Optical fiber links in VLBI networks and remote clock comparisons: the LIFT/MetGeSp project

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Overview

- LIFT/MetGesp project: a brief history
- LIFT reaching Matera

  first tests towards common-clock exp
- Clock timing via rms phase noise

  VLBI experiments: 2018/2019
- Conclusions
- Future developments

Dissemination for Astronomy

T/F fibre links for Radioastronomy :

- ❑ Faster operations
- ❑ Better mm-VLBI: above 80 GHz, H-Masers are the main limit to resolution

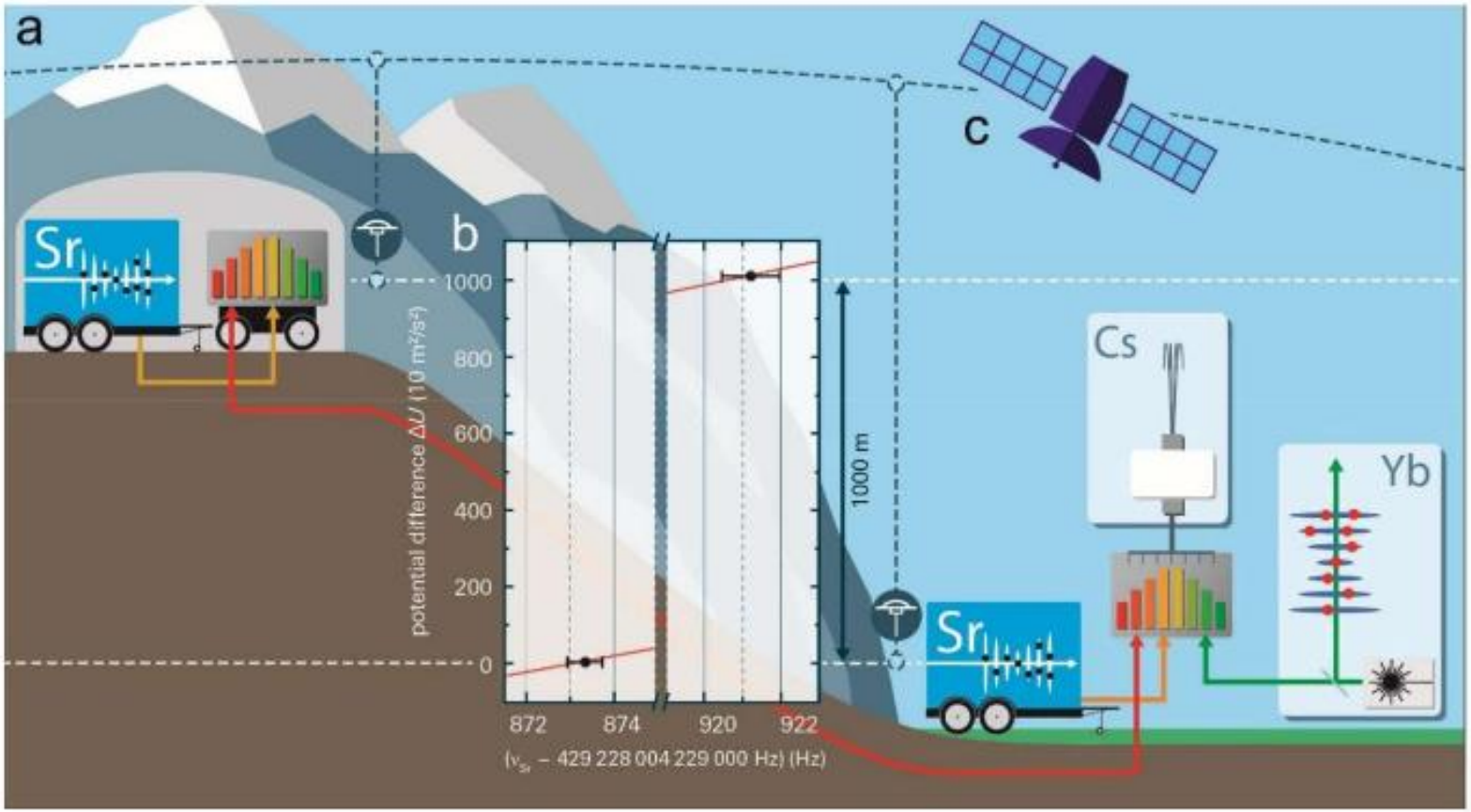
  M. Rioja, et al. Astron. J., vol. 144, no. 4, art. no. 121, 2012.
  B. Nikolic, et al. Astron. Astrophys., vl. 552, art. no. A104, Apr. 2013.
  M. Rioja and R. Dodson, Astron. J., vol. 141, no. 4, art. no. 114, 2011
- ❑ Existing mm-VLBI Telescope in Europe: MPIfR (Germany), IRAM (Spain), Onsala (Sweden), Metsahovi (Finland),

- ❑ Study of compact radio sources (better angular resolution) and interstellar molecular clouds
- ❑ In Geodesy VLBI, accuracy is relevant and 1-mm positioning accuracy requires clocks uncertainties at 1e-16.

  A. Neill, et al. Report of Working Group 3 to the IVS Directing Board, Sep. 2005.
- ❑ Studying Pulsar through absolute accurate time

