BMSTU – Federico II MoU Online Startup Meeting

October 20th, 2021

Pinto's Group Presentation

Innocenzo M. Pinto

Professor of Electromagnetics
OSA Fellow
LIGO-Virgo-KAGRA Member

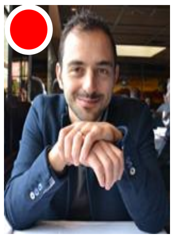
People

… 4 (academic) generations
in different Universities …

Vincenzo
Fiumara

Vincenzo
Galdi

Vincenzo
Pierro



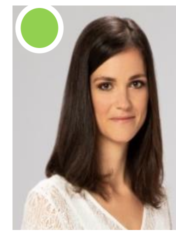
Vincenzo
Matta

Francesco
Chiadini

Giuseppe
Castaldi

Paolo
Addesso

Fabio
Postiglione



Maria
Principe

Adele
Fusco

Cinzia
DiGiorgio

Rosalba
Fittipaldi

Veronica
Granata

Richard
Pedurand

Elena
Mejuto-Villa

Ofelia
Durante

Joshua
Neilson

“The Waves Group” as of 2000

Research – I Electromagnetics

- *Electromagnetics in nonlinear media*

  general/systematic approach for solving Maxwell equations in nonlinear media, based on Volterra functional series, Lindsted-Poincare' renormalization, and Pade' resummation [A1,A2]; applications to harmonic generation in guided- and free-space problems [A3,A4]; living cells with electrically non-linear membranes [A5,A6], and gravito-electric coupling [A7];

- *Chaos signatures in electromagnetic reverberating chambers (ERC)*

  [A8] applications to antenna free-space radiation pattern retrieval from measurements in reverbe-rating environments [A9,A10]; reverberating chambers in the pulsed regime [A11];

- *Study of a new class of boundary value problems that exhibit eikonal chaos*

  full-wave (asymptotic) analysis showing characteristic chaos signatures [A12,A13];

- *Radiation from regular-non-periodic antenna arrays*

  (planar Penrose tilings, Rudin-Shapiro, Fibonacci's, and other recursive sequences [A14, A15]).

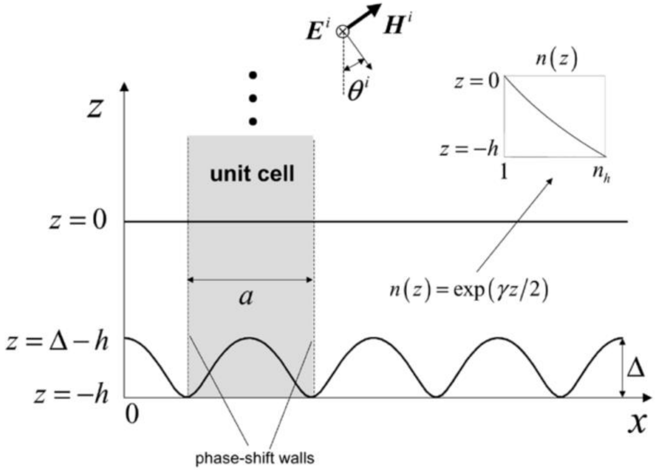
- *Applications of Feynman path-integrals and Donsker-Kac formula to waveguides*

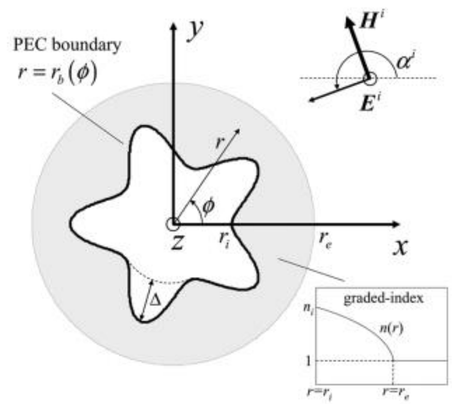
  dominant eigenvalues/eigenfrequencies in complex/hybrid geometries [A16, A17];

- *Miscellaneous work* :
  - *coding-theory approach to EM field configurations in complex environments* [A19];
  - *generalized Leontóvich boundary conditions* [A20];
  - *neural-net based large-array faulty-element diagnostics* [A21];
  - *recursive algorithms for GTD ray-tracing over hilly landscapes* [A22];
  - *defected fractal multilayers* [S22];
  - *percolation thresholds in urban short-wave propagation* [A23];
  - *tune-shifts & beam-coupling impedances in complex accelerator pipes (LHC)* [A24];
  - *effects of weak (sub-thermal) pulsed EM fields on living cells with dispersive membranes* [A25], *etc.*

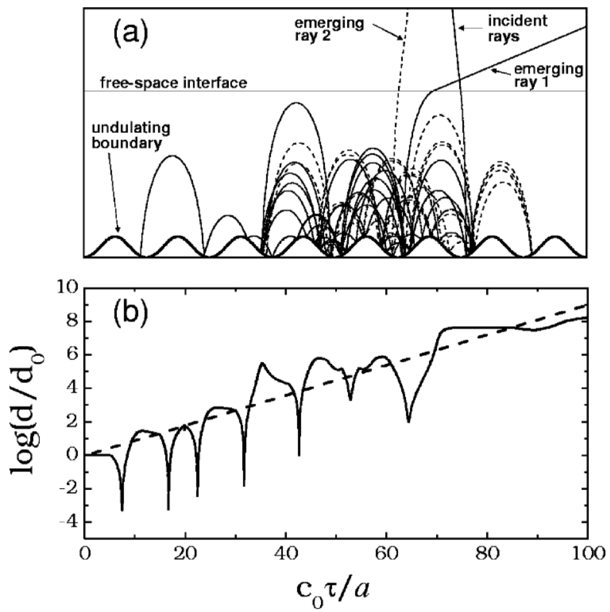
New Class of EM Boundary Value Problems Exhibiting Eikonal Chaos

I.M. Pinto, L.B. Felsen et al., IEEE T-AP 53 (2005) 753; ibid. T-AP 56 (2008) 2638

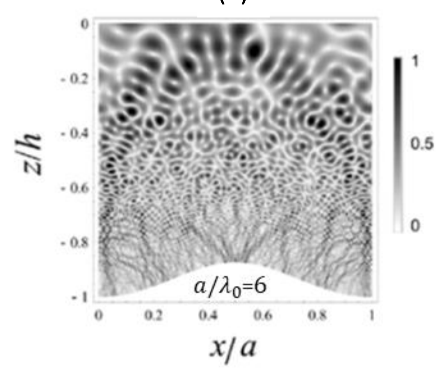




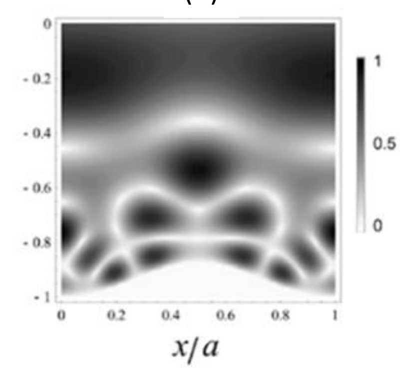
… and study of chaos footsteps in the $\lambda \longrightarrow 0$ asymptotic *full wave* regime.



(c)



(d)



(a) Nearby-incident ray paths evolution;

(b) Separation d between nearby-incident rays (scaled to initial value) as a function of the (scaled) "ray time" ;

(c,d) Meandric (Chladni) level-maps of full wave solution as $\lambda/a \longrightarrow 0$.

Radiation from Regular/*non-Periodic* Antenna Arrays

V. Pierro, I.M. Pinto , L.B. Felsen et al., IEEE T-AP 53 (2005) 635, ibid. T-AP 53 (2005) 2044, ibid. T-AP 53 (2005) 3568, IEEE T-AP 55 (2007) 1554, etc.

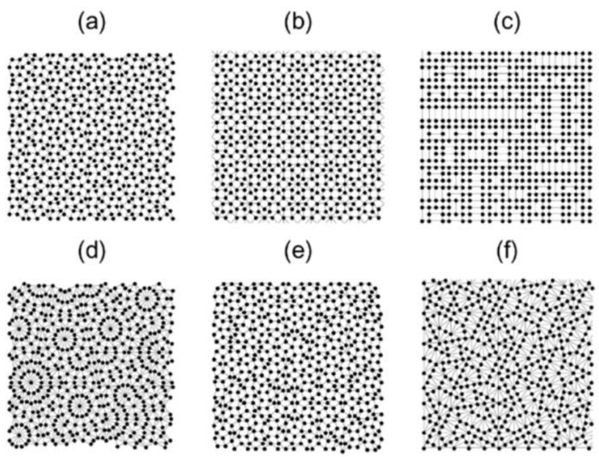


Fig. 5. Array antenna configurations obtained from square patches (of side L) of six representative categories of aperiodic tilings. Tiling geometries are sketched in background with light lines, and antenna element positions are marked with black dots. (a) *Penrose thick-and-thin* ($N = 530, d_{\rm av} = 0.818d_0, d_{\min} = 0.613d_0, d_{\max} = 1.075d_0$); (b) *octagonal* ($N = 532, d_{\rm av} = 0.898d_0, d_{\min} = 0.834d_0, d_{\max} = 1.089d_0$); (c) *table* ($N = 538, d_{\rm av} = d_{\min} = d_{\max} = 0.88d_0$); (d) *Danzer* ($N = 529, d_{\rm av} = 0.697d_0, d_{\min} = 0.64d_0, d_{\max} = 1.438d_0$); (e) *binary* ($N = 534, d_{\rm av} = 0.855d_0, d_{\min} = 0.662d_0, d_{\max} = 1.073d_0$); (f) *pinwheel* ($N = 532, d_{\rm av} = 0.8d_0, d_{\min} = 0.726d_0, d_{\max} = 1.148d_0$). The reference interelement spacing d_0 pertains to a square periodic 23×23 element array of side L.

