A Geodetic Reference Frame for the Virgo Interferometer

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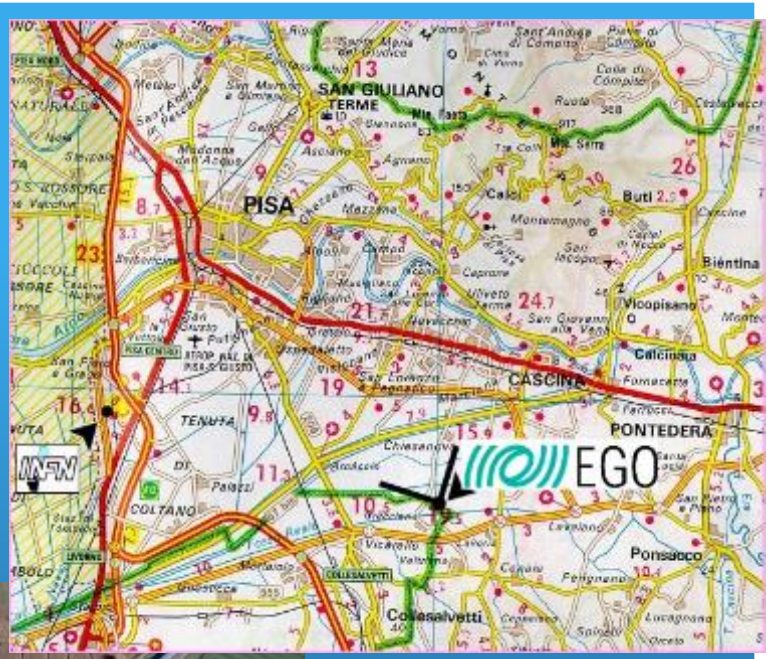
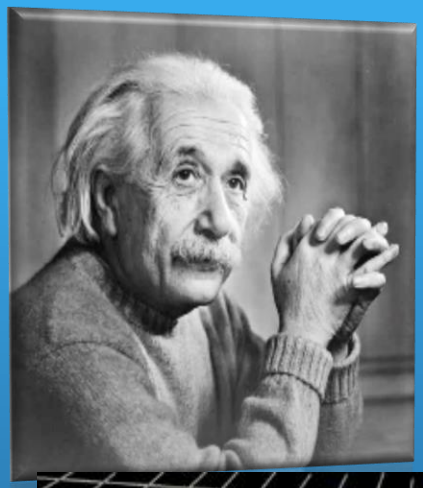
OUTLINE

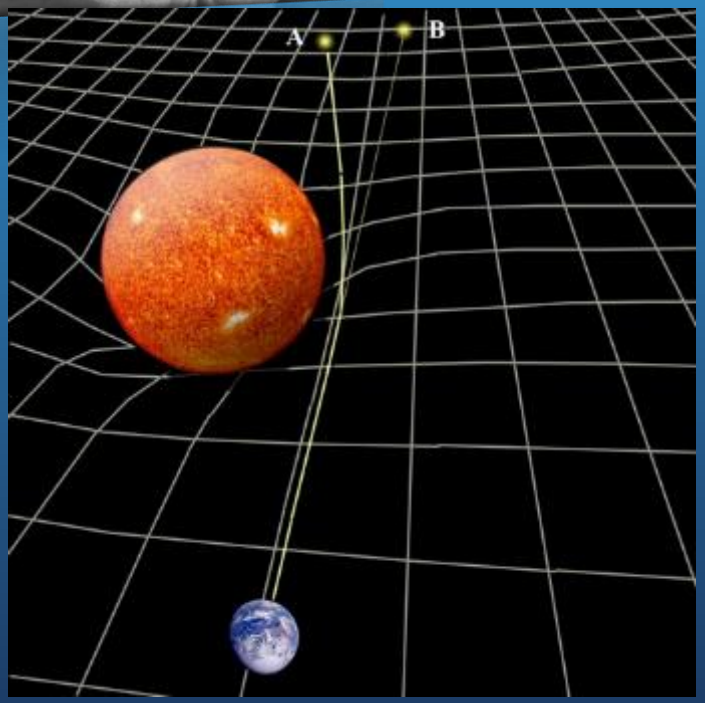
- Introduction: EGO and Gravitational Waves Network
- Surveying activities over years
- VRS network monumentation
- Establishment of VRS for Advanced Virgo
- Geographic Location of the detector
- 2011-16: Alignment Activities

The European Gravitational Observatory, site of the Virgo interferometer, is located in the countryside of the Comune of Cascina, a few kilometers from town of Pisa



GENERAL RELATIVITY





$$G_{mn} = \frac{8\pi G}{c^4} T_{mn}$$

GEOMETRY

MASS-ENERGY

ON GRAVITATIONAL WAVES.

BY

A. EINSTEIN and N. ROSEN.

ABSTRACT.

undulatory gravitational fields, we investigate rigorously the case of cylindrical gravitational waves. It turns out that rigorous solutions exist and that the problem reduces to the usual cylindrical waves in euclidean space.

I. APPROXIMATE SOLUTION OF THE PROBLEM OF PLANE WAVES AND THE PRODUCTION OF GRAVITATIONAL WAVES.

It is well known that the approximate method of integration of the gravitational equations of the general relativity theory leads to the existence of gravitational waves. The method used is as follows: We start with the equations

$$R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R = -T_{\mu\nu}. \qquad (1)$$

We consider that the $g_{\mu\nu}$ are replaced by the expressions

$$g_{\mu\nu} = \delta_{\mu\nu} + \gamma_{\mu\nu}; \qquad (2)$$

GW 150914: FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP); BEST-FIT WAVEFORM (MIDDLE-BOTTOM)

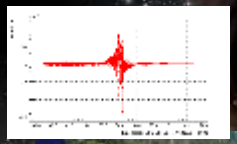
observed by	LIGO WA, LA
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
distance	1.3 Gly, 410 Mpc
redshift	0.09
Detector Frame Masses $M_\odot$	
total mass	70
chirpmass	30
primary BH	39
secondary BH	31
remnant BH	67
Source Frame Masses $M_\odot$	
total mass	65
chirpmass	28
primary BH	36
secondary BH	29
remnant BH	62
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.7
spin in orbital plane	~ 0
remnant size, area	180 km, 3.5 x 10^5 km^2
orientation	face-on/off
sky location	southern hemisphere
resolved to	600 sq. deg.

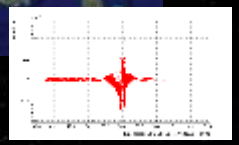
arrival time delay between WA and LA	7 ms
signal-to-noise ratio	24
false alarm prob.	< 2 x 10^{-7}
false alarm rate	1 in 200,000 yr
coalescence rate	2-600 Gpc^{-3} yr^{-1}
peak strain	1 x 10^{-21}
peak displacement of interferometers arms	0.004 Fermi
peak amp. frequency	150 Hz
peak speed of black holes	~ 0.6 c
peak luminosity	3.6 x 10^{56} erg s^{-1}
radiated energy	3 $M_\odot$, 5% of mass
remnant BH ringdown frequency	250 Hz
remnant BH damping time	4 ms
mass ratio	0.8
duration from 30 Hz	200 ms
# cycles from 30 Hz	10
consistent with general relativity	Yes
graviton mass bound	< 1.2 x 10^{-22} eV
online trigger latency	2 minutes
offline analysis pipelines used	5
CPU hours consumed	~ 50 million
papers on Feb 11, 2016	13
no. of researchers	~1000 in 16 countries

1st Detection - September 14, 2015 at 09:50:45 UTC
Observation of Gravitational Waves from a Binary Black Hole Merger

2nd Detection - December 26, 2015 at 03:38:54 UTC

The era of gravitational wave astronomy has started!