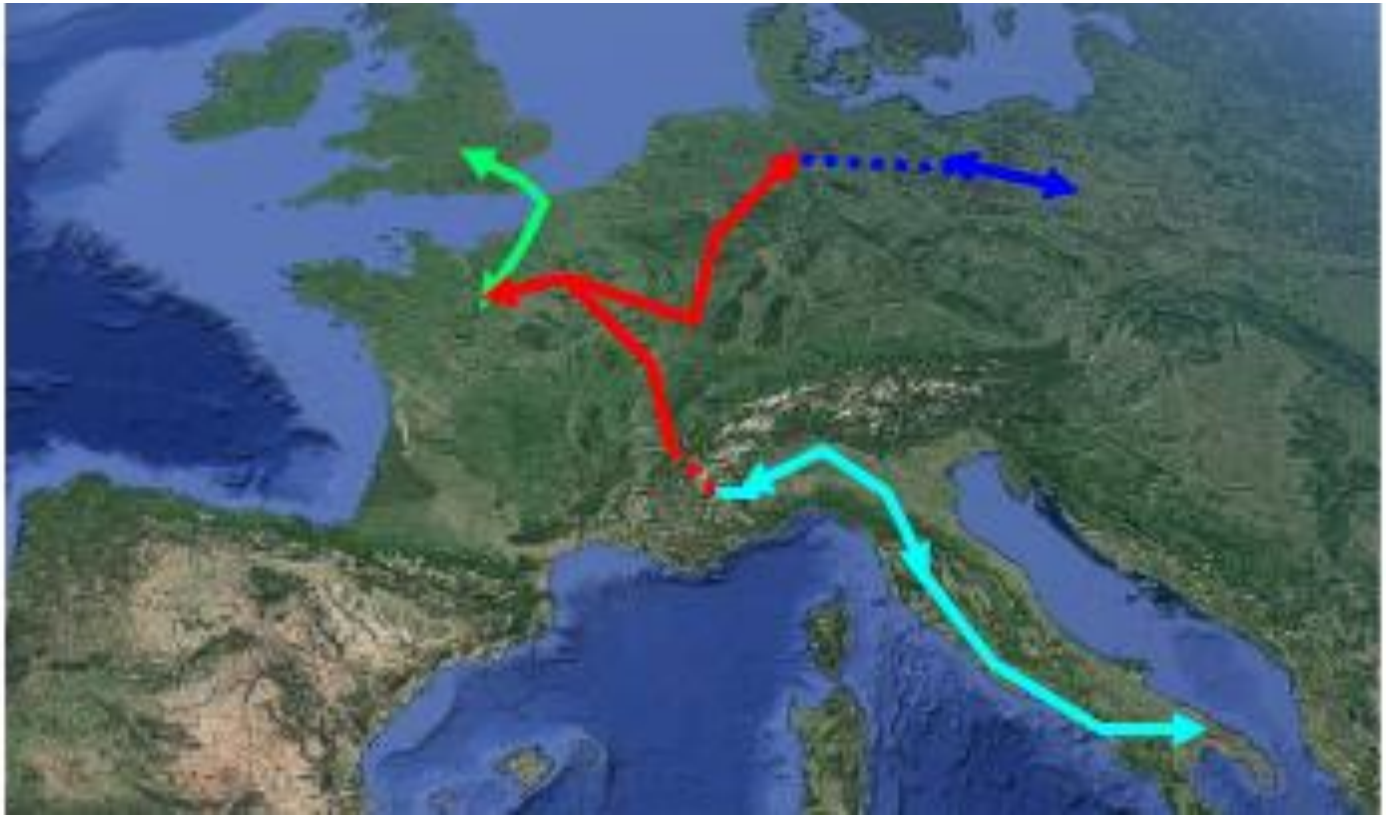
  Andrew Lyne, EFTF2016

Relativistic Geodesy



Grotti et al., Nature Phys 14, 2018

Clock Metrology



- Fiber-based clock comparison: Lisdat et al. Nat. Comm., 2016
- Redefinition of the SI second based on Sr/Yb Optical clocks:
  Riehle el al., Nat. Photonics, 2017

From LIFT to MetGeSp

ITALIAN QUANTUM BACKBONE, 1800 km

- Quantum Technologies
- Radioastronomy
- Ultracold atoms Physics
- Space - Galileo
- Finance

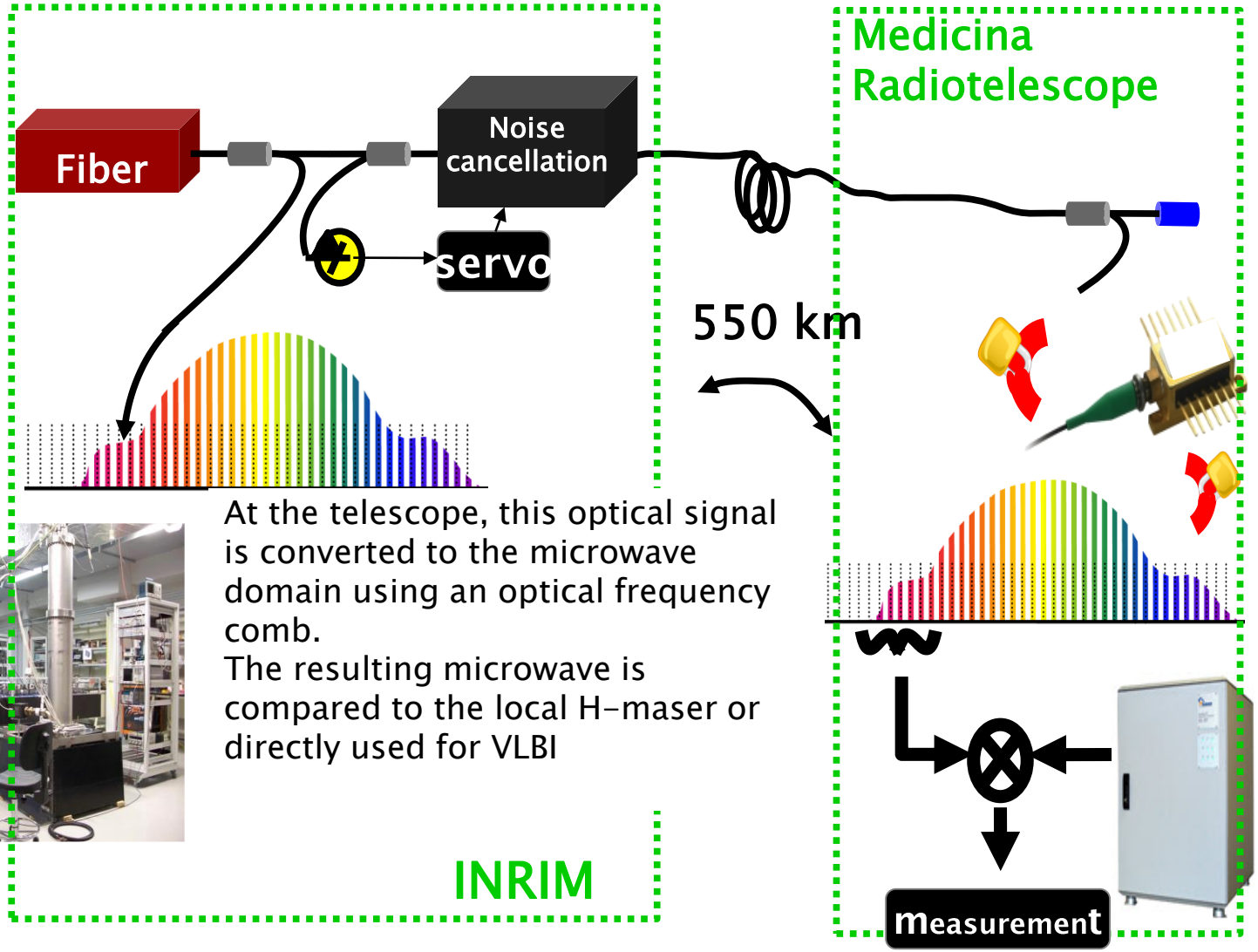
7 Research Institutes linked:
CNR – National Research Council
ASI – Italian Space Agency
INAF – Italian Astrophysics Institute