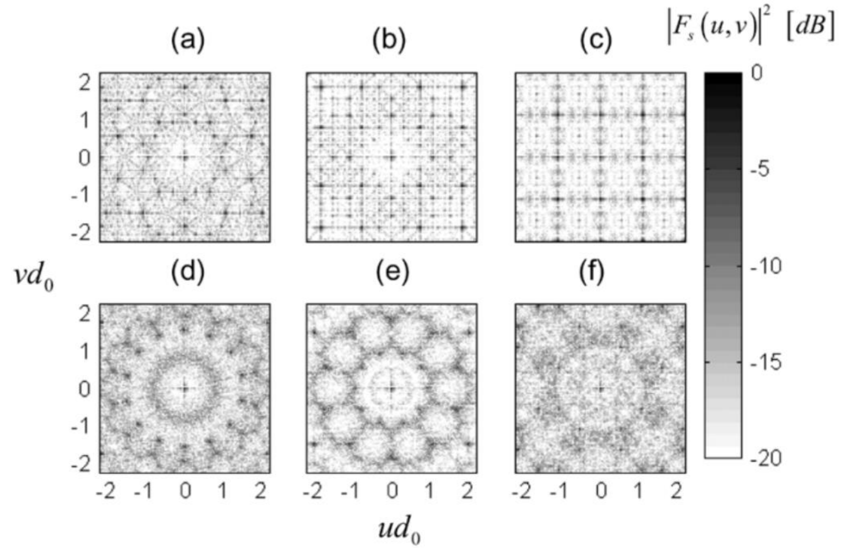


Fig. 7. Radiation spectra $|F_s(u,v)|^2$ in (4) pertaining to the arrays in Fig. 5. (a) *Penrose* thick-and-thin; (b) *octagonal*; (c) *table*; (d): *Danzer*; (e) *binary*; (f) *pinwheel*.

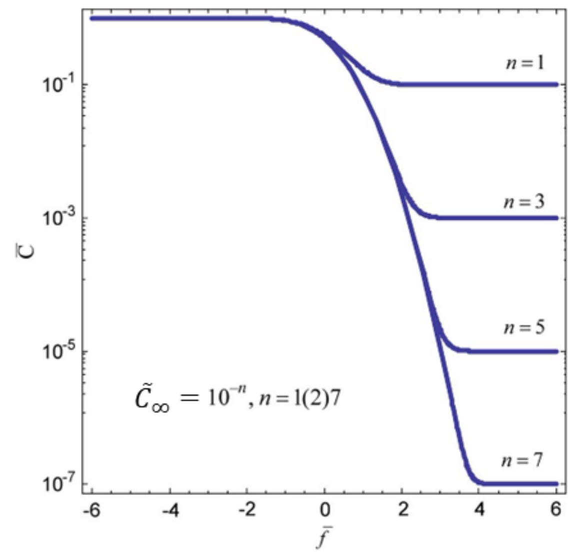
… originated a plethora of further developments, on behalf of our own & other Groups. Ended up in a fruitful cooperation (and personal friendship) with prof. Nader Engheta (Univ. of Pennsylvania), and a new research line on functional metamaterials (V. Galdi)

Thermal Effects on Cell Membranes under Nonthermal Pulsed Exposure

A. DeVita, I.M. Pinto et al., IEEE T-PS 38 (2010) 149; ibid. PS-42 (2014) 2236

… toy model of frequency-dispersive cell membrane

$$\begin{cases} \tilde{C}_m(\omega) = \tilde{C}_\infty - \frac{1}{2}(\tilde{C}_\infty - \tilde{C}_0)\,\mathrm{Erfc}\left(\frac{\omega-\omega_0}{\Delta\omega}\right), & \omega \geq 0 \\ \tilde{C}_m(\omega) = \tilde{C}_m(-\omega), & \omega < 0 \end{cases}$$



… implies fast *selective* heating of the membrane (up to protein denaturation -> cell apoptosis) under pulsed EM radiation, with almost *no* bulk cytoplasm heating - motivated by results by prof. K Schoenbach (Old Dominion University, Norfolk VA, US) on medical applications (melanoma ablation) of pulsed fields.

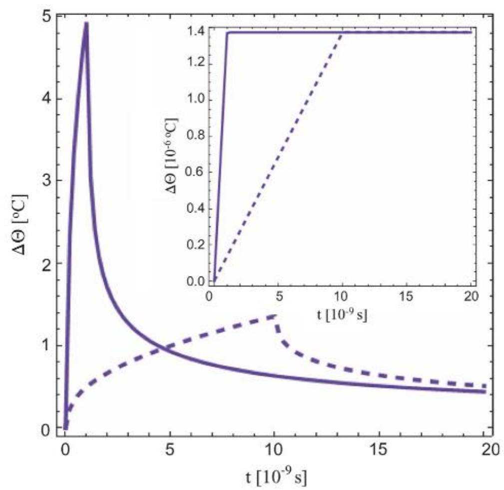


Fig. 4. Increase of (average) membrane temperature versus time, for an incident (rectangular) pulse with a specific absorption dose of 1 J/kg, applied at $t = 0$. (Full line) Pulsewidth = 1 ns. (Dashed line) Pulsewidth = 10 ns. The corresponding temperature increase in the cytoplasm is shown in the inset.

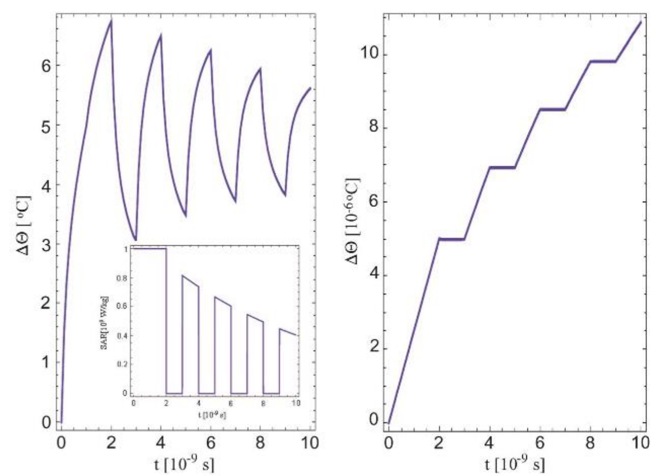


Fig. 6. Membrane (left panel) and cytoplasm (right panel) temperature response versus time for an exponentially damped train of applied pulses (shown in the inset). First pulse: 2 J/kg; second pulse: 0.77 J/kg. Total delivered dose: 4.35 J/kg. Time constant of pulse energy decay: 10−8 s

EM-GW Coupling

(GW induced parametric conversion
in coupled EM resonators)

Microwave Apparatus for Gravitational Waves Observation

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CERN, Geneva, Switzerland

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E. Picasso
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CERN, Geneva, Switzerland

In this report the theoretical and experimental activities for the development of superconducting microwave cavities for the detection of gravitational waves are presented.

Contents

The 2005 INFN "MAGO" GW experiment proposal

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The USannio – (L-S-X band) RS Satellite Groundstation (2006)

Was meant to support the environment-protection policies of the local (regional and prefectural) Administration. Project co-led with USannio Colleagues D. Villacci and M. DiBisceglie. Relied on past experience in building a smaller-scale station (X and L band) at UniSA (project co-led qith UniSA Colleagues M. Longo and F. Rossi) Possibly the 1st University-scale RSGS in Italy, State funded through MIUR-CIPE.

The tripod sustaining the 5m spherical radome was designed by artist Mimmo Palladino.

Our EM Lab Facilities (-2015)

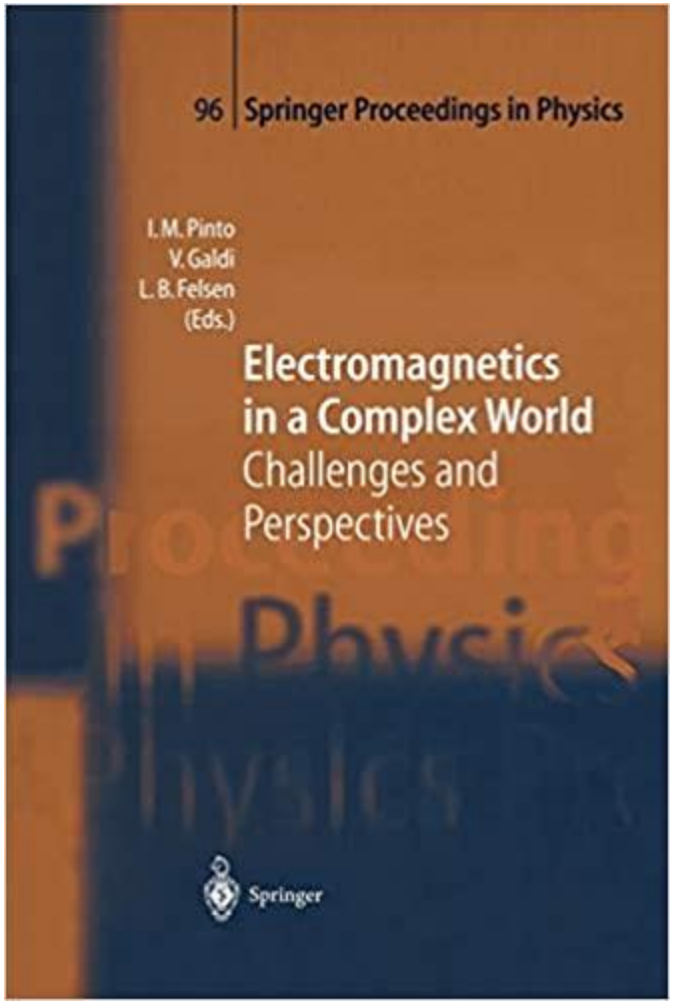
Microwave Measurements	Vector Network Analyzer AGILENT 85107B (bundle, 45MHz-50GHz).
Antenna Measurements	4-channel Microwave Sampling Scope & TDR Hewlett-Packard HP 54121+54124T (up to 26GHz).
	EM Shielded Anechoic Chamber 4x3x5 [m] (LxHxP), TDK absorbers. Frequency range 1-50 GHz
	NF-FF scanner ORBIT/FR AL-4952-1-1-7-V with Z-roll unit AL-610, multi-axis controller AL-4706 and power unit PSU AL-4146; Floor slide+ L-bracket ORBIT/FR with Azimuth-Elevation positioner (2xAL560); MiDAS planar, cylindrical and spherical scanning SW.
	Microwave Receiver AGILENT 85301C (8530A+8511B+83651B bundle, 45MHz-50GHz).
Cryogenics	SUMITOMO pulse-tube Cryocooler (0.5W@4.2K and 10W@45K) SRP-052A-W71D (bundle).
Environmental EM Fields	Seibersdorff SL383 Biconical Antenna
	Handheld Spectrum Analyzer ANRITSU 2711A 100KHz-3.0GHz.
	Isotropic Field Meter Holaday HI-4422+SW Holaday Probe-View
	ELF-VLF Field Meter Holaday HI3603+3604+3615
Dielectric Properties	Dielectric Probe Meter Agilent 85070 series + SW bundle.
Microwave Power App.s	3 x 2 KW closed multi-purpose mode stirred applicator 120x120x120 cm, home-made [operated at Salerno University]