GW Network

H1- Hanford – Washington State

Virgo – Cascina (Pisa) – EGO Site

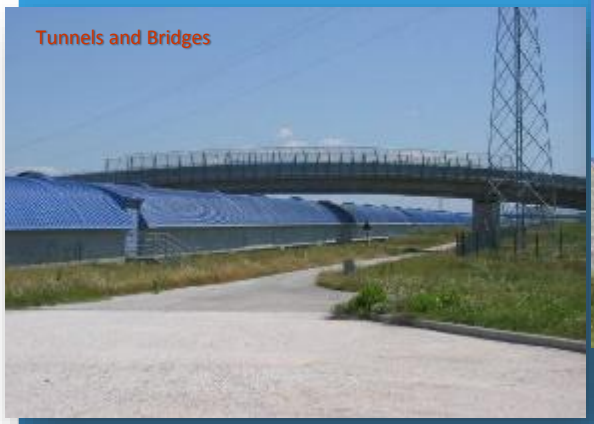
GEO600 – Hannover - Germany

L1- Livingston – Louisiana State

SSU E/PO, Aurore Simonnet

SURVEYING ACTIVITIES OVER YEARS

Realization of civil engineering works: Experimental Buildings, Tunnels, Technical Buildings, Office Buildings, Roads, Bridges, Site Layout Works
Main issue: realization of the 3+3km orthogonal tunnels with earth curvature correction


Tunnels and Bridges


West End Building


Central Building


Site Layout Works


Inside Tunnel


Construction of Tunnels


EGO Main Building

SURVEYING ACTIVITIES OVER YEARS

- 1994-95: 1st levelling/GPS surveys of the Virgo Area
- 1998-99: Alignment of the central interferometer
- 2000-02: Alignment of the vacuum tubes and End Towers
- 2003-16: Monitoring of buildings/tunnel displacements
- 2011-16: Alignment of Advanced Virgo








NETWORK MONUMENTATION

VRS (Virgo Reference System) network used for surveying activities developed over years and periodically checked and maintained


EGO European Gravitational Observatory

Virgo Reference System (VRS)

Control Point Network Monographs

VIR-0523T-13

M.Marsella[1], C.Nardinocchi[1], A.Sonnessa[1], M.A.Tini[2], L.Vittuari[2], C.Fabozzi[3], A.Paoli[3].

Date: July 21, 2016

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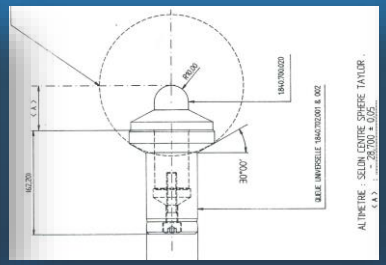
[2] DICAM - Università di Bologna
[3] EGO - European Gravitational Observatory

It includes ~500 internal main reference points, materialized with accurate centering system and monographed:

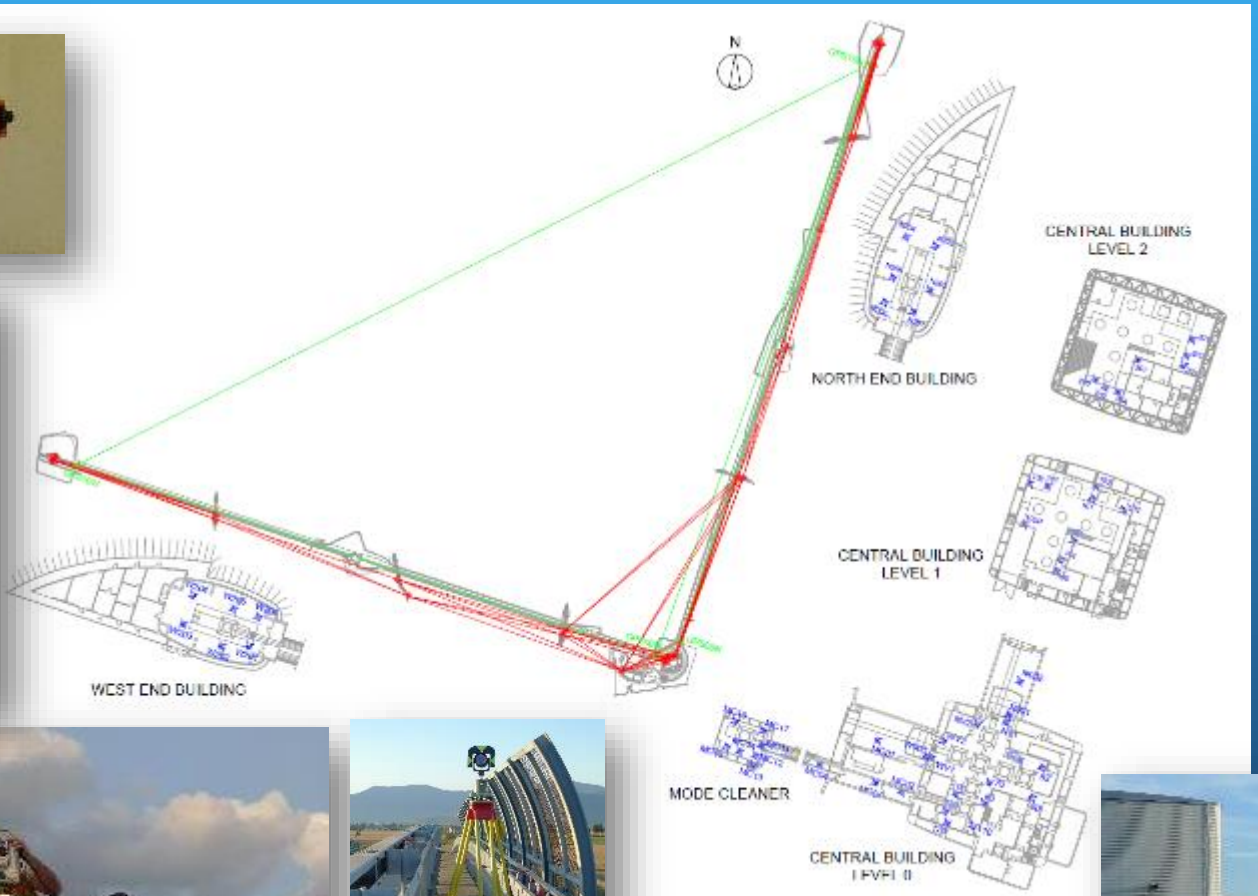
- ~80 located in 4 Experimental Buildings
- 200 + 11 GPS in the North Tunnel
- 200 + 11 GPS in the West Tunnel



External network made of ~30 concrete pillars distributed along the tunnels and at the experimental building areas

VRS NETWORK SURVEY

- 2011-14: Installation, survey and establishment of VRS
- Integrating TS measurements (red) with GNSS baselines (green)
- Trimble GNSS receivers; Leica TM50 & TDA5000 + Wild NL plummet



VRS ESTABLISHMENT

- 5 GNSS stations – 3 session each lasting 24h processed separately (Bernese) - network solution including 10 permanent stations