3 Industrial Users
Thales Alenia Space Italy
Telespazio;
Consortium Top-IX

Coherent Technique (now)
To be added: WR-PTP

INRiM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA

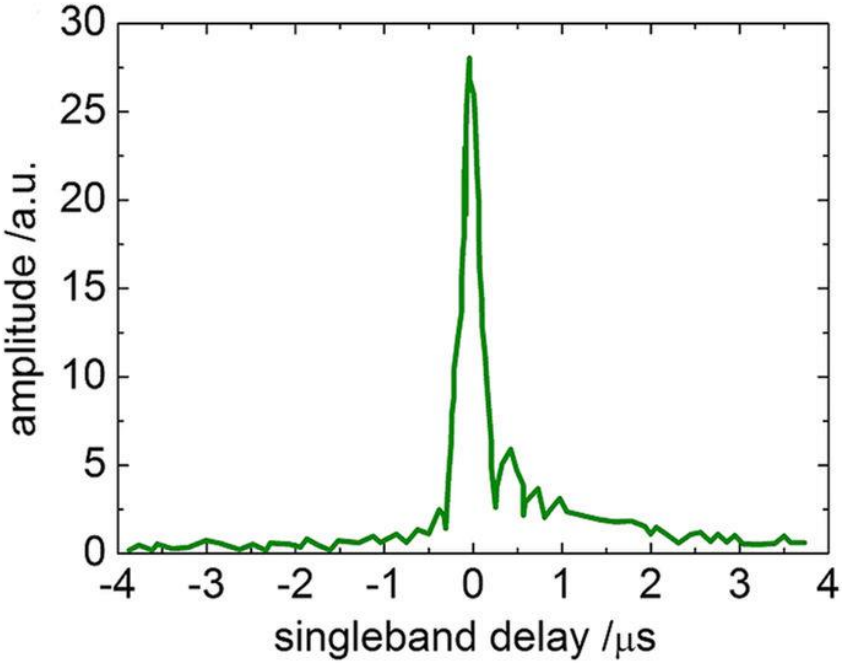
Optical Frequency Comb



At the telescope, this optical signal is converted to the microwave domain using an optical frequency comb.
The resulting microwave is compared to the local H-maser or directly used for VLBI