… was an underground facility that was literally swept away by the flood that hit Benevento on October 15 2015, as an effect of exceptional rainfall and subsequent flooding of the two rivers (Sabato and Calore) that encircle the city …

Personal Memories

USannio Laurea Honoris Causa bestowed on professor Leopold B. Felsen (02/02/2003)

… and Proceedings of the related Symposium



Research – II Gravitational Waves

• *Gravitational waves from inspiraling binary systems*

Exact solution of Peters-Mathews equation [B1] for orbital evolution under GW emission; phasing errors due to nonzero orbital eccentricity and periastron advance [B2,B3]; fast and accurate computation of gravitational radiation from eccentric binaries (based on Carlini-Meissel expansion & Kapteyn series [B4]);

• *Minimally-redundant template-families for matched-filter CBS-GW detection*

Based on Shannon-Kotel'nikov theorem [B5,B6]; including generalization to higher PN orders via Tanaka-Tagoshi transformation [B7], and optimum-tiling of the source parameter-space [B8]; statistical characterization of the correlator bank-supremum including proximity (template-correlation) effects [B9];

• *Study of detectors based on the phenomenon of stochastic resonance*

[B10] relevant to continuous GW from spinning neutron stars;

• *Time-frequency representation based GW data analysis techniques*

including CBS-GW [B12], DOA retrieval for un-modeled transients [B13], and TF-skeleton sparsification techniques [B14];

• *Modeling of glitch noise in interferometric detectors*

including robust detection statistics for a network of interferometers observing un-modeled signals [B15], NN-based glitch classification [B16], and MIMO model based BSS-aided constructiin of glitch-dictionaries [B17];

• *Chirp-mass retrieval for eccentric binaries from their GW TF skeleton (PIRT-2021 Procs)*

GWs from Eccentric Inspiraling Binaries

IL NUOVO CIMENTO VOL. 111 B, N. 5 Maggio 1996

Exact solution of Peters-Mathews equations for any orbital eccentricity

V. PIERRO and I. M. PINTO
Dipartimento di Ingegneria dell'Informazione e Ingegneria Elettrica
Università di Salerno - Salerno, Italy

(ricevuto il 26 Ottobre 1995; approvato il 12 Gennaio 1996)

Summary. — The standard (Peters-Mathews) model for binary star orbital damping under gravitational wave emission is completely solved in analytic form, for any value of the initial orbital eccentricity, resulting into a *universal* decay scenario. The limits of validity of the model are established in a general handy form. Possible extensions of these results to higher-order post-Newtonian models are discussed.

PACS 04.20 – General relativity.

1. – Introduction

The simplest model for gravitational wave emission from binary stars was introduced by Peters and Mathews (henceforth PM) about thirty years ago in a couple of seminal papers [1, 2], under the point-mass, weak-field, slow-motion and quadrupole-radiation approximations.

Mon. Not. R. Astron. Soc. **325**, 358–372 (2001)

Fast and accurate computational tools for gravitational waveforms from binary stars with any orbital eccentricity

V. Pierro,[1] I. M. Pinto,[1★] A. D. Spallicci,[1] E. Laserra[2] and F. Recano[2]
[1]*Waves Group, University of Sannio at Benevento, Italy*
[2]*IMA, University of Salerno, Salerno, Italy*

Accepted 2001 February 23. Received 2001 February 1; in original form 1996 October 17

ABSTRACT

The relevance of orbital eccentricity in the detection of gravitational radiation from (steady state) binary stars is emphasized. Computationally effective (fast and accurate) tools for constructing gravitational wave templates from binary stars with any orbital eccentricity are introduced including tight estimation criteria of the pertinent truncation and approximation errors.

Key words: gravitational waves – methods: data analysis – binaries: general.

1 INTRODUCTION

Gravitational wave detection experiments in space including the satellite Doppler-Tracking (Bertotti & Iess 1999) and *LISA* (http://lisa.jpl.nasa.gov) will hopefully open a window on the low-frequency part of the gravitational wave (henceforth GW) spectrum of cosmic origin. In these frequency bands binary stars are among the most promising continuous detectable source.

A substantial fraction of binaries are expected to have orbits with *non-negligible eccentricity* (Barone et al. 1988; Hils et al. 1992; Pierro & Pinto 1996c) resulting into the emission of *several harmonics* of the fundamental orbital frequency. The importance of this fact from the standpoint of signal detection and estimation has been already noted.

THE ASTROPHYSICAL JOURNAL, 469:272–279, 1996 September 20

STEADY STATE POPULATION STATISTICS OF COMPACT BINARY STARS

V. PIERRO AND I. M. PINTO
Dipartimento di Ingegneria dell'Informazione ed Ingegneria Elettrica, Università di Salerno, Italy
Received 1995 September 13; accepted 1996 March 29

ABSTRACT

An estimate of the steady state population statistics of compact binary stars as a function of orbital eccentricity and scaled period, the scaling being dependent on the companion masses, is obtained starting from Peters-Mathews equations for orbital damping under gravitational wave emission.

Subject headings: binaries: close — gravitation

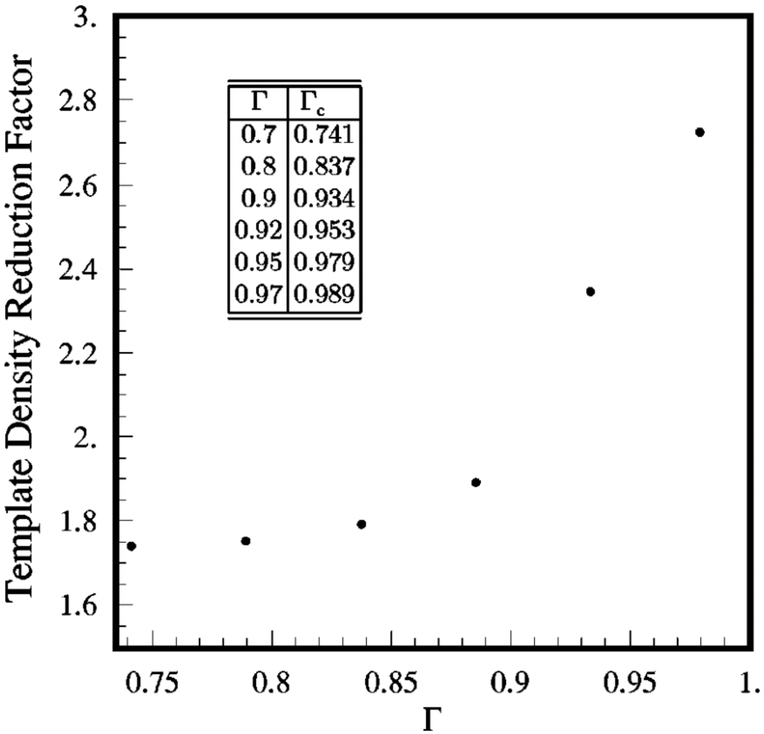
1. INTRODUCTION

The abundance of binary stars as a function of orbital period and eccentricity has been investigated by several authors, both from a theoretical and an observational standpoint (Staniucha 1982; Hils et al. 1990). It is a topic of special interest for space-borne gravity wave detectors, which are expected to open a window on the ELF to LF part of the gravitational wave spectrum of cosmic origin (Spallicci et al. 1993).

Noninteracting, doubly compact binary stars belonging to *clean* environments are expected to evolve only by the emission of gravitational waves causing orbital shrink and circularization. This entails a unique relationship at equilibrium between abundance and birthrate as functions of orbital period and eccentricity. In this paper we adopt the well-known Peters-Mathews model (Peters & Mathews 1963; Peters 1964) (weak field, slow motion, quadrupole approximation) to derive this relationship explicitly.

The paper is organized as follows. The steady abundance is obtained in § 2. Explicit solutions describing the main ensemble properties are obtained in § 3 for the possibly simplest (but easily generalizable) birthrate. Conclusions follow in § 4. Mathematical details have been collected in Appendices A and B.