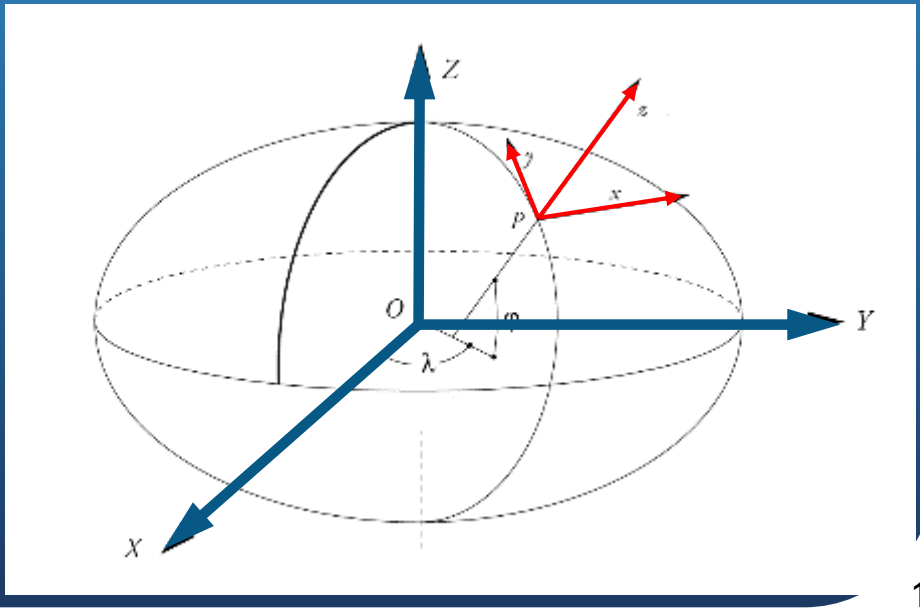
  3 solutions averaged both for the coordinates and the corresponding errors $\sigma_X\ \sigma_Y\ \sigma_Z$

- ~ 65 internal + 30 external stations TM50 (TDA5000)
  - *3 (pos.I) + 3 (pos.II) obs. each point*
  - *Slope distance values corrected for the refraction taking into account the atmospheric parameters (T, p, RH) provided by EGO meteo station*
  - *Azimuthal and Zenithal measurements corrected to refer them to the ERS (Eulerian Reference System) using formula of Brovelli M. et al. (1989)*

ETRF Geocentric Cartesian Reference System
ERF Eulerian Reference System

Appr. pos. O(x,y,z) ERS in correspondence of the center of Virgo interferometer

ϕ_o, λ_o and (X_0, Y_0, Z_0) rotation angles and translation parameters ETRF → ERS



VRS ESTABLISHMENT

- Network adjustment in ERS using both TS and GNSS observations; GNSS baselines used to constrain the network using the associated rms ($\sigma_{\Delta x}$, $\sigma_{\Delta y}$ 1mm; $\sigma_{\Delta z}$ 2mm)
- Network adjustment performed using both the scientific software CALGE and the commercial software StarNet (MicroSurvey Inc.)
- ERS coordinates finally rototranslated to VRS (Virgo Reference System) oriented in accordance with the laser beam directions (X_{VRS} = -West beam; Y_{VRS} = North beam)

Achieved accuracy of the computed VRS coordinates			
	σ_x [mm]	σ_y [mm]	σ_z [mm]
Average	0.91	0.86	1.42
St.Dev.	0.61	0.52	1.05

VRS ESTABLISHMENT – process scheme

GNSS Survey in ETRF frame

Definition of the ERS reference frame

Transformation from ETRF to ERS of the ΔX, ΔY, ΔZ calculated between baselines

Transformation from LRF to ERS of the TS survey

TS Survey in a LRF frame

Network Adjustment in the ERS. GNSS OBSERVATION USED AS ΔX, ΔY, ΔZ IN ORDER TO CONSTRAIN THE NETWORK

- Estimation of the rotation angle between ERS and VRS
- Estimation of the translation along x and y axis of the network towards the origin of the old reference system. The transformation parameters were calculated with a least square method on a set of five points (NV1-NV2-WV1-70-80) known both in the ERS and old VRS reference systems

Shift in the Z direction, calculated as the average of the differences between 70-80-NV1-NV2-WV1-108P point height, belonging to the Central Building and the corresponding heights determined by previous surveys.


EGO European Gravitational Observatory

Advanced Virgo

Virgo Reference System (VRS)

Control Point Network Monographs

VIR-05235-13

M.Marsella[1], C.Nardinocchi[2], A.Sonnessa[1], M.A.Tini[2], L.Vittuari[3], C.Fabozzi[3], A.Paoli[3].

Date: March 22, 2016

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[3] EGO - European Gravitational Observatory


EGO European Gravitational Observatory

Advanced Virgo

Virgo Advanced Reference System

Integration of the Virgo Reference System (VRS) – Design and network adjustment of the external reference system network

VIR-0030A-15

P.J.V. D'Aranno[1], M. Marsella[1], C. Nardinocchi[1], A. Sonnessa[1], S. Scifoni[2], M.A. Tini[1], L. Vittuari[3], C.Fabozzi[4], A.Paoli[4].

Date: January 29, 2015

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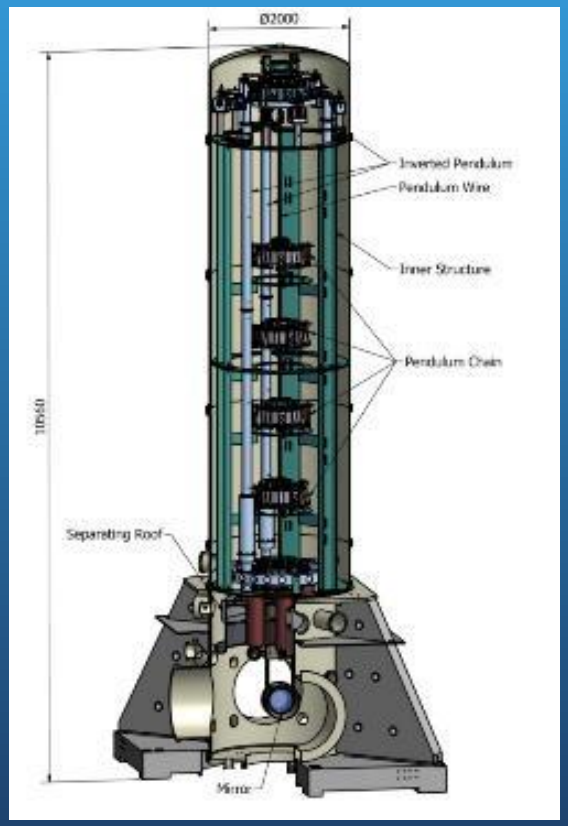
[3] DICAM - Università di Bologna
[4] EGO - European Gravitational Observatory

GEOGRAPHIC LOCATION

- Establishing VRS reference frame and the transformation parameters ETRF → VRS allowed the calculation of the position of the Virgo vertexes, i.e the centers of the suspended mirrors, not directly visible

- Coordinates calculated by the inverse transformation VRS → ETRF

- Geographic location and orientation of Advanced Virgo respect the other detectors are fundamental informations for the contemporary detection of GW signals

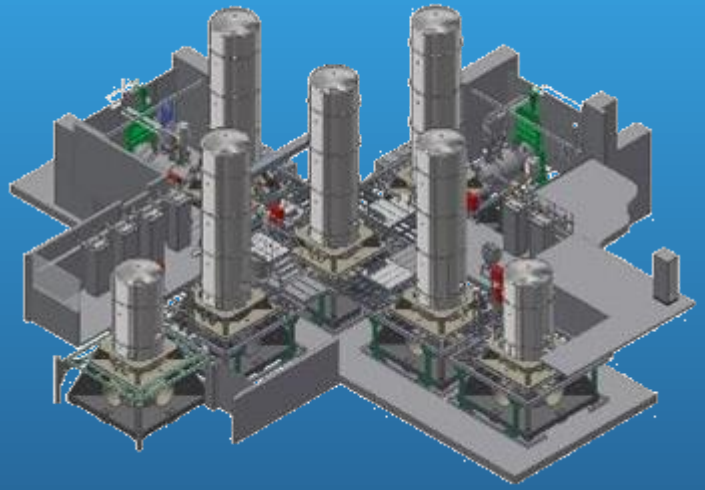


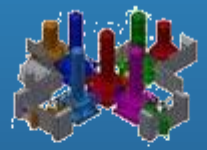
Point ID	LAT	LONG	h (m)
BS	43° 37' 53".1061 N	10° 30' 16".2095 E	53.089
NE	43° 39' 24".9464 N	10° 31' 00".8387 E	52.899
WE	43° 38' 25".4873 N	10° 28' 09".7533 E	51.575