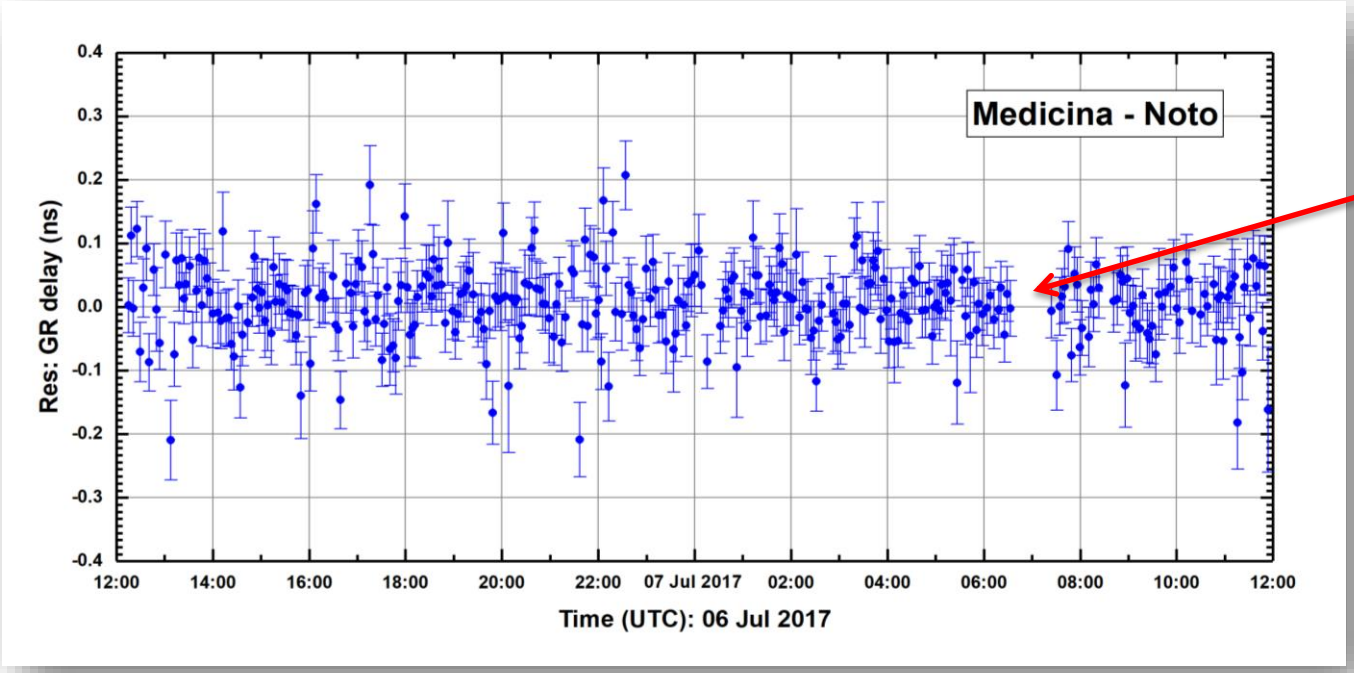
EUR137

- European Geodetic VLBI exp: 24 hours in SX bands on Sep 7-8 2015
- Aim: tectonic studies on the European plate
- 6 stations involved: DSS65A, Mh, Ny, On, Wz + Mc (in tag-along mode)
- Data correlated using Bonn DiFX correlator (by A. Bertarini and T. Artz) treating Medicina (local clock) and MEDILIFT (remote clock) as separate experiments
- Fringe fitting in HOPS *fourfit* → Calc/SOLVE/nuSolve used for analysis
- Results: Clivati et al., Nature Scientific Reports, 2017



VITA004

- Date: July 6-7, 2017
- Precursors: VITA001…003 (tests of VLBI ITA network w/ local clocks)
- Aim: remote clock infrastructure testing on 24-hr S/X-band geodetic exp
- Stations involved: Ma, Nt, Mc (24 hrs w/ remote clock link on)
- Data correlated using Bologna DiFX correlator by M. Stagni and RR
- Fringe fitting in HOPS *fourfit* and analysis with CALC/SOLVE/nuSolve
  →problems: a few link unlocks sanitized in post-processing

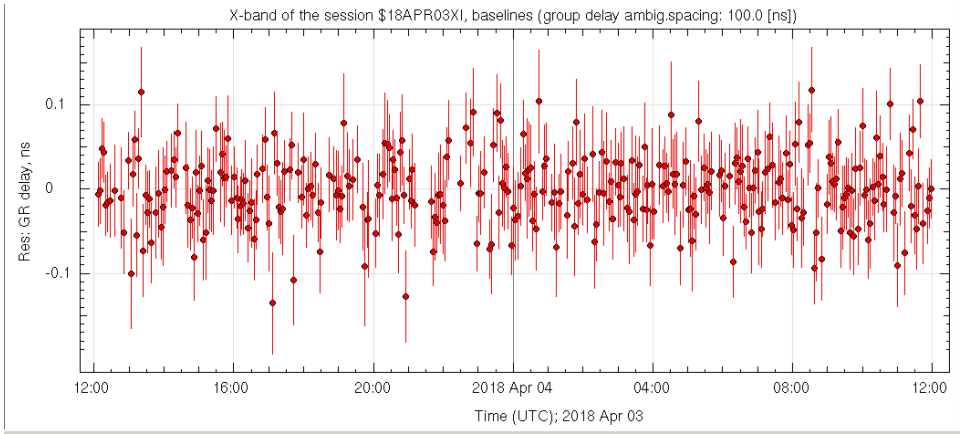


unlocks

Mc-Nt baseline Wrms= 56 ps. Full exp Wrms = 46 ps

VITA005 (Apr 2018)

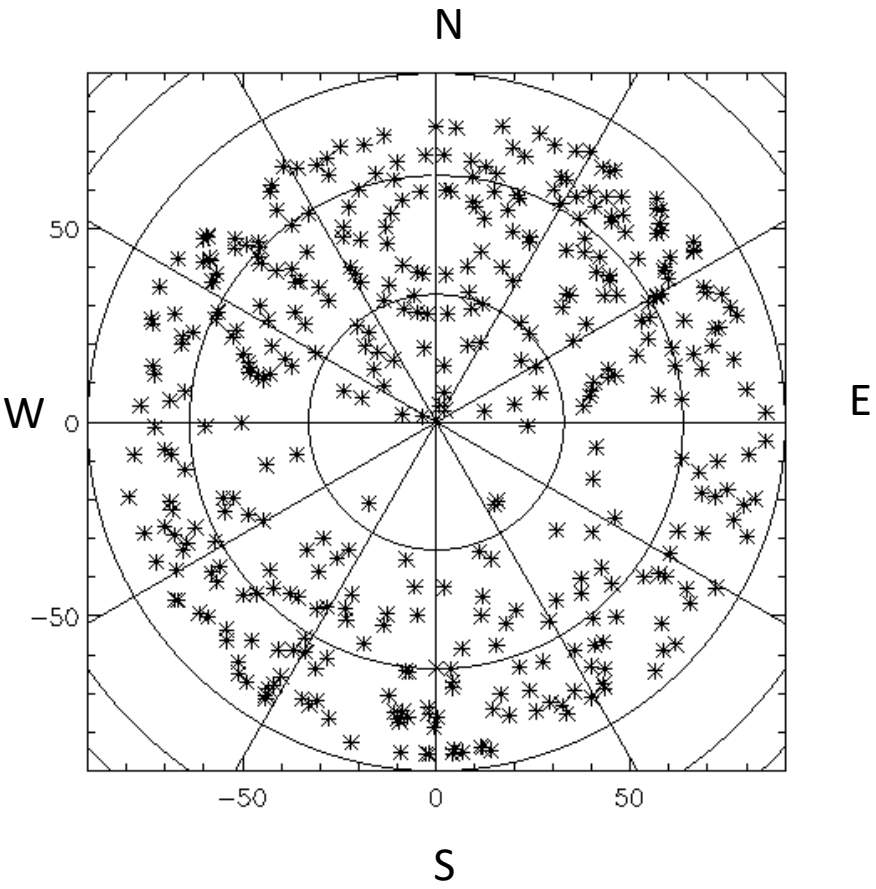
Standard geodetic S/X experiment with Mc, Nt, Ma (Mc with Turin remote clock)



