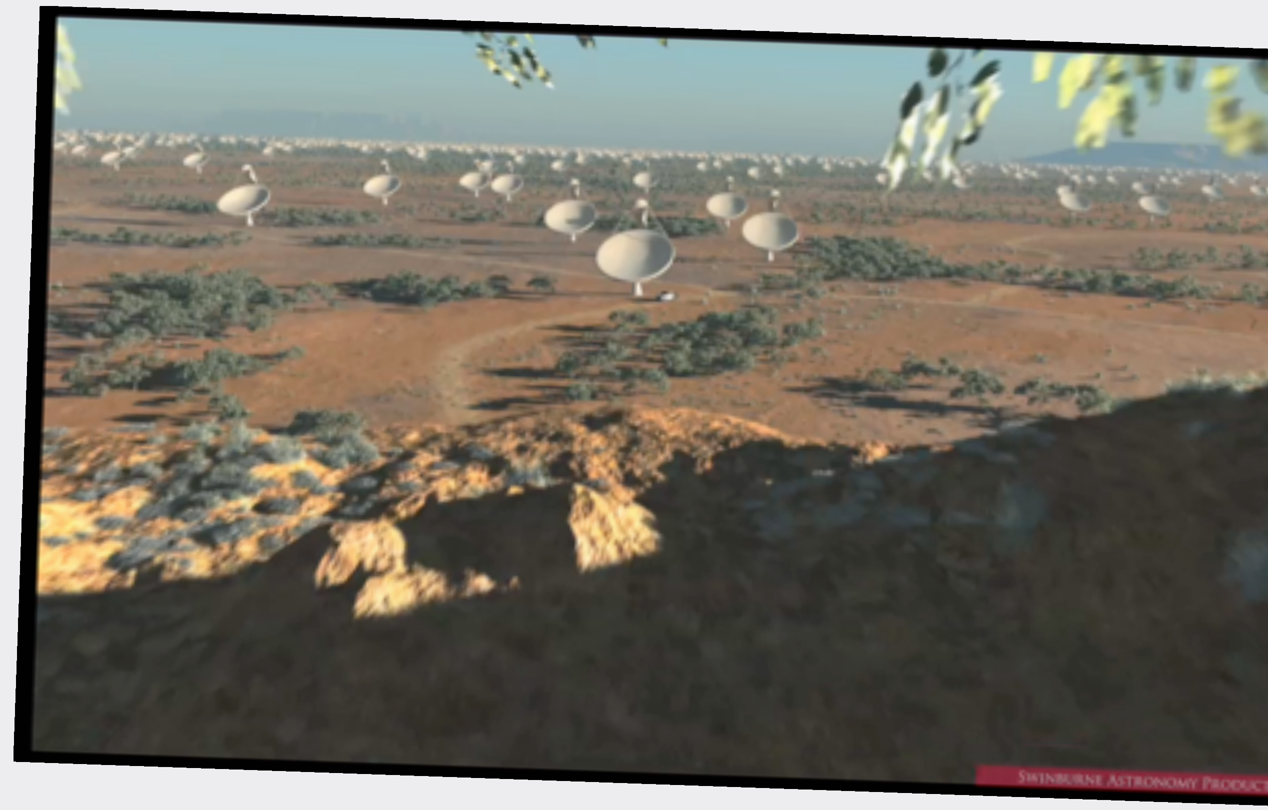
- VLBI depends on availability of extremely accurate clock and frequency standard (10^{-15})
  - All telescopes must have 100k€ maser clock
    - In principle can be distributed over dedicated fibre
- Investigate clock distribution on public network
  - Requires dedicated wavelength and stable amplification
  - To measure return loop



- Will improve stability, operations
- And many more VLBI sites!

VLBI Future

- Unique science: long baselines and high frequencies
  - Keep up with EVLA/MERLIN sensitivity
    - Going for 4Gbps in 2011
  - Follow up LOFAR, MeerKAT, ASKAP
- Like to link up with
  - US and VLBA antennas
  - African VLBI Network
    - Under ‘construction’



- Even in the SKA era
  - At least for phase I
  - Most certainly phase II
  - Spacecraft applications (and geodesy) need Northern Hemisphere

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