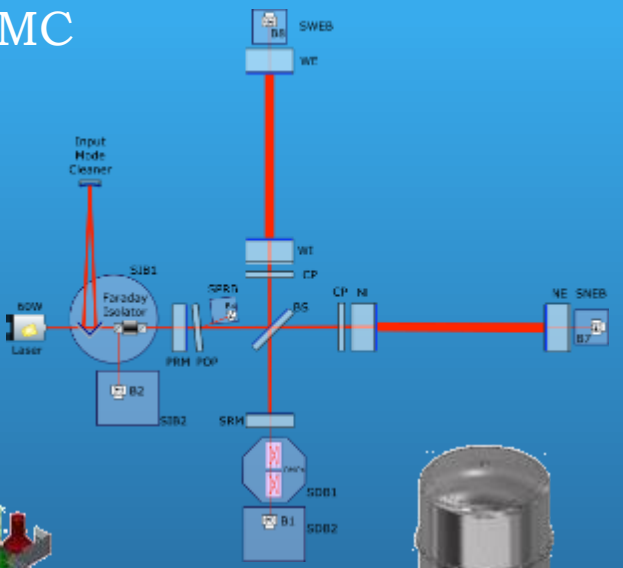
ADVANCED VIRGO - SURVEY ACTIVITY

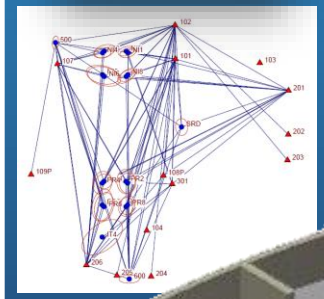
- Displacement and alignment of large vacuum chambers:
  - 7 “long” towers (11m H; ~30 tons): BS, NI, WI, PR, SR, NE, WE
  - 3 “short” towers (6.5m H; ~20 tons): IT, DT, MC

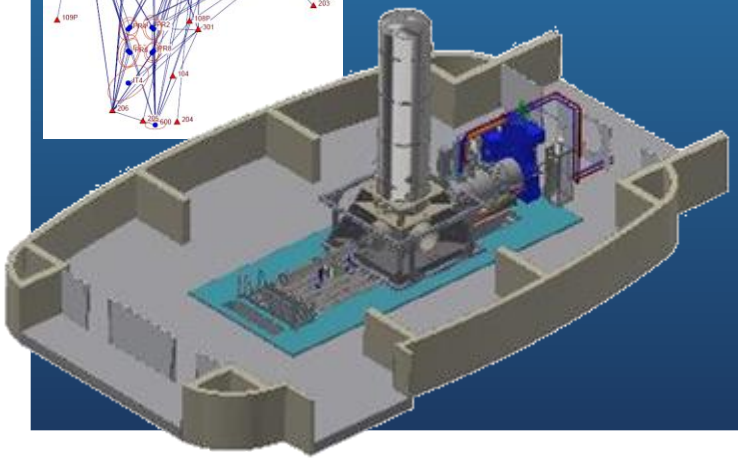
- Displacement range for AdV: from 2 to 626mm

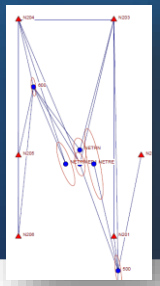






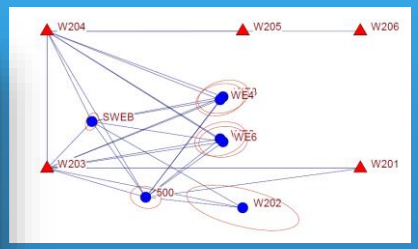


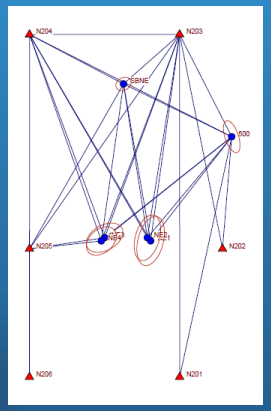


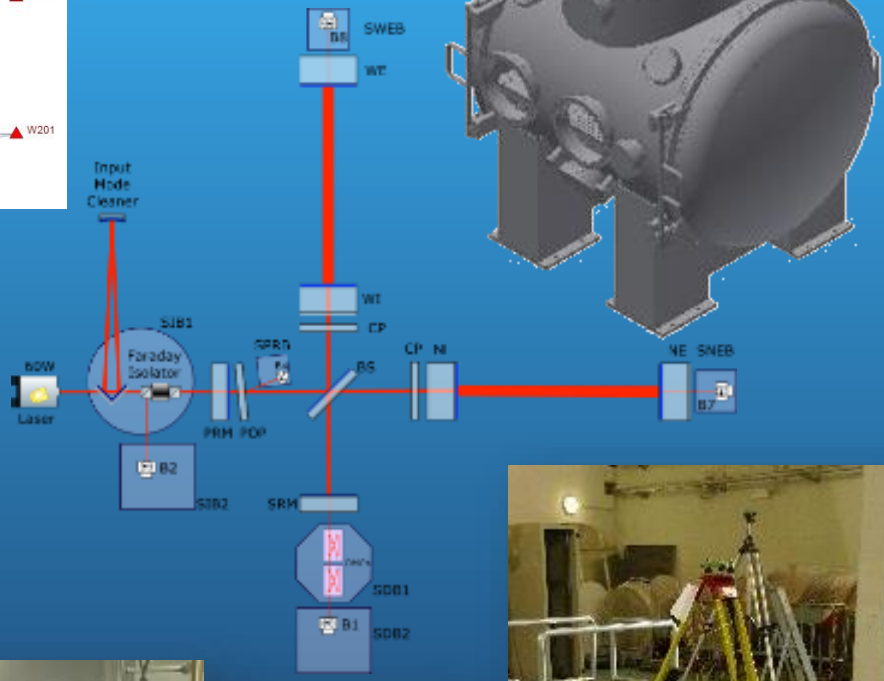


ADVANCED VIRGO - SURVEY ACTIVITY

- Alignment of 5 new vacuum chambers “minitowers”:
  - SIB2, SDB2, SPRB in Central Building
  - SNEB, SWEB in North and West End Building