Group delay wrms = 37.1 ps

96 parameters adjusted

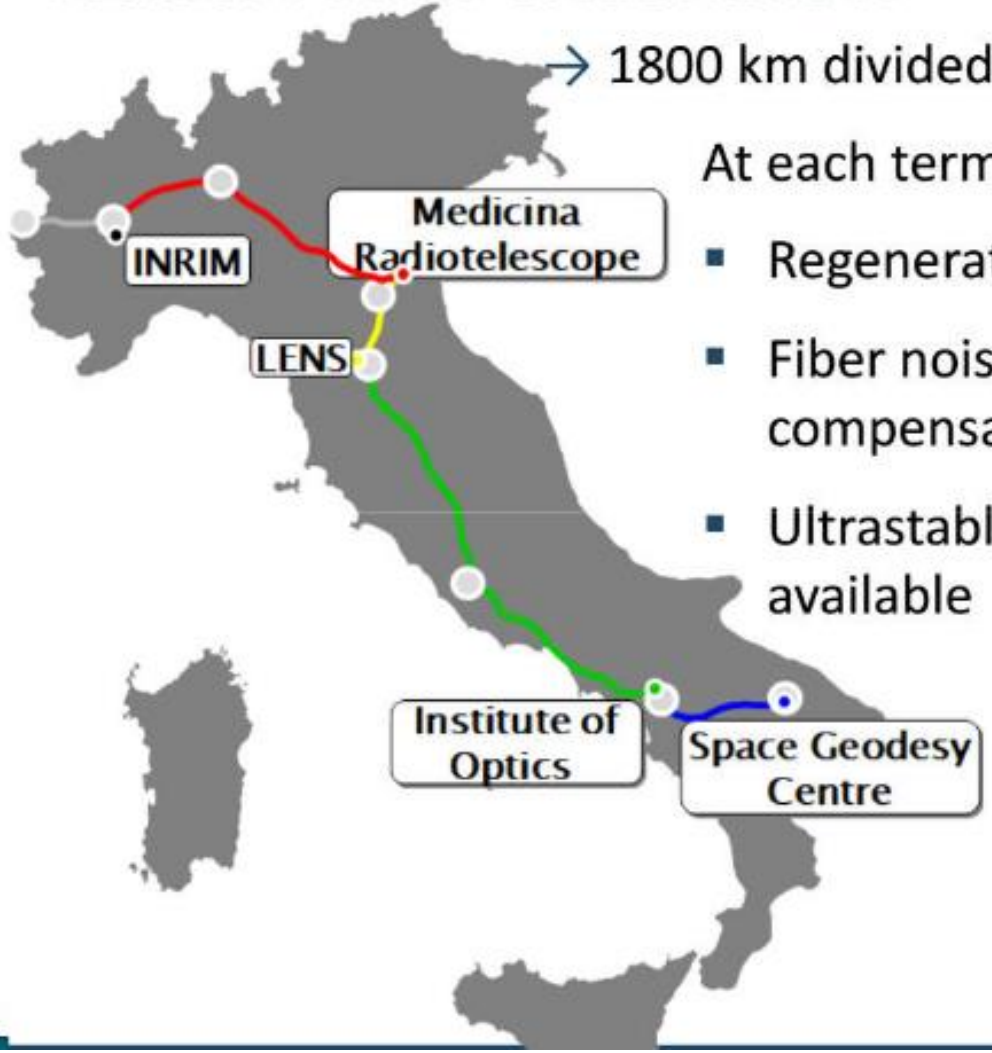
338 /402 obs pairs used



Sky coverage

LIFT reaching Matera

Italian link extension

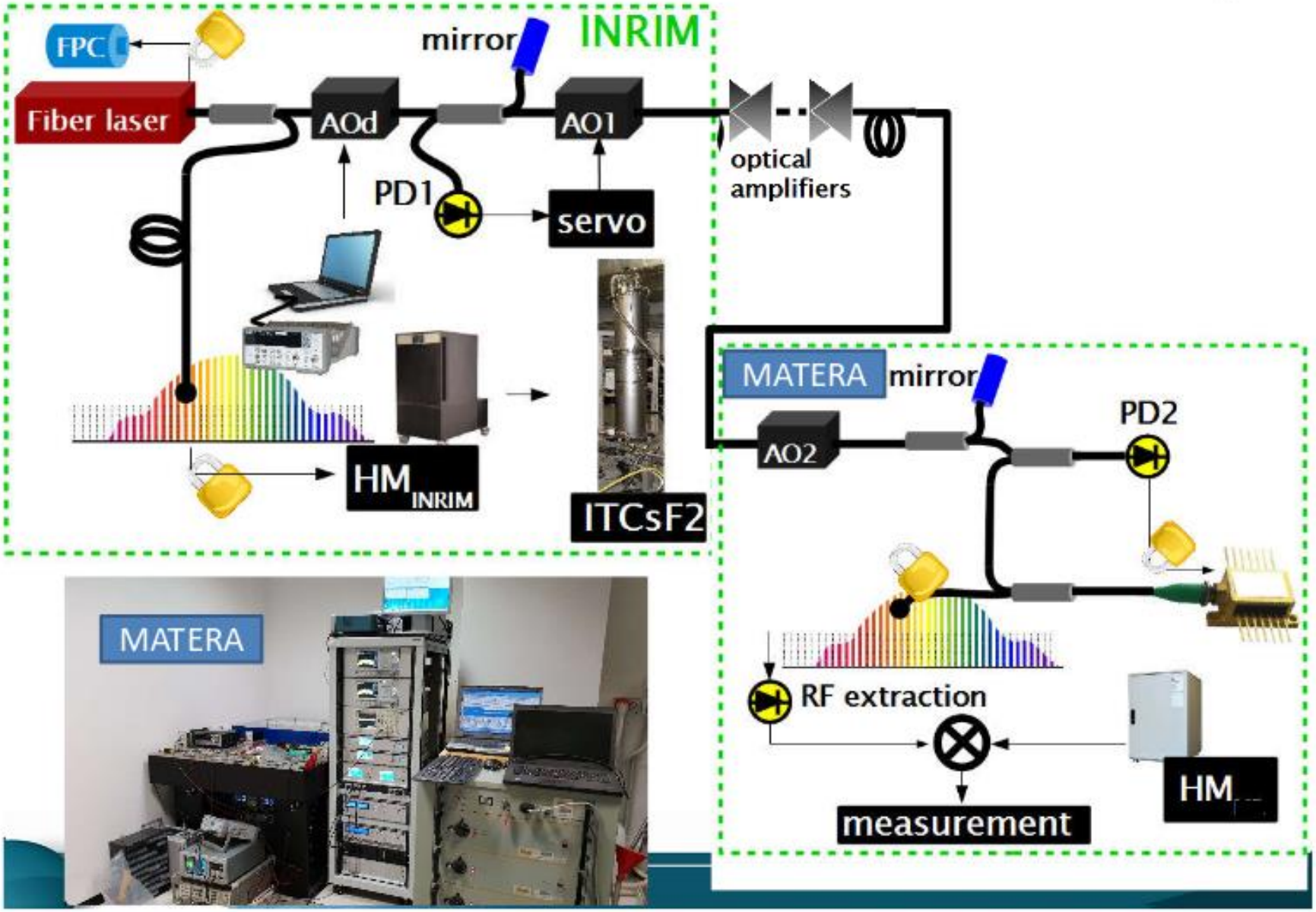


→ 1800 km divided into 4 spans

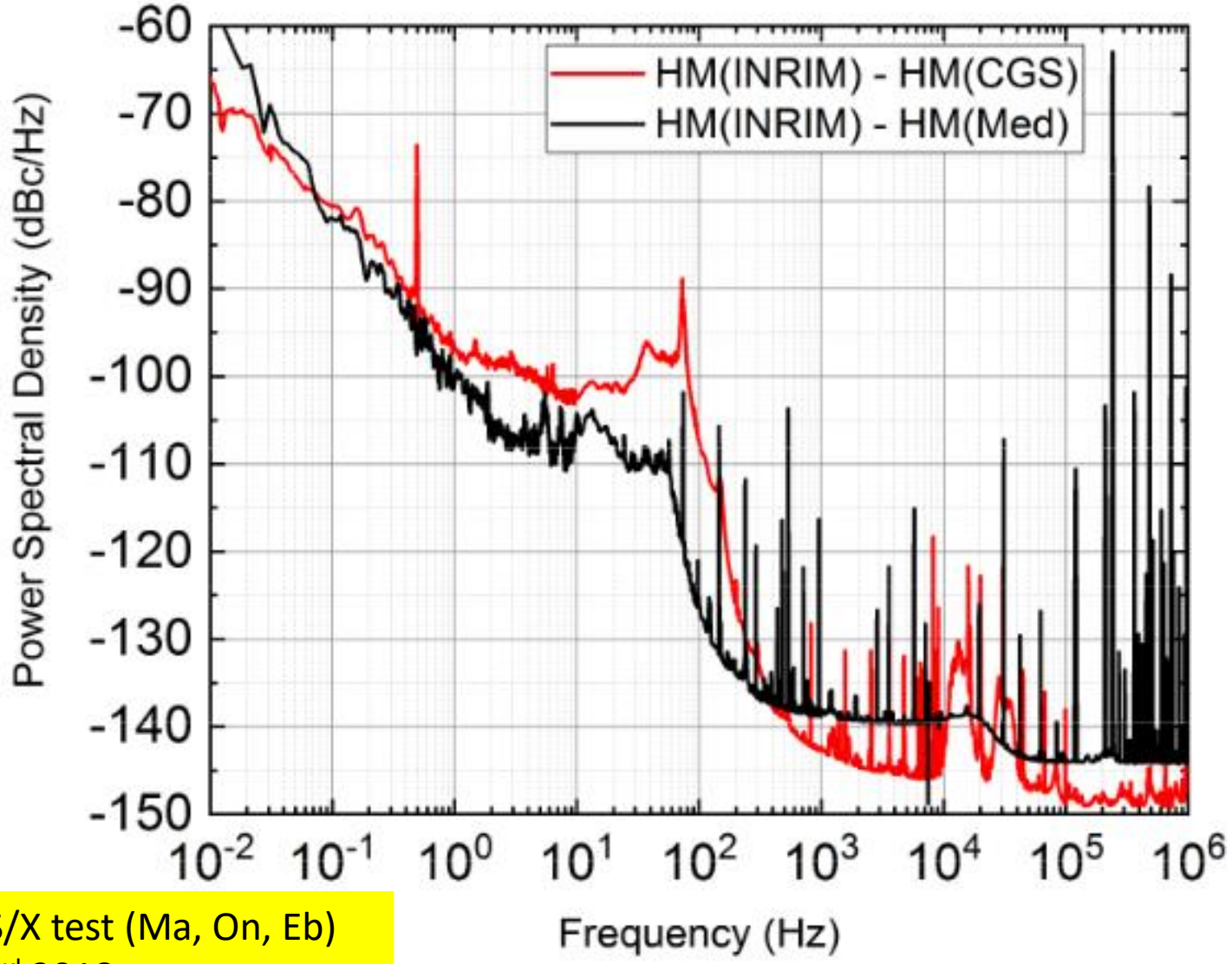
At each terminal:

- Regeneration laser
- Fiber noise compensation
- Ultrastable laser available

Fiber Link from INRIM to Matera: set-up



Matera first light: Nov 7th 2018
Ma-Mc HM clock comparison



First VLBI S/X test (Ma, On, Eb)
On Nov 23rd 2018

VLBI Clock Timing (VT exp's)

- Night time observations, possibly in Winter season ➔ min atm instability
- Bright geodetic standard calibrator ➔ point-like source
- Observing at medium/high telescope elevations ➔ min air mass
- Long scan lenghts (~15 min) in 3 hr long runs
- Rms phase noise statistics used to estimate clock synchronization
- Reference project: Krehlik et al. (2017)

	Date	stations	Band	Mc remote clock?
VT001	2018 Jan 18th	Mc, Nt, Ma, Ys, Mh	S/X	No
VT003	2018 Jan 24th	Mc, Nt, Tr	C	No
VT005	2018 Feb 19th	Mc, Nt, Tr	C	No
VT006	2018 Feb 20th	Mc, Nt, Tr, Ys	C	Yes
VT008	2019 Feb 5th	Mc, Sr	C	Yes
VT009	2019 Feb 4th	Mc, Sr	C	No

VLBI Timing experiments (II)