Template Interpolation and Optimum tiling of Parameter Space for Correlation Based Detection / Source Parameter Estimation of GWs from Inspiraling Binaries



Template density reduction factor upon cardinal (Shannon-Kotel'nikov) interpolation

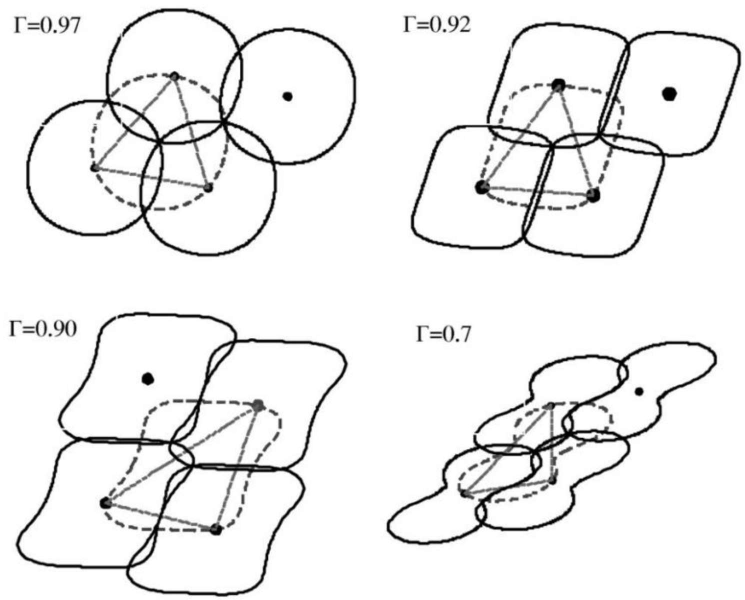


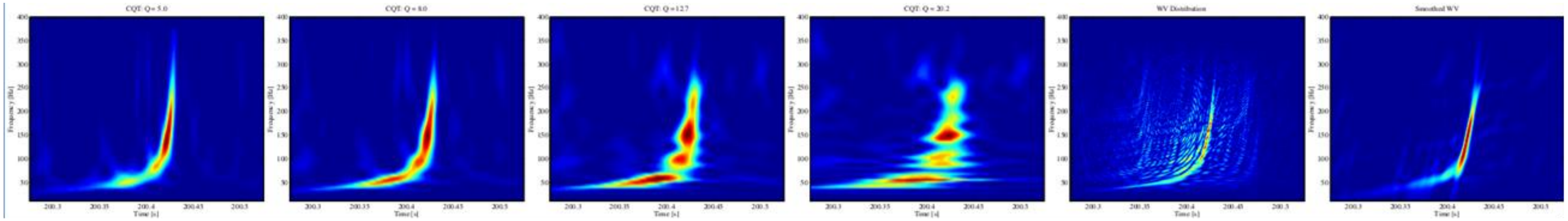
FIG. 6. Optimum triangular tilings and template lattices for several values of Γ (LIGO-I, 2.5PN).

The patches are the regions of parameter space where the center-template matches the received waveform to a level exceeding Γ

V. Pierro, I.M. Pinto et al., PRD 62 (2000) 121101R, PRD 62 (2000) 124020, PRD 64 (2001) 042005, PRD 64 (2001) 087101, PRD 65 (2002) 102003, CQG 20 (2003) S803, PRD 70 (2004) 122001, CQG 20 (2003) S803, CQG 21 (2004) 4955; etc.

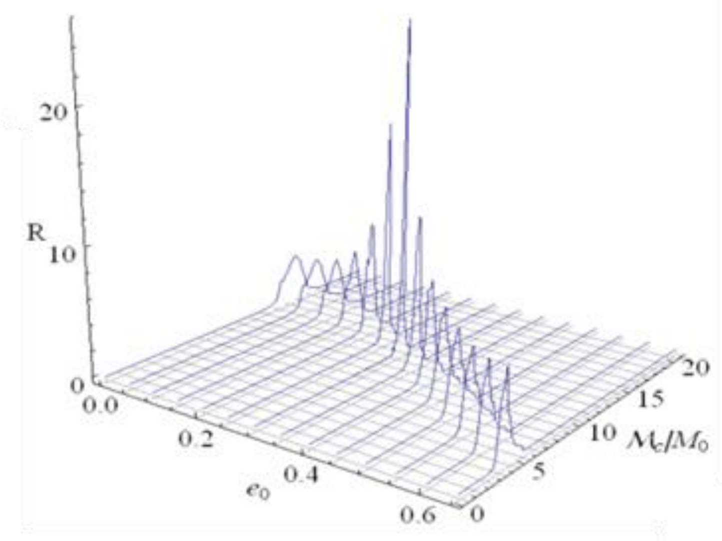
Time-Frequency Based GW Detection and Estimation

Work on time-frequency methods in GW data analysis started in 1994, and is still ongoing :



TFRs of public domain LIGO GW150914 (Hanford).
Left to right: Q transforms for various Q; WV distribution; sparsified WV

P. Flandrin and P. Borgnat, IEEE Trans.-SP58 (2010) 2974, doi.org/10.1109/TSP.2010.2044839
P. Addesso et al., Proc. 3rd CoSeRa Workshop (2015), doi.org/10.1109/CoSeRa.2015.7330283
P. Addesso et al., arxiv.org/pdf/1605.03496.pdf



T-norm data fusion in the TF plane for DOA and chirp-mass estimation [E. Mejuto Villa, I.M. Pinto et al, Int. J. Approx. Reas. 113 (2019) 372 ; IEEE Trans. Fuzzy Sys., 28 (2020) 534;]

Chirp mass retrieval from TF skeletons of GW from eccentric binaries
I.M. Pinto, PIRT 2021 Proceedings

Stochastic-Resonance Based Detection of Weak Quasi-Monochromatic Signals

$$\dot{x} = -\frac{d}{dx} V(x) + A \sin(\omega_s t + \phi) + \epsilon n(t),$$

$$V(x) = -a \frac{x^2}{2} + b \frac{x^4}{4}, \quad a,b>0,$$

$$E[n(t)n(t+\tau)] = \delta(\tau).$$

$$\frac{\partial p(x,t)}{\partial t} = \frac{\partial}{\partial x}\left\{\left[\frac{dV(x)}{dx} - A \sin(\omega_s t + \phi)\right] p(x,t)\right\} + \frac{\epsilon^2}{2}\frac{\partial^2}{\partial x^2} p(x,t), \quad p(x,0) = \delta(x - x_0).$$

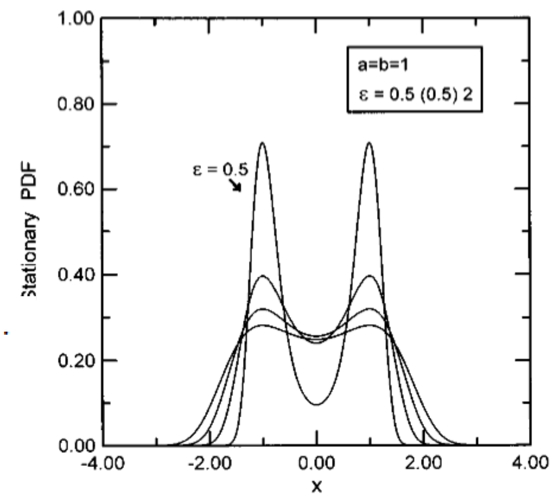
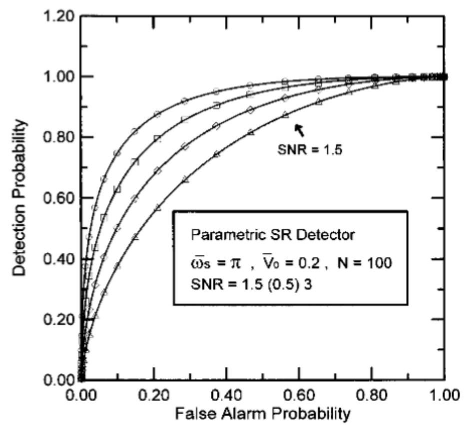
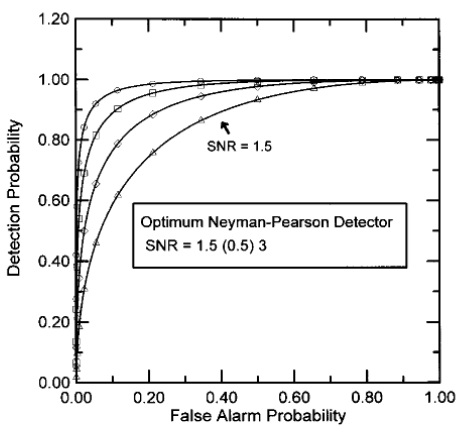


FIG. 1. Stationary (steady-state) output PDF relevant to the QPLE, in the absence of a signal.

Under suitable conditions, the system may *lock* to the time-harmonic forcing term

$$T_s \sim 2T_K, \quad T_K = \frac{\sqrt{2}\pi}{a} \exp\left[\frac{2V_0}{\epsilon^2}\right]$$ (Kramers switching time)





V. Galdi, V. Pierro, I.M. Pinto, PRE-57 (1998) 6470 , ibid. E69 (2004) 062104

Research – II Gravitational Waves, cont.d

● *Study of radiation-pressure driven chaos in multi-pendular Fabry-Perot resonators* [B18] may explain observed excess noise in interferometric detectors in the transition between the seismic and thermal noise dominated spectral regions.

● *Thermal noise minimization in the HR optical coatings of interferometric GW antennas*, explicit coating design method for thermal noise minimization at a prescribed transmittance [B19], and methods for the direct measurement of coating thermal noise [B20,B21], etc. –
These ideas were adopted by the advanced LIGO and Virgo detectors.

● *Impact of laser beam profile on thermal noise, and cavity mode optimization for thermal noise minimization* [B22,B23]
Abstract and realistic bounds (based on prolate spheroidal basis mode representations) on substrate-Brownian, coating, and substrate-thermoelastic noise are derived, indicating fair margins of further noise reduction; comparison with Gaussian, flat-top and Gauss-Laguerre modes.