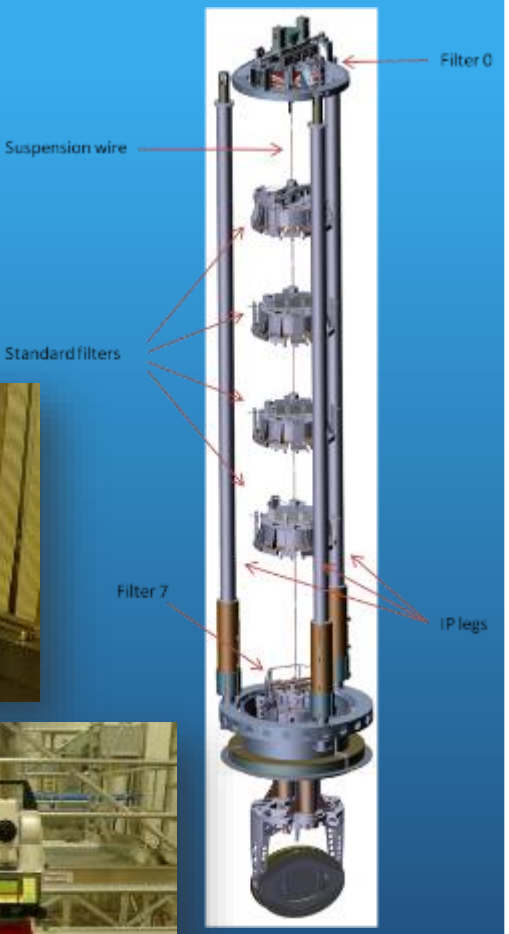






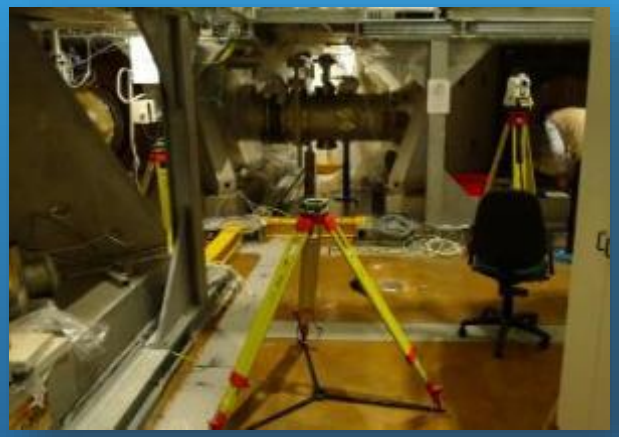
ADVANCED VIRGO - SURVEY ACTIVITY

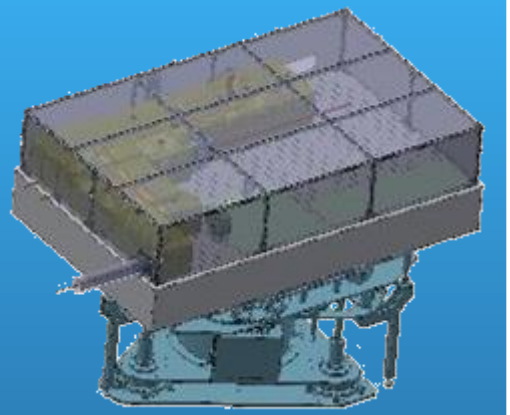
- Alignment of mirror suspensions:
  - 7 “long” towers: BS, NI, WI, PR, SR, NE, WE
  - 3 “short” towers: IT, DT, MC

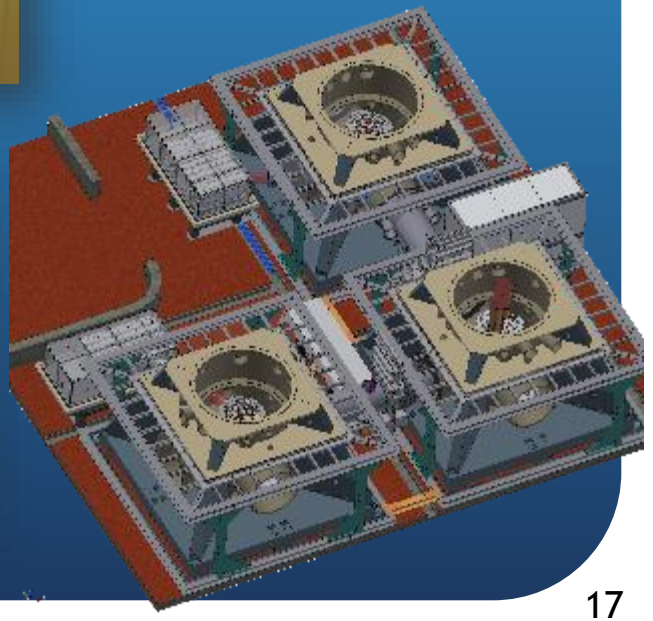


ADVANCED VIRGO - SURVEY ACTIVITY

- Alignment of 7 in-air and 2 in-vacuum optical benches:
  - Injection System: LB, IB, EIB
  - Detection System: DB, EDB
  - Thermal Compensation System: NI, WI, NE, WE







ADVANCED VIRGO - SURVEY ACTIVITY

- Alignment of external references for ITF pre-commissioning activity:
  - Central Building: PRF, NIF, SRF, WIF
  - North End Building: NEF, SNEBF
  - West End Building: WEF, SWEBF

ADVANCED VIRGO - SURVEY ACTIVITY

- Local networks around the surveyed points, including max possible number of VRS benchmarks
- Observations of sD, H and Z of each point repeated 3 times in both pos.I + pos.II and averaged
- High redundancy of observations for the network adjustment
- Network adjustment performed using the commercial software StarNet (MicroSurvey Inc.)
- Most part of the coordinates obtained for the surveyed points with rms (σ_x , σ_y , σ_z) ≤ 0.2 mm

…THANKS for your attention

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EGO EUROPEAN GRAVITATIONAL OBSERVATORY

Survey Lab

SAPIENZA
UNIVERSITÀ DI ROMA

EGO EUROPEAN GRAVITATIONAL OBSERVATORY

SPARE SLIDES

EGO EUROPEAN GRAVITATIONAL OBSERVATORY

MONITORING SOIL SETTLEMENTS AT THE VIRGO SITE

MONITORING of BUILDINGS

Since the end of the construction a significant subsidence of the tunnels was observed
The interferometer must be in a plane
Virgo and its vacuum tubes are designed for re-alignment of the modules

Our reference is the Central Building (CB)
Relative displacements for both the tunnel ref. pts. (H) and the GPS pts. (plan.)

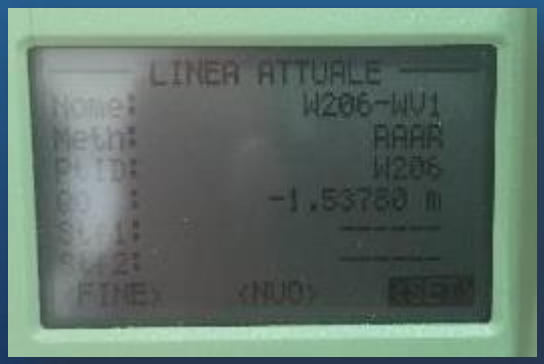
Accurate levelings: 205 stations/tunnel
15m distance between each station
and 7.5m for the staff
Not big variation of T and RH
Tunnel are not ventilated

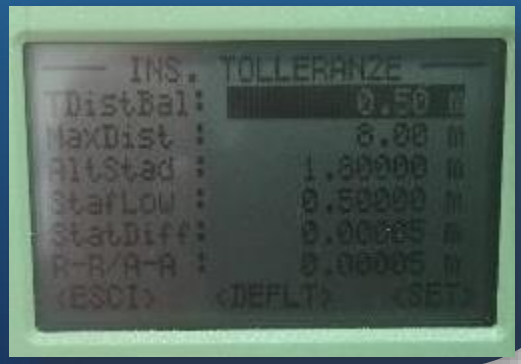
Period	Frequency of monitoring	Instrument
2001	Initial survey	TDA5000
2002÷2006	6 months	NA2+GPM3; DNA03
2007÷2011	12 months	DNA03
2012÷2015	24 months	DNA03