AIPS rms phase noise stats in @ 900 sec (15min) - stddev(delta_phi)
averaged over 80% of the channels used for stats

target: 1156+295

		VT003 24/01 scan: No0003 local H-maser even	odd	VT005 19/02 scan: No0002 Local H-maser even	odd	VT006 20/02 scan: No0002 remote H-maser even	odd
Mc-Nt	1RR	2.2444	2.0208	4.42298	4.52849	4.89879	4.98553
	2RR	3.1187	2.0758	4.33117	4.46659	4.75475	4.89925
	3RR	2.4396	2.0334	4.38129	4.70633	4.78743	4.73432
	4RR	2.4219	2.0976	4.49920	4.82239	4.73296	5.01417
		[450]	[300]	[444]	[296]	[444]	[296]
Mc-Tr	1RR	2.2599	1.8594	3.29524	3.18306	3.65587	3.14996
	2RR	--	--	3.27009	3.13762	4.81444	3.57780
	3RR	--	--	3.31410	3.05380	3.23695	2.95854
	4RR	--	--	3.63847	3.38014	3.30058	3.01559
		[450]	[300]	[258]	[172]	[258]	[172]
Nt-Tr	1RR	2.7107	2.7049	2.43536	2.45431	4.73028	4.54811
	2RR	--	--	2.82560	2.59229	5.82526	5.12456
	3RR	--	--	2.71327	2.72862	4.34278	4.02559
	4RR	--	--	2.76949	2.84002	4.22193	3.97130
		[450]	[300]	[258]	[172]	[258]	[172]

No good data
Scheduling problems

		VT001 S-band 20/01 local maser 018-0510 scan even	odd	VT001 S-band 20/01 local maser full run even	odd
Ma-Mc	4RR	25.6488	22.5378	26.1588	23.1572
Ma-Nt	4RR	30.3198	26.0273	--	--
Ma-Ys	4RR	35.8112	30.4577	44.3894	38.6602
Mc-Nt	4RR	15.9083	14.7744	--	--
Mc-Ys	4RR	20.8147	18.7728	19.5824	17.1660
Nt-Ys	4RR	22.8662	20.0487	--	--
		[240]	[160]	[5004]	[3336]

values in degrees
relative error: 1/sqrt([N]) (even/odd)

Sampling rate: 1 sec

Even stats: 450 couples (ph2-ph1, ph4-ph3, etc.)

Odd stats: 300 triplets (ph2-(ph3+ph1)/2, etc.)

C-band
IF1: 4.9745 GHz
IF2: 4.9825 GHz
IF3: 4.9905 GHz
IF4: 4.9985 GHz

IF BW: 8 MHz
32 ch in each IF

AIPS data reduction with the help of E. Kravchenko

VLBI Timing experiments (III)

$$D t_{rms} = \frac{D f_{rms}}{2 p n_0}$$

AIPS rms phase noise stats @ 900 sec (15min) - stddev(delta_t)
averaged over 80% of the channels used for stats

target: 1156+295

		VT005 19/02 scan: No0002 Local H-maser even	odd	VT006 20/02 scan: No0002 remote H-maser even	odd	VT003 24/01 scan: No0002 local H-maser even	odd
Mc-Nt	1RR	2.47(12)	2.53(15)	2.74(13)	2.78(16)	1.25(6)	1.13(7)
	2RR	2.41(11)	2.49(14)	2.65(13)	2.73(16)	1.74(9)	1.16(7)
	3RR	2.44(12)	2.62(15)	2.66(13)	2.64(15)	1.36(7)	1.13(7)
	4RR	2.50(12)	2.68(16)	2.63(12)	2.79(16)	1.35(7)	1.17(7)
		[444]	[296]	[444]	[296]	[450]	[300]
Mc-Tr	1RR	1.84(11)	1.78(14)	2.04(13)	1.76(13)	1.26(6)	1.04(6)
	2RR	1.82(11)	1.75(13)	2.68(17)	1.99(15)	--	--
	3RR	1.84(11)	1.70(13)	1.80(11)	1.65(13)	--	--
	4RR	2.02(13)	1.88(14)	1.83(11)	1.68(13)	--	--
		[258]	[172]	[258]	[172]	[450]	[300]
Nt-Tr	1RR	1.36(8)	1.37(10)	2.64(16)	2.54(19)	1.51(8)	1.51(9)
	2RR	1.58(10)	1.45(11)	3.25(20)	2.86(22)	--	--
	3RR	1.51(9)	1.52(12)	2.42(15)	2.24(17)	--	--
	4RR	1.54(10)	1.58(12)	2.35(15)	2.21(17)	--	--
		[258]	[172]	[258]	[172]	[450]	[300]

VT001: Ma,Mc,Nt,Ys
VT003: Mc,Nt,Tr
VT005: Mc,Nt,Tr
VT006: Mc,Nt,Tr,[Ys]

C-band
IF1 = 4.9745 GHz
IF2 = 4.9825 GHz
IF3 = 4.9905 GHz
IF4 = 4.9985 GHz

S-band
IF4 = 2.26799 GHz

		VT001 S-band 20/01 local maser 018-0510 scan even	odd	VT001 S-band 20/01 local maser full run even	odd
Ma-Mc	4RR	31.4(2.0)	27.6(2.2)	32.0(0.5)	28.4(0.5)
Ma-Nt	4RR	37.1(2.4)	31.9(2.5)	--	--
Ma-Ys	4RR	43.9(2.8)	37.3(2.9)	54.4(0.8)	47.4(0.8)
Mc-Nt	4RR	19.5(1.3)	18.1(1.4)	--	--
Mc-Ys	4RR	25.5(1.6)	23.0(1.8)	24.0(0.3)	21.0(0.4)
Nt-Ys	4RR	28.0(1.8)	24.6(1.9)	--	--
		[240]	[160]	[5004]	[3336]

values in picoseconds; stat. errors in round brackets; couples and triples in square brackets

- Good agreement with Krehlik et al.
- Similar stability to VITA004
- Similar rem. and local H-maser stats
- AIPS TV001 X-band
- Phase self-cal to improve stats

VLBI Timing Experiments (IV)