● *Study of nm-layered materials (in particular, Silica/Titania, and Silica/Alumina) for low noise HR optical coatings* (collaboration with Caltech and NTHU) [B24];
Extensive experimental work is ongoing in our Lab to test the most promising nanolayered "formulas" (in particular, Silica/Titania for high-index, and Alumina-Silica for low-index materials);

● *Methods for thermal noise minimization in ternary* (and more generally, multimaterial) *coatings,* at ambient and cryogenic temperatures [B25], under prescribed transmittance And absorbance bounds, based on Pareto-manifold (trade-off) analysis.

Chaos in Multi-Pendular Fabry-Perot Resonators

V. Pierro, I.M. Pinto Phys. Lett. A185 (1994) 14

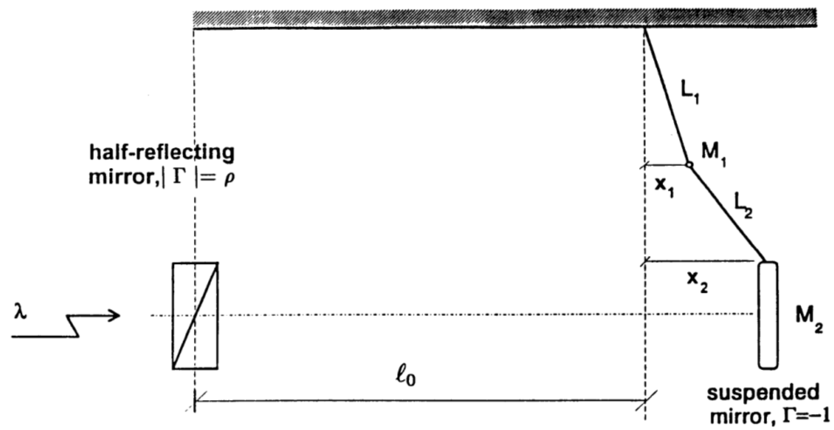


Fig. 1. Sketch of plane double pendular FPR.

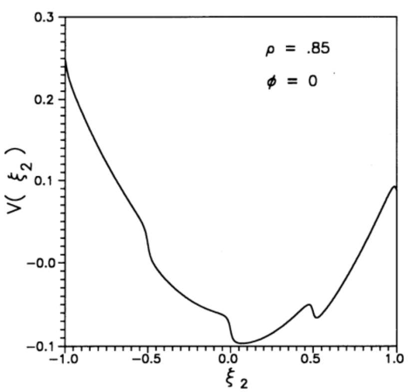


Fig. 8. Potential function $V(\xi_2)$.

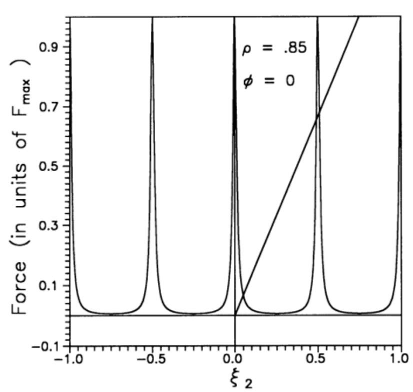


Fig. 9. The solution of eq. (A.2).

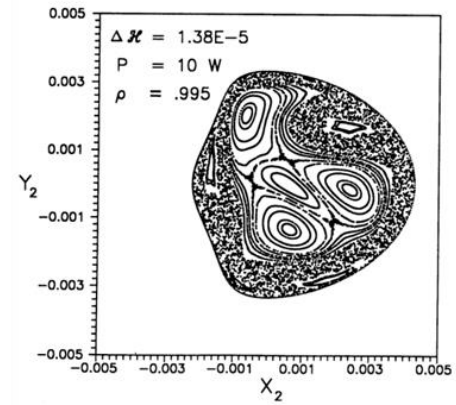
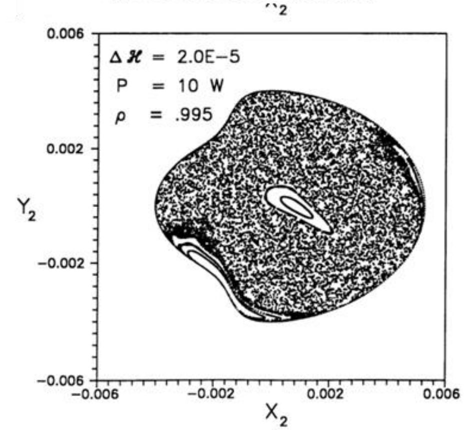


Fig. 3. Poincaré section of phase flow.



$$X_i = (\tfrac{1}{2}\Omega_i)^{1/2} q_i, \quad Y_i = (1/2\Omega_i)^{1/2} p_i,$$

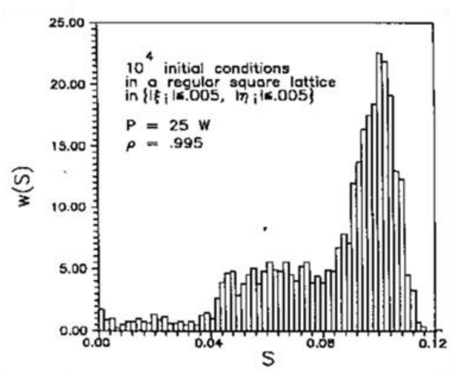


Fig. 6. Statistical density of the Sinai entropy.

…may explain excess noise in GW IFOs at the boundary between seismic and thermal noise dominated regimes…

Minimizing Thermal noise in Interferometric GW Detector Mirrors

Optimized multilayer dielectric mirror coatings for gravitational wave interferometers

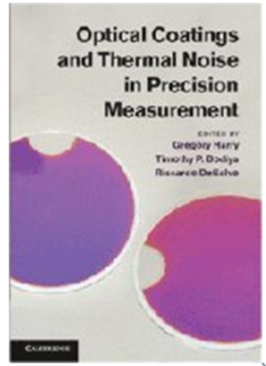
Juri Agresti [a,b], Giuseppe Castaldi [c], Riccardo DeSalvo [a], Vincenzo Galdi [c], Vincenzo Pierro [c], and Innocenzo M. Pinto [c]

[a] LIGO Laboratory, California Institute of Technology, Pasadena, CA 91125, USA;
[b] Department of Physics, University of Pisa, I-56127, Pisa, Italy;
[c] Waves Group, Department of Engineering, University of Sannio, I-82100, Benevento, Italy

ABSTRACT

The limit sensitivity of interferometric gravitational wave antennas is set by the thermal noise in the dielectric mirror coatings. These are currently made of alternating quarter-wavelength high/low index material layers with low mechanical losses. The quarter-wavelength design yields the maximum reflectivity for a fixed number of layers, but *not* the lowest noise for a prescribed reflectivity. This motivated our recent investigation of *optimal* thickness configurations, which guarantee the lowest thermal noise for a targeted reflectivity. This communication provides a compact overview of our results, involving *nonperiodic genetically-engineered* and *truncated periodically-layered* configurations. Possible implications for the advanced Laser Interferometer Gravitational wave Observatory (LIGO) are discussed.

Advances in Thin-Film Coatings for Optical Applications III, edited by Michael J. Ellison,
Proc. of SPIE Vol. 6286, 628608, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.678977



ISBN: 9781107003385 (2012)

12

Reflectivity and thickness optimization

INNOCENZO M. PINTO, MARIA PRINCIPE, AND RICCARDO DESALVO

12.1 Introduction

This chapter is focused on design strategies for minimizing Brownian (see Chapter 4) and, more generally, thermal noises (see Chapters 3 and 9) in high-reflectivity optical coatings. It is organized as follows: in Section 12.2 we review the basic formulas needed to describe the optical properties of dielectric coatings (an *ab-initio* derivation of these formulas is included in the Appendix). Brownian noise formulas are the subject of Section 12.3. Section 12.4 presents the key ideas of coating thickness optimization. Thermo-optic noise issues are reviewed in Section 12.5, together with a discussion of pertinent minimization criteria. Section 12.6 contains a few comments on material characterization, and touches the important topic of glassy mixture modeling and optimization.

12.2 Coating formulas

In this section we summarize the basic coating formulas on which the subsequent analysis is based. A compact *ab-initio* derivation of these results is given in the Appendix.

Optical coatings are modeled as stacks of planar layers terminated on both sides by homogeneous halfspaces; the relevant geometry and notation is sketched in Figure 12.1. Layers are identified by an index $i = 1, 2, \dots, N_L$. It is understood that $i = 0$ and $i = N_L + 1$ correspond to the left halfspace and the substrate, respectively. It is convenient to introduce a local coordinate system (x, y, z_i) for each layer, so that the internal layers $i = 1, 2, \dots, N_L$ correspond to $-d_i \leq z_i \leq 0$, the left halfspace is defined by $-\infty < z_0 \leq 0$, and the substrate by $0 \leq z_{N_L+1} < \infty$. Plane wave incidence from the leftmost halfspace is assumed.[1] An $\exp(\imath 2\pi f t)$ time dependence of the field is understood and omitted.

[1] This is the usual (optical limit) approximation. The general case of an incident Gaussian beam, and its optical limit, are discussed in Hillion (1994).

Optical Coatings and Thermal Noise in Precision Measurement, eds. Gregory M. Harry, Timothy Bodiya and Riccardo DeSalvo. Published by Cambridge University Press. © Cambridge University Press 2012.