TUNNEL MONITORING

Leveling parameters

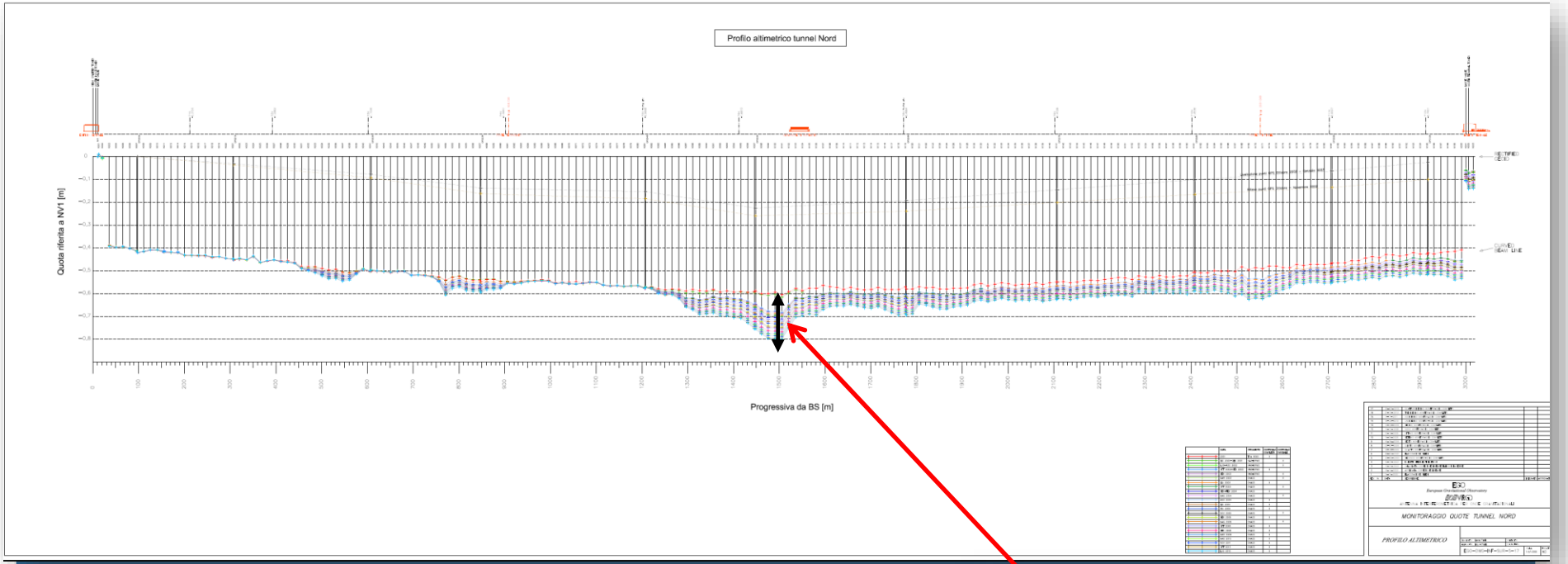
L [m]	3006/line
method (NA2)	NV1(WV1)→N206 (W206); N206→NV1
method (DNA03)	BF NV1(WV1)→N206 (W206); N206→NV1
method (DNA03)	BFFB, aBFFB
n. stations	205/line
starting point	NV1 (WV1), N206 (W206)
measure type	Avg 3 of 5; chk σ/20m < 0.00005 m
tolerances	St > 0.5m; DBal < 0.5 m; Dmax 8m
max closure error (NA2)	4.42 mm
min closure error (NA2)	3.76 mm
max closure error (DNA03)	0.98 mm
min closure error (DNA03)	0.04 mm



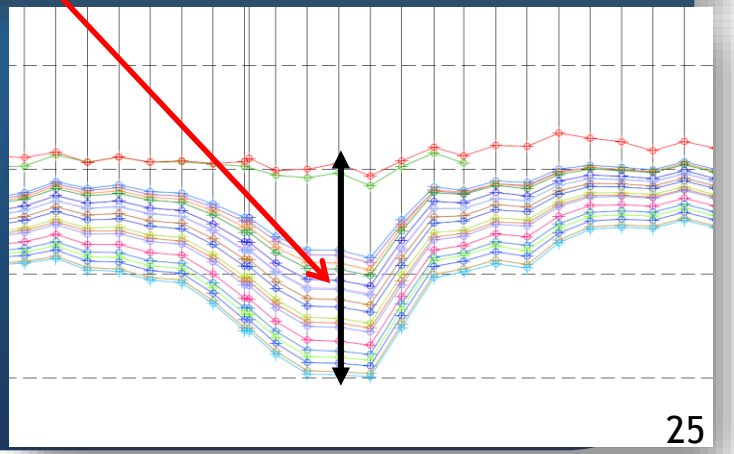


TUNNEL MONITORING

North Tunnel

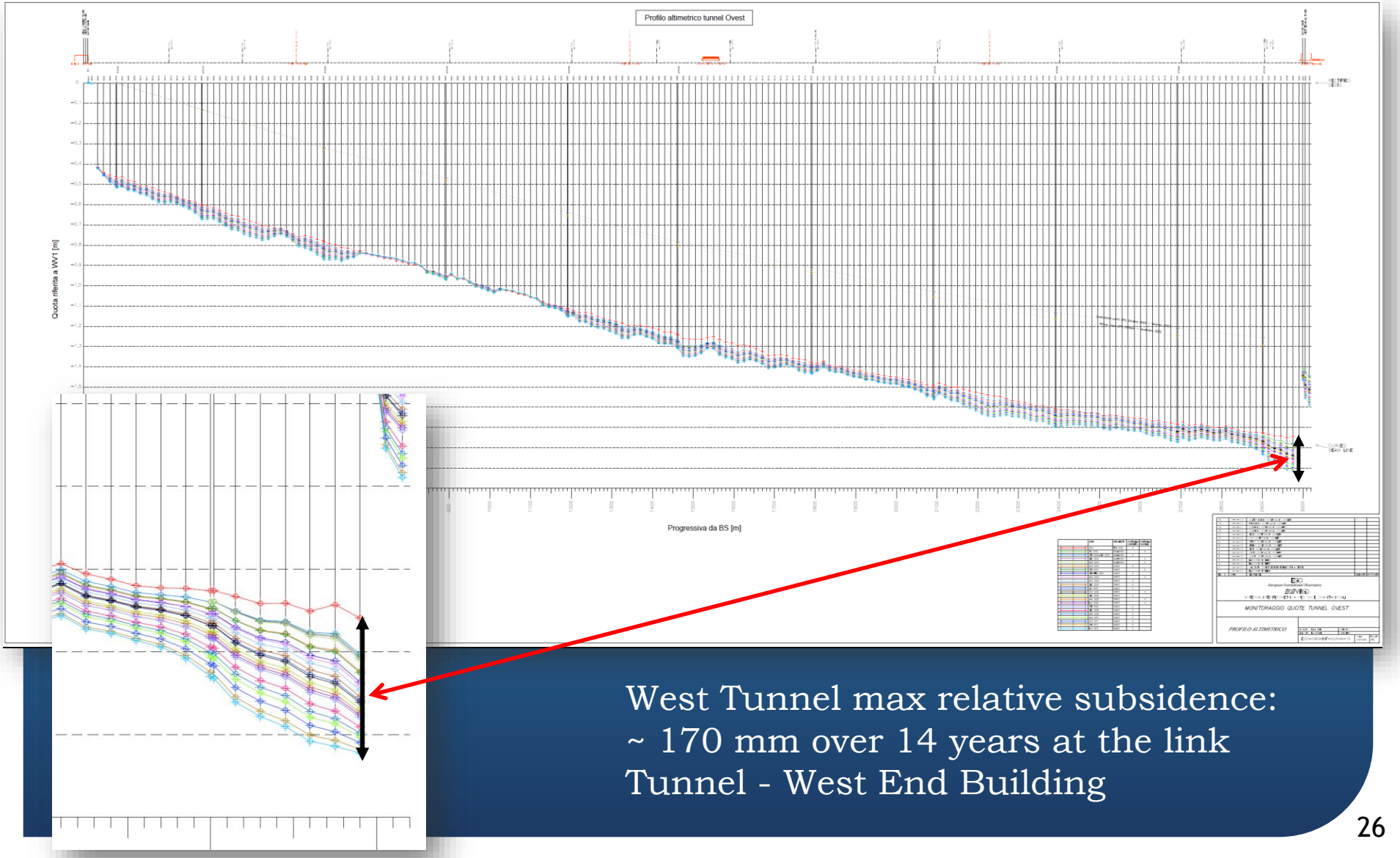


North Tunnel max relative subsidence:
~ 205 mm over 14 years at middle of the Tunnel