Stations: Mc, Sr
VT009: 22:00-04:00 UT Feb 4-5 2019 (local HM in Mc)
VT008: 22:00-04:00 UT Feb 5-6 2019 (remote HM in Mc)
Targets: 0738+313, 1156+295
Integration time: 1 s
First difference analysis (ph2-ph1): 9823 couples
Dual pol'n: RR/LL
1 IF: center frequency 6.662.48 MHz

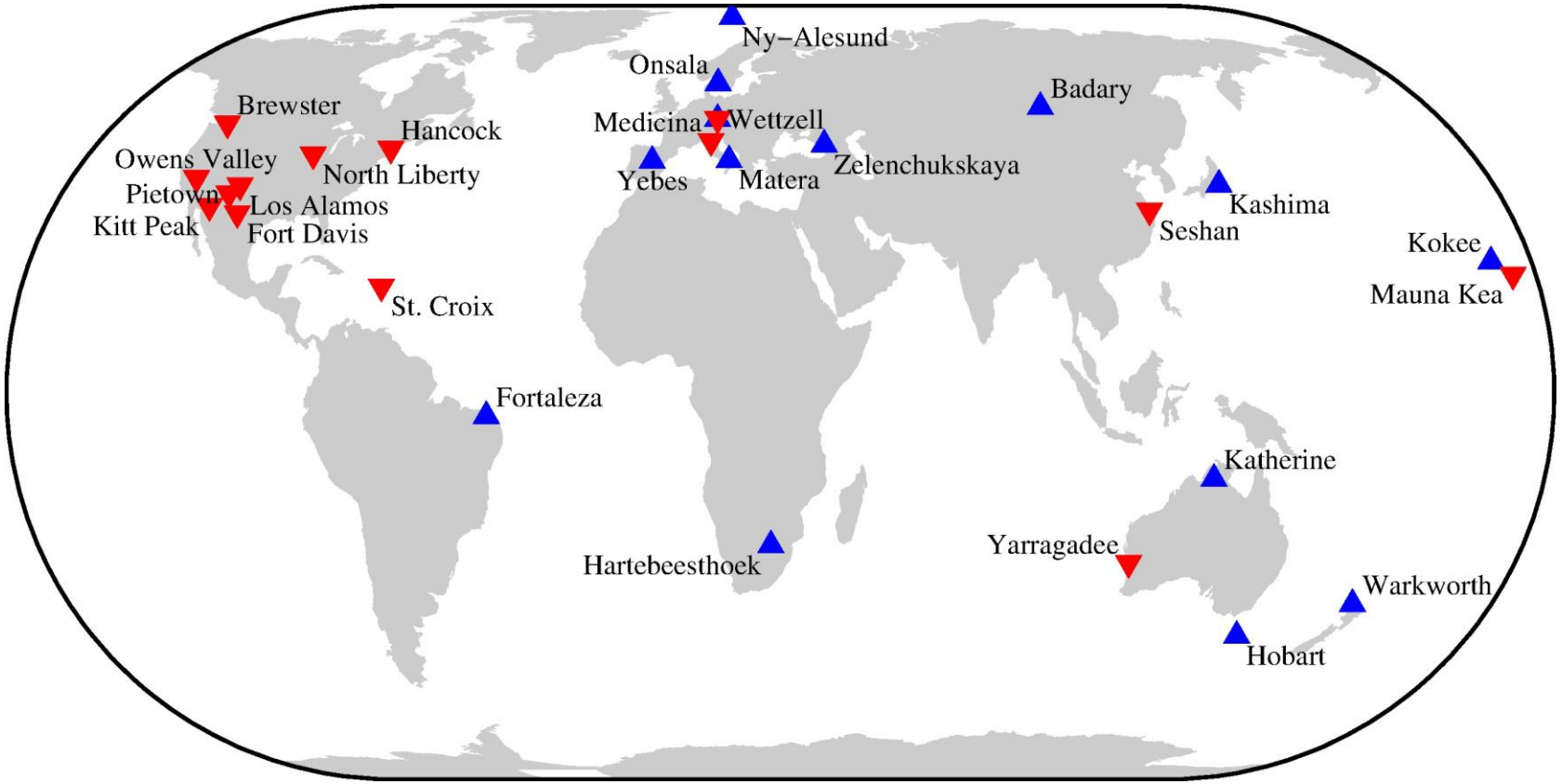
Proj/pol/HM	Delta t_rms (ps)	+/-
VT008/RR/rem	3.08	0.03
VT009/RR/loc	2.31	0.03
VT008/LL/rem	3.79	0.04
VT009/LL/loc	2.79	0.03

Conclusions

- LIFT is an infrastructure to deliver frequency standard signal from the Italian metrological Institute (INRIM) to remote locations via optical fiber link with unprecedented stability (order of 10^{-19})
- Geodetic VLBI experiments are performed with remote frequency standard provided by INRIM with ten's of ps wrms residuals in group delay: on par with exp's utilizing local clocks
- LIFT reached Matera CSG in Nov 2018 covering a fibre optic span of 1800 km
- Rms interferometric phase noise statistics was succesfully used in remote and local clock timing with radio/geo VLBI technique

Future developments

- VLBI vs GPS σ_y analysis in CONT17 campaign (2017 Nov 28- Dec 12) for co-located stations: Ma and On w.r.t. Wz



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- Common clock experiment: Medicina and Matera receive remote clock frequency standard from Turin ➔ first experiment in May 2019

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- Optical clock comparison between Japan's NICT and Italy's INRIM via VLBI: Japanese MARBLE small (2.4-m ⦸) antennas (one in Medicina -> INRIM and one in Koganei -> NICT) observing with 34-m antenna in Kashima

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- ASI collaboration: receiving carrier signal from interplanetary space probe. VLBI experiment Mc-Nt or Mc-Ma. Mark5B/VDIF -> RDEF -> ΔDOR (Differential One-way Ranging)
- Possible future VLBI timing experiment between Medicina/Turin and Polish Torun/KM-FAMO optical clocks
- Testing of White Rabbit/Precise Time Protocol technology for digital dissemination of frequency standard and clock synchronization

Thank you!