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PHYSICAL REVIEW D **81,** 122001 (2010)

Measurement of thermal noise in multilayer coatings with optimized layer thickness

Akira E. Villar, Eric D. Black, Riccardo DeSalvo, and Kenneth G. Libbrecht
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Christophe Michel, Nazario Morgado, and Laurent Pinard
Laboratoire des Matériaux Avancés, Université Claude Bernard Lyon 1, CNRS/IN2P3, Villeurbaune, France

Innocenzo M. Pinto, Vincenzo Pierro, Vincenzo Galdi, Maria Principe, and Ilaria Taurasi
Waves Group, University of Sannio at Benevento, Benevento, Italy, INFN and LSC
(Received 7 April 2010; published 3 June 2010)

A standard quarter-wavelength multilayer optical coating will produce the highest reflectivity for a given number of coating layers, but in general it will not yield the lowest thermal noise for a prescribed reflectivity. Coatings with the layer thicknesses optimized to minimize thermal noise could be useful in future generation interferometric gravitational wave detectors where coating thermal noise is expected to limit the sensitivity of the instrument. We present the results of direct measurements of the thermal noise of a standard quarter-wavelength coating and a low noise optimized coating. The measurements indicate a reduction in thermal noise in line with modeling predictions.

DOI: 10.1103/PhysRevD.81.122001

PHYSICAL REVIEW D **91,** 022005 (2015)

Material loss angles from direct measurements of broadband thermal noise

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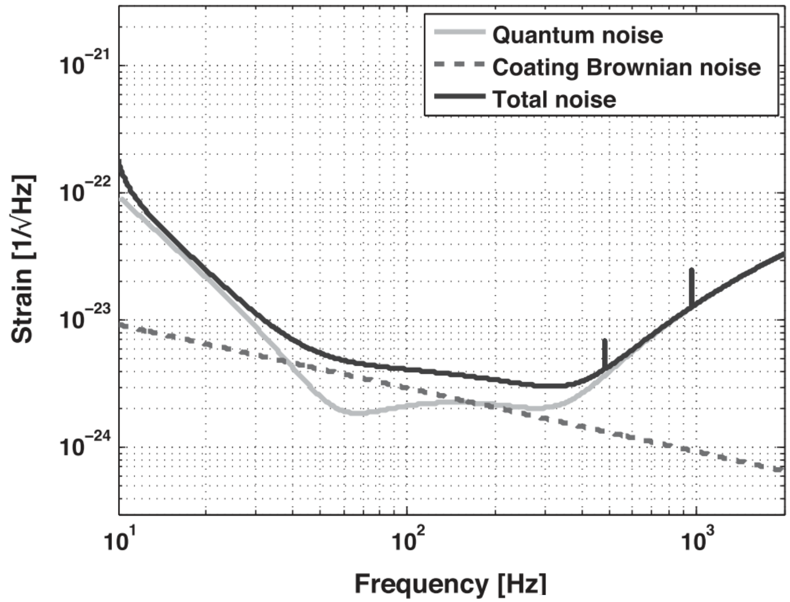
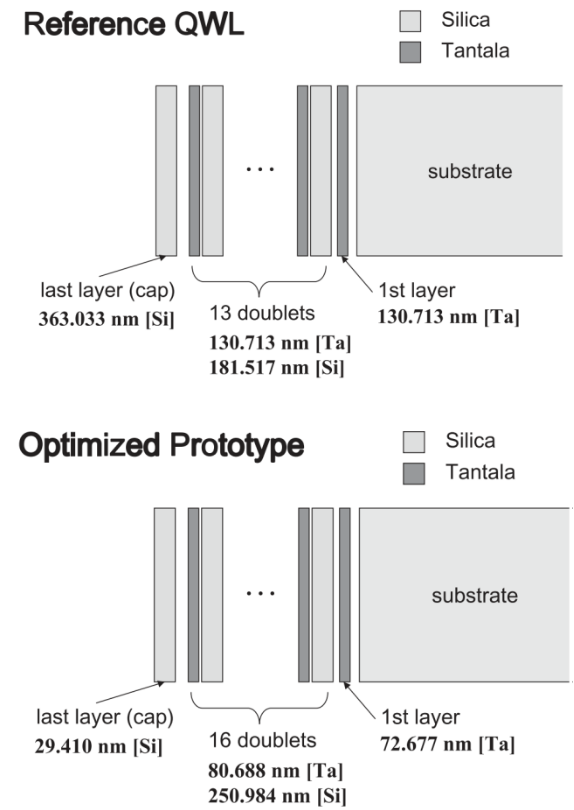
(Received 27 August 2014; published 23 January 2015)

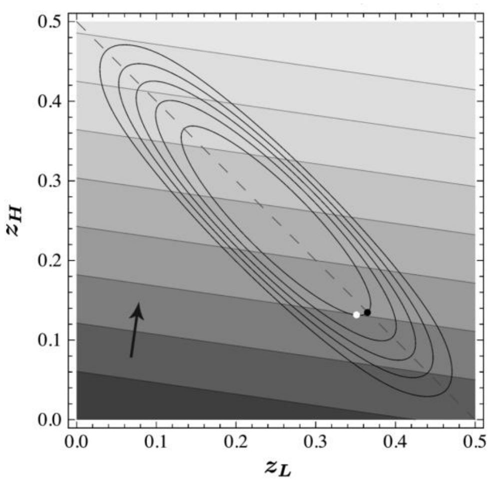
We estimate the loss angles of the materials currently used in the highly reflective test-mass coatings of interferometric detectors of gravitational waves, namely Silica, Tantala, and Ti-doped Tantala, from direct measurement of coating thermal noise in an optical interferometer testbench, the Caltech TNI. We also present a simple predictive theory for the material properties of amorphous glassy oxide mixtures, which gives results in good agreement with our measurements on Ti-doped Tantala. Alternative measurement methods and results are reviewed, and some critical issues are discussed.

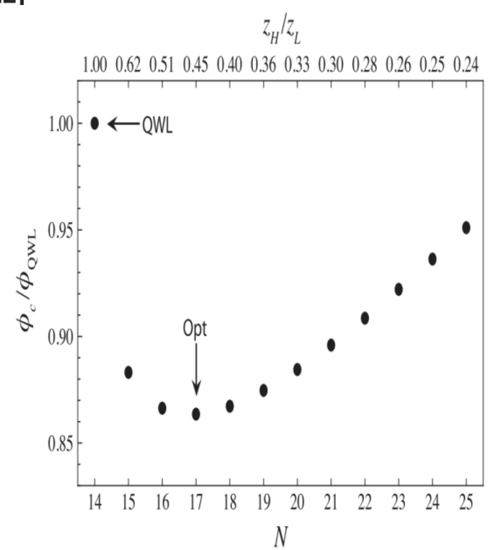
DOI: 10.1103/PhysRevD.91.022005 PACS numbers: 04.80.Nn, 05.40.Ca, 07.60.Ly, 95.55.Ym

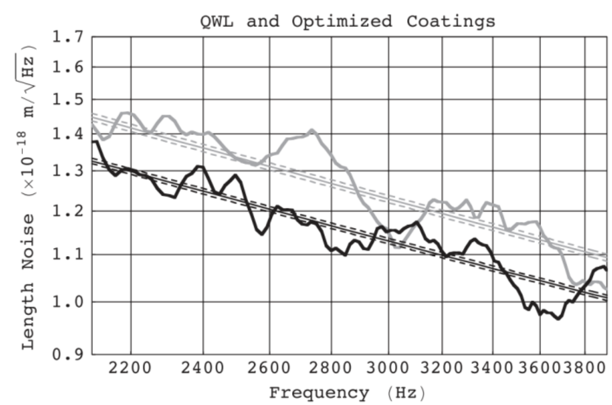
Coating Design Optimization for Minimum Brownian Noise







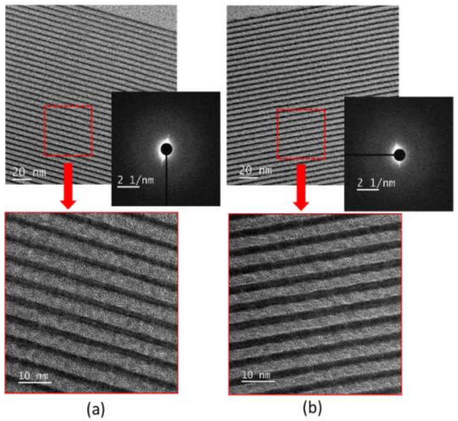




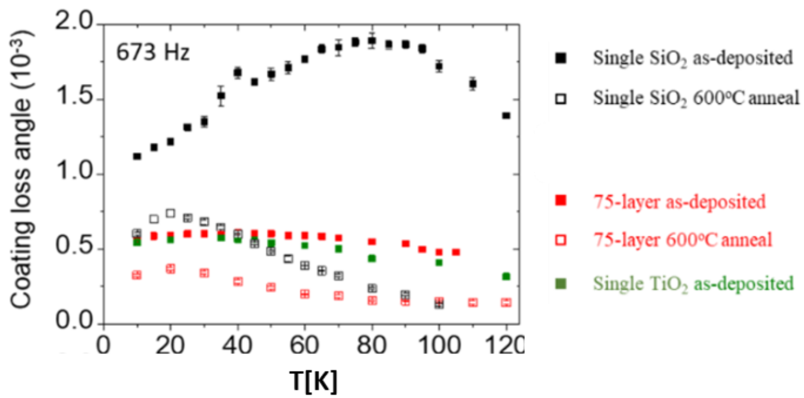
[A. Villar, I.M. Pinto et al., PRD 81 (2010) 122001]

Nanolayered Coating Materials & Optimized Ternary (Multimaterial) Coatings

… nanolayering prevents crystalization upon annealing, and mitigates the peak in mechanical loss observed e.g. in Silica, allowing to synthetize new coating materials with higher optical contrast and lower mechanical losses down to cryo-temperatures