TUNNEL MONITORING

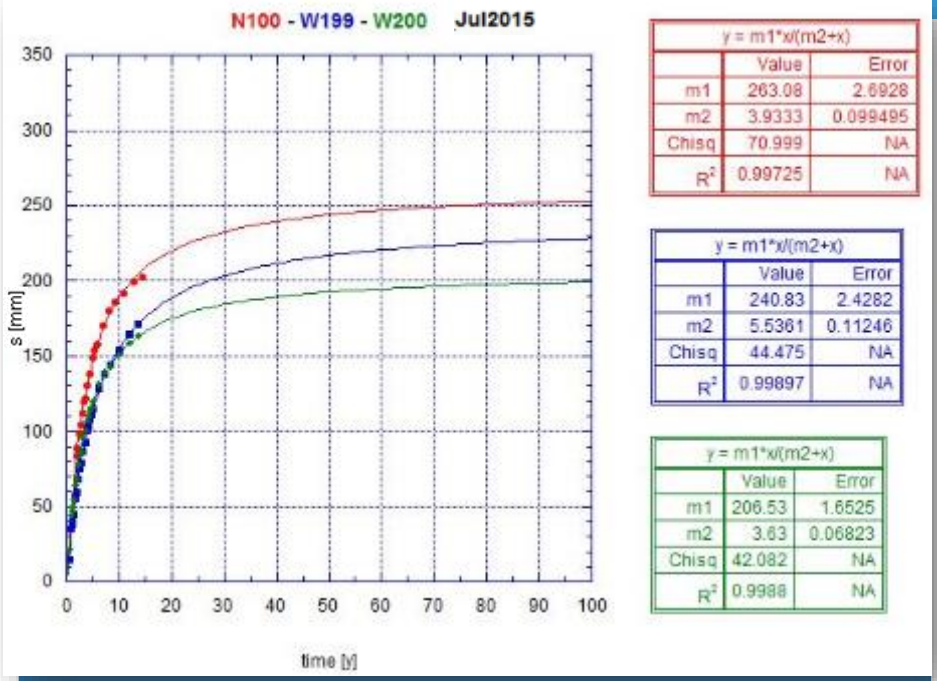
West Tunnel



West Tunnel max relative subsidence:
~ 170 mm over 14 years at the link Tunnel - West End Building

TUNNEL MONITORING

Trendlines for the major displacements observed



y = m1*x/(m2+x)		
	Value	Error
m1	263.08	2.6928
m2	3.9333	0.099495
Chisq	70.999	NA
R^2	0.99725	NA

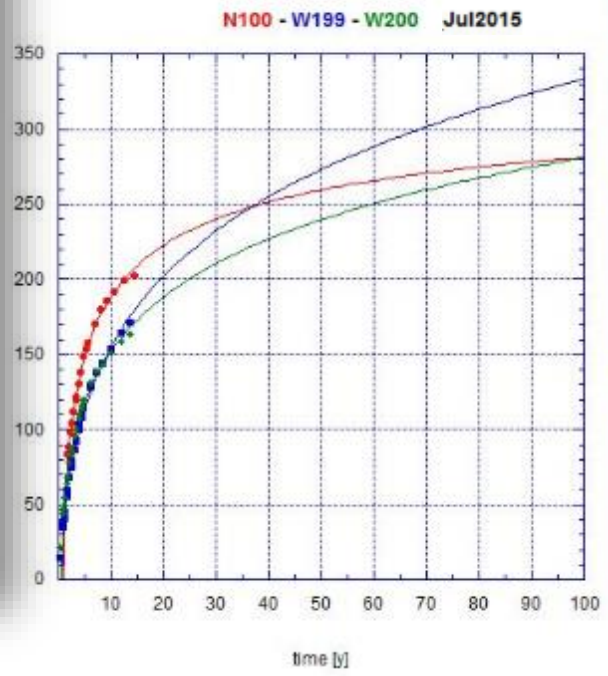
y = m1*x/(m2+x)		
	Value	Error
m1	240.83	2.4282
m2	5.5361	0.11246
Chisq	44.475	NA
R^2	0.99897	NA

y = m1*x/(m2+x)		
	Value	Error
m1	206.53	1.6525
m2	3.63	0.06823
Chisq	42.082	NA
R^2	0.9988	NA

Analysis for max displacement at t=∞ in the range 200÷300 mm

Several fit curves: best R^2 according logarithmic law (order 2) or $m_1 \cdot x/(m_2+x)$

No big problem: settlements compatible with the realignment system (…and the roof of the tunnel!)



y = m1+m2*log(x)+m3*(log(x))^2		
	Value	Error
m1	33.846	4.6338
m2	184.5	14.188
m3	-30.442	9.8457
Chisq	124.32	NA
R^2	0.99518	NA

y = m1+m2*log(x)+m3*(log(x))^2		
	Value	Error
m1	36.894	0.84716
m2	87.009	3.109
m3	30.568	3.089
Chisq	112.03	NA
R^2	0.99741	NA

y = m1+m2*log(x)+m3*(log(x))^2		
	Value	Error
m1	46.381	0.94099
m2	92.897	3.4533
m3	12.252	3.4311
Chisq	138.22	NA
R^2	0.99607	NA

Left curves more coherent with geotechnical studies available in literature

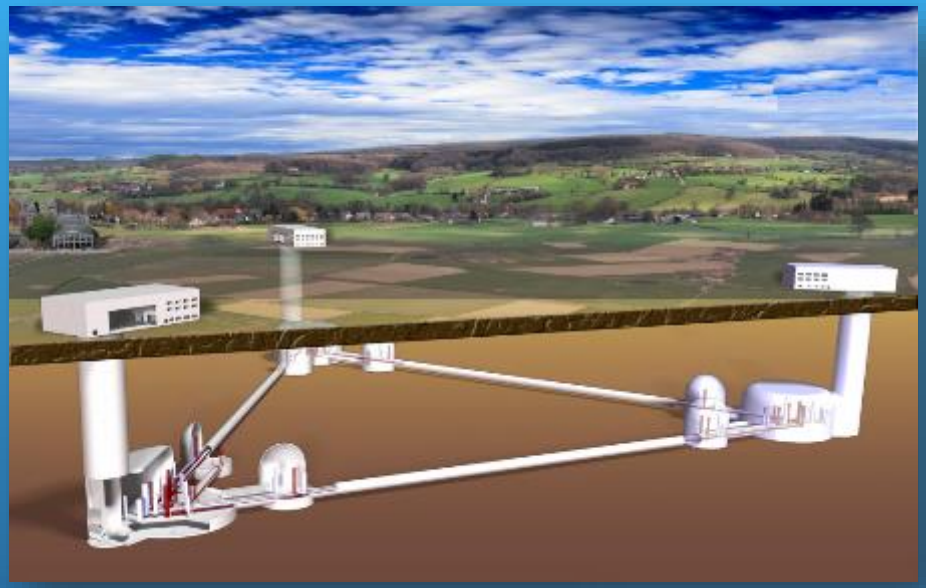
Hypothesis with constant external factors (i.e. no large variations of the water deep stratum height or loading of the adjoining soil)