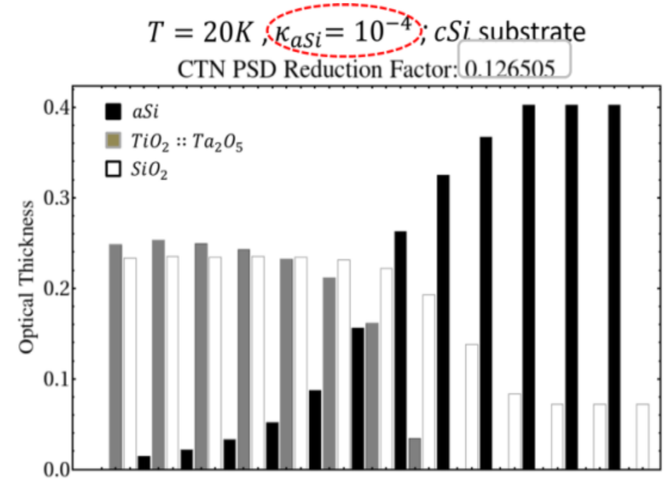
75 nanolayers Silica-Titania QWL film TEM and ED (insets)
as deposited (a) and after 12h 600C annealing in air (b)



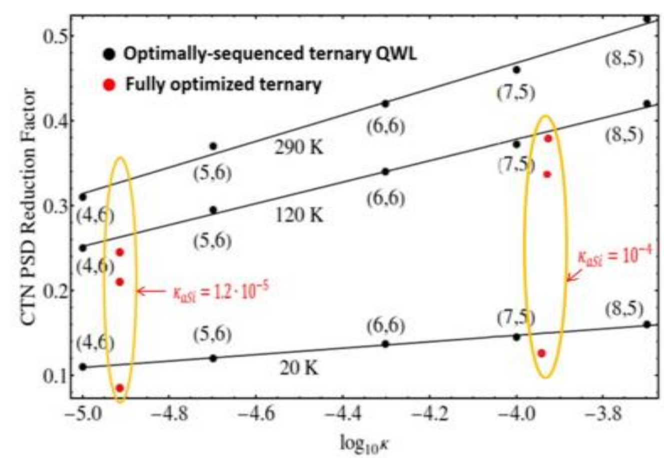
Measured mechanical losses (clamped cantilever) before and after annealing

[S. Chao, I.M. Pinto et al, Opt. Expr. 22 (2014) 29487; IEEE 2019 PIERS Proc, etc.]

… Optimal design of coatings using optically dense but *lossy* materials (e.g., *a*Si)



… allows tenfold CTN reduction @20K…

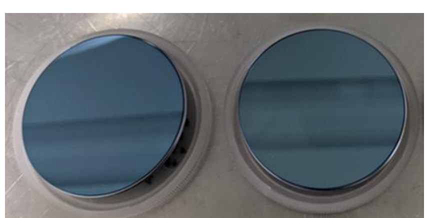


[V. Pierro , I.M. Pinto, et al., PRR 3 (2021) 023172; LIGO-G2101479, etc.]

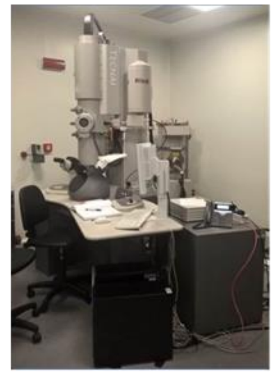
Our Optical (Nano) Film LAB Facilities (2021)

@USannio

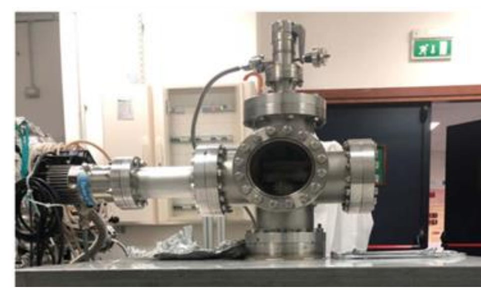
Ion-assisted, fully GUI programmable dual e-beam thin film deposition facility, with Xtal thickness-monitoring and controlled substrate heating.
Up to six co-deposited materials, per run, with sub - nanometer deposition accuracy/repetability.



@UniSA

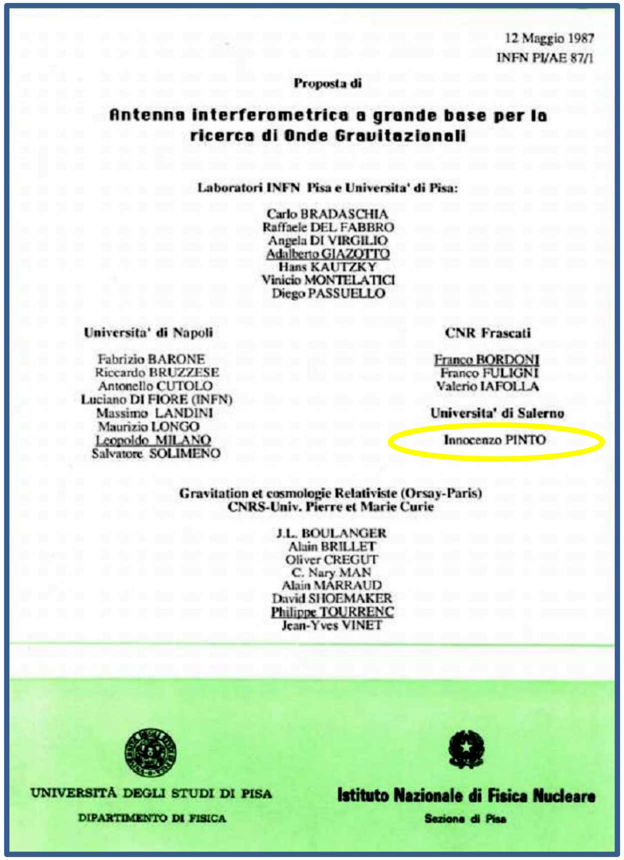


Left to right, top to bottom: FEI Tecnai-20 (TEM); Zeiss LEO-EVO 50 (EDS - SEM); Zeiss Sigma Gemini (FE-SEM) Renishaw Invia (Raman); JPK Nanowizard-3 (AFM); Philips 'Xpert-Pro (XRD) ; custom annealing over (3 inch), w. controlled atmosphere (air, vacuum, nitrogen), & fully programmable thermal schedule



Direct (QDPI) thermal noise measurement facility under contruction (tbc 2022).

Personal Memories (1987-1990)



12 Maggio 1987
INFN PI/AE 87/1

Proposta di

Antenna interferometrica a grande base per la ricerca di Onde Gravitazionali

Laboratori INFN Pisa e Universita' di Pisa:

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Raffaele DEL FABBRO
Angela DI VIRGILIO
Adalberto GIAZOTTO
Hans KAUTZKY
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Maurizio LONGO
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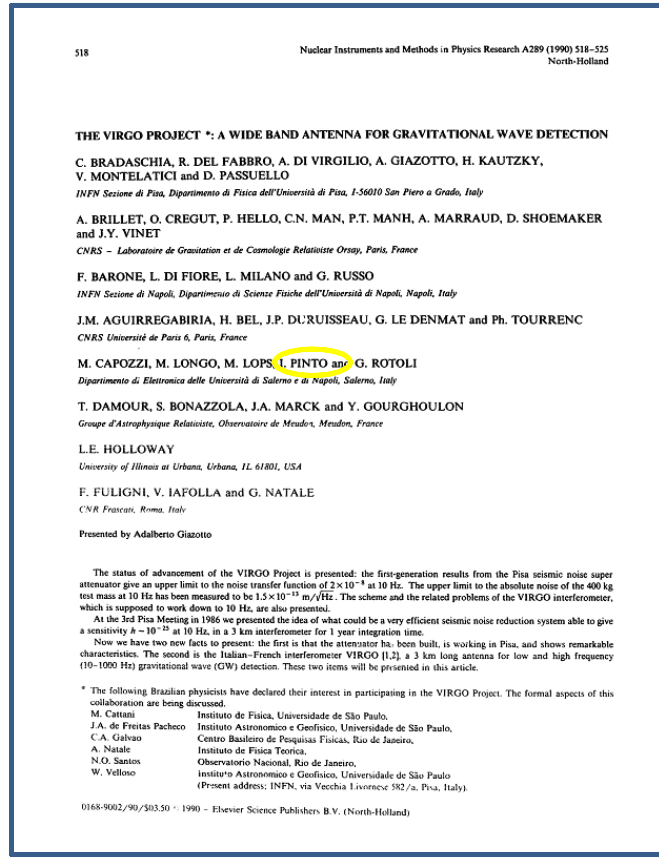
Philippe TOURRENC
Jean-Yves VINET

UNIVERSITÀ DEGLI STUDI DI PISA
DIPARTIMENTO DI FISICA

Istituto Nazionale di Fisica Nucleare
Sezione di Pisa

1st Virgo proposal to INFN (1987)



518 — Nuclear Instruments and Methods in Physics Research A289 (1990) 518–525
North-Holland

THE VIRGO PROJECT *: A WIDE BAND ANTENNA FOR GRAVITATIONAL WAVE DETECTION

C. BRADASCHIA, R. DEL FABBRO, A. DI VIRGILIO, A. GIAZOTTO, H. KAUTZKY, V. MONTELATICI and D. PASSUELLO
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J.M. AGUIRREGABIRIA, H. BEL, J.P. DURUISSEAU, G. LE DENMAT and Ph. TOURRENC
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F. FULIGNI, V. IAFOLLA and G. NATALE
CNR Frascati, Roma, Italy

Presented by Adalberto Giazotto

The status of advancement of the VIRGO Project is presented: the first-generation results from the Pisa seismic noise super attenuator give an upper limit to the noise transfer function of 2×10^{-8} at 10 Hz. The upper limit to the absolute noise of the 400 kg test mass at 10 Hz has been measured to be 1.5×10^{-13} m/$\sqrt{\text{Hz}}$. The scheme and the related problems of the VIRGO interferometer, which is supposed to work down to 10 Hz, are also presented.