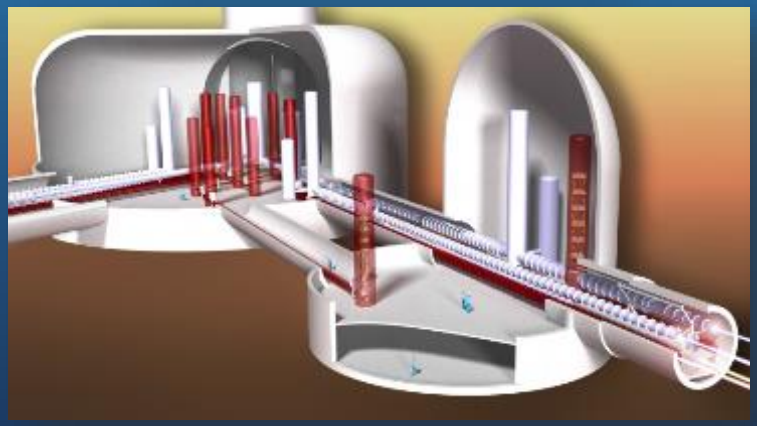
EGO EUROPEAN GRAVITATIONAL OBSERVATORY

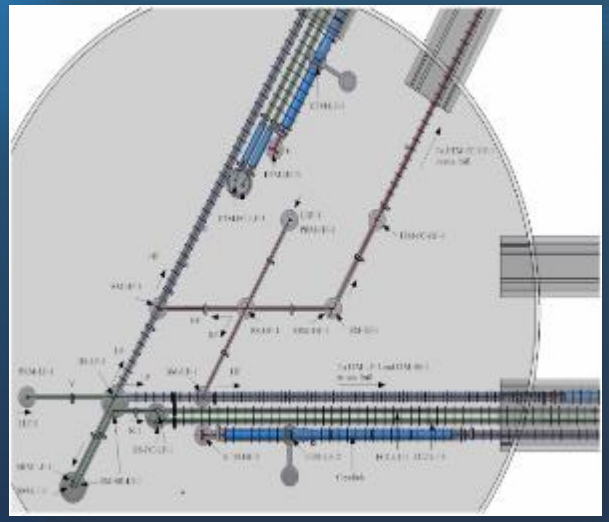
FUTURE GRAVITATIONAL WAVES PROJECT

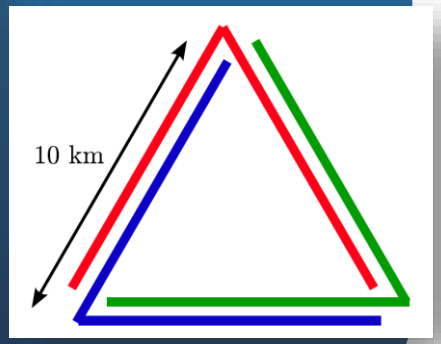
GEODESY & METROLOGY for FUTURE PROJECTS

Einstein Telescope









EINSTEIN TELESCOPE

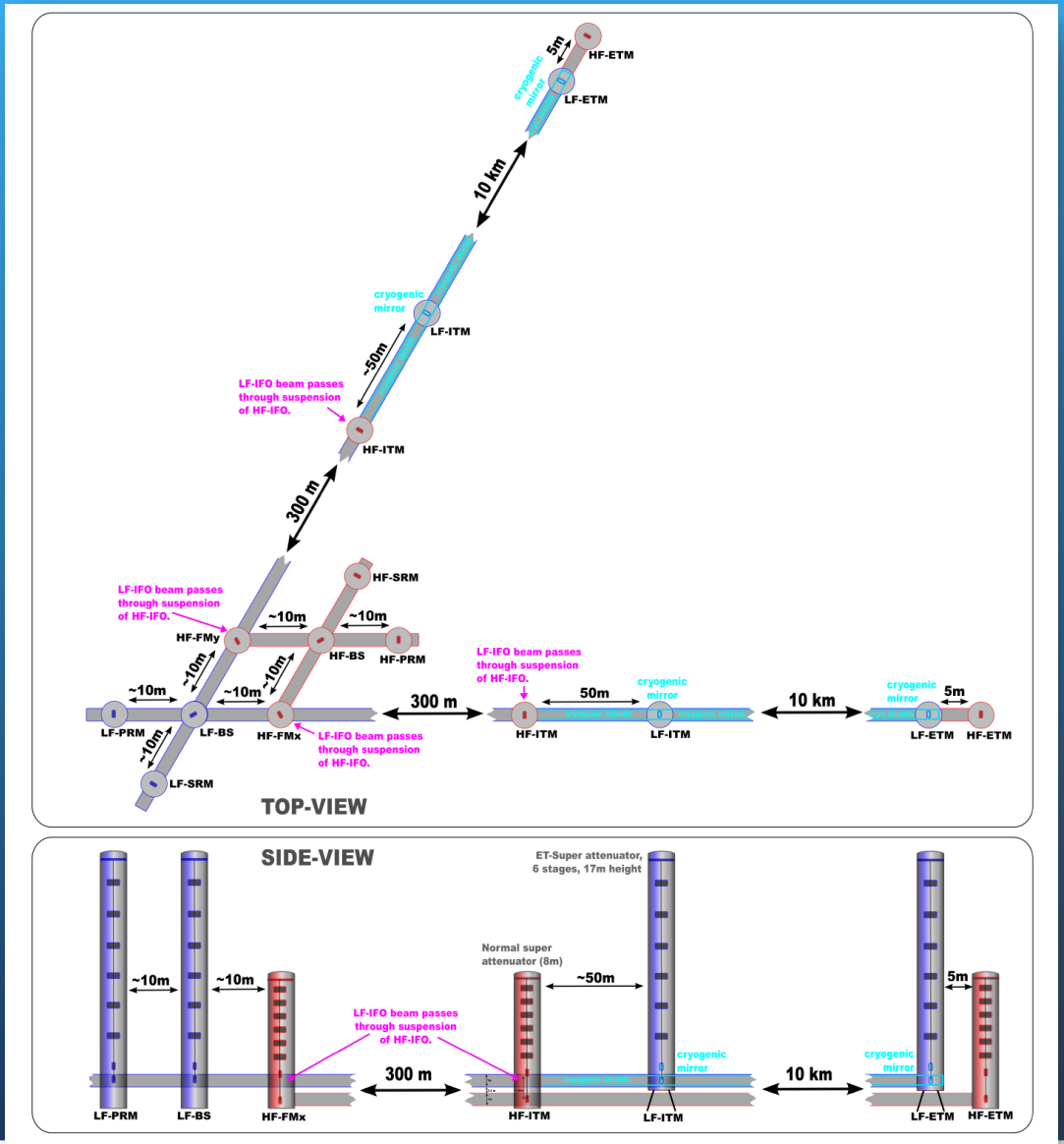
Conceptual Design

Main features and infrastructure facilities

- 3 nested detectors arranged in a triangular shape with 10 km side
- from 100m to 200m depth underground (hopefully > 200m?)
- Xylophone scheme up to 6 folded interferometer
- 3 interferometer for Low frequency – 3 for High frequency
- LF interferometer → cryogenic test masses
- HF interferometer → high power laser
- 3 underground corner caverns (Ø 65m, H 30m) and 6 satellite caverns (Ø 30m, H 30m)
- Tunnel inner Ø 5.5÷6.0m; double tunnel (300m) linking corner and satellite caverns
- Surface facilities and vertical shafts (in relation to the site location)

EINSTEIN TELESCOPE

Scheme of LF and HF core interferometers of a single ET detector



	Virgo	AdV	aLIGO	ET
1985	R&D			
1990	White Paper, CDR (1989)			
1995	R&D Approval (1994) Final Design, TDR (1995) Beginning Infrastructure (1996)		R&D	
2000	Completion installation Detector (2003)	R&D First AdV sensitivity projection (2004)	CDR (1999) R&D	
2005	Scientific data taking (2007)	AdV White Paper, CDR (2005) Approval (2009)	Funding (2006) Building (2008)	First Idea (2005) R&D
2010	Decommissioning (2011)	First orders (2010) TDR (2012)	Installing completion (2014)	CDR (2011) R&D
2015		Completion Installation (2015) First data taking (2016)	Data taking (2015)	
2020				TDR ?
2025				Construction ?

EINSTEIN TELESCOPE

…thinking to the start of the Tech Design

- *Design of surface and underground Reference Network*
- *Materialization of the reference points network*
- *Definition of specifications and planning for surveys and monitorings*
- *Transfer of the surface network to underground: technologies, study and design*
- *"Fiducialisation" and optimization of the reference point network; design for the different components of the LF and HF interferometers*
- *Integration of the fiducials in the mechanics, vacuum and optics*
- *…..and many other topics!*