At the 3rd Pisa Meeting in 1986 we presented the idea of what could be a very efficient seismic noise reduction system able to give a sensitivity $h \sim 10^{-25}$ at 10 Hz, in a 3 km interferometer for 1 year integration time.

Now we have two new facts to present: the first is that the attenuator has been built, is working in Pisa, and shows remarkable characteristics. The second is the Italian–French interferometer VIRGO [1,2], a 3 km long antenna for low and high frequency (10–1000 Hz) gravitational wave (GW) detection. These two items will be presented in this article.

* The following Brazilian physicists have declared their interest in participating in the VIRGO Project. The formal aspects of this collaboration are being discussed.

M. Cattani	Instituto de Fisica, Universidade de São Paulo,
J.A. de Freitas Pacheco	Instituto Astronomico e Geofisico, Universidade de São Paulo,
C.A. Galvao	Centro Basileiro de Pesquisas Fisicas, Rio de Janeiro,
A. Natale	Instituto de Fisica Teorica,
N.O. Santos	Observatorio Nacional, Rio de Janeiro,
W. Velloso	Instituto Astronomico e Geofisico, Universidade de São Paulo (Present address: INFN, via Vecchia Livornese 582/a, Pisa, Italy).

0168-9002/90/$03.50 © 1990 – Elsevier Science Publishers B.V. (North-Holland)

1st Virgo paper (1990, NIM A289)

Personal Memories (1998-2000)

1998-2000 EU Senior visiting scientist @ NAO for TAMA-300
… first medium-size (300m arm) operational interferometric GW antenna …

Memorandum of Understanding
between The Waves Group - University of Sannio at Benevento, Italy
and the TAMA Project, Japan

The purpose of this MOU is to establish and define a joint collaboration between the Waves Group of the University of Sannio at Benevento, Italy, and the TAMA Project, Japan, under the "guidelines for joint collaborations using TAMA data".

1. The TAMA Project, Japan, is a cooperation consisting among others of the following Institutions: National Astronomical Observatory (NAO); the Institute of Cosmic Ray Research (ICRR); The University of Tokyo, the Institute of Laser Science (ILS); the High Energy Accelerator Research Organization (KEK), the Yukawa Institute for Theoretical Physics (YITP), Osaka University and Miyagi University of Education. The TAMA project has constructed and is operating TAMA300, a 300m Fabry-Perot recombined interferometer with power recycling system. The goal of TAMA is to detect gravitational waves, and to advance knowledge in the field of gravitational wave detectors.
2. The Waves Group (TWG) - University of Sannio at Benevento is a research group consisting of: Innocenzo M. Pinto (full professor), Vincenzo Pierro (assistant professor), plus typically three post doctoral Fellows, and two Ph.D students. The members of TWG are actively working on several issues relevant to gravitational wave detection experiments.
3. The collaboration between TWG and TAMA will focus primarily on data analysis and the application of the Wigner-Ville time-frequency, methods developed by TWG to the TAMA data, with special reference to data sieving and/or noise characterization.
4. TWG will communicate to TAMA its research results related to data analysis, their interpretation and implications for TAMA.
5. TAMA will communicate to TWG its research results related to data analysis, and make available to TWG reports and internal memos relevant to the issue of data analysis.
6. Any kind of publication arising out of the joint collaboration, including but not limited to Journal articles or oral presentations at Conferences shall be done jointly in the names of TWG and TAMA. The content and fitness for publication shall be investigated jointly, and the parties shall come to a mutual agreement.
7. Each party in this agreement continues to be responsible for all support of its own staff, including travel costs associated with the activities under this agreement.
8. This Memorandum of Understanding will remain in force until the parties mutually agree to terminate it. Annual Attachments will define specific activities to be carried out during the following year, and list the members of TWG who will participate in the planned cooperation activities.

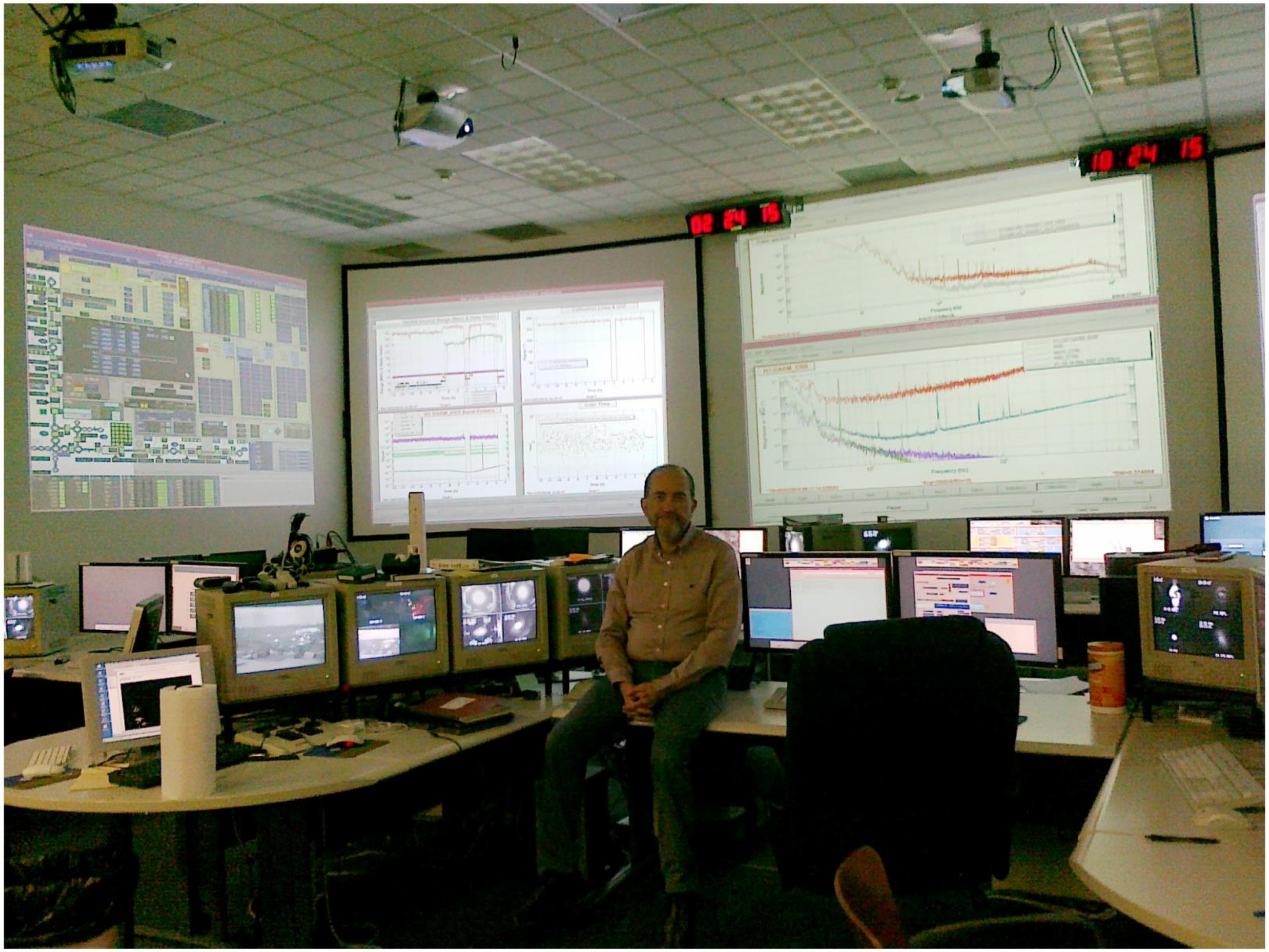
Approved:

Yoshihide Kozai TAMA Principal Investigator	Pietro Perlingieri President, University of Sannio
神田展行 Nobuyuki Kanda TAMA Data Analysis Group Leader	Innocenzo M. Pinto The Waves Group Principal Investigator
Date Feb. 1, 2000	Date 10 Feb. 2000

MoU with TAMA for TF data analysis of early TAMA-300 data
(in R.P. Croce PhD thesis, supervised by M.K. Fujimoto & I.M. Pinto)

Personal Memories (2005-)

Our group joined LIGO in 2005, and is still an active member of LIGO and the LVK.



Night ("owl") shift @ LIGO-Hanford control room (2007)

Selected Papers (last 10 years)

- V. Pierro, I.M. Pinto et al., "*Ternary Quarter Wavelength Coatings for Gravitational Wave Detector Mirrors: Design Optimization via Exhaustive Search,*" Phys. Rev. Research 3 (2021) 023172
https://doi.org/10.1103/PhysRevResearch.3.023172

- O. Durante, I.M. Pinto et al., "*Emergence and Evolution of Crystallization in TiO_2 Thin Films: a Structural and Morphological Study,*" Nanomaterials 11 (2021) 1409
https://doi.org/10.3390/nano11061409

- R. DeSalvo, G. Pelosi, I.M. Pinto, S. Selleri, "*Stepped Beam-Pipes and Helical Baffles for Scattered Light Absorption in Future Gravitational Wave Detectors,*" Rev. Sci. Instr. 91 (2020) 054505
https://doi.org/10.1063/1.5144862

- E. Mejuto-Villa, L. Troiano, I.M. Pinto, "*Triangular Norms for Gravitational Wave Data Fusion,*" IEEE Trans. Fuzzy Sys., 28 (2020) 534
https://doi.org/10.1109/TFUZZ.2019.2910453

- The KAGRA Collaboration, including I.M. Pinto, "*KAGRA: 2.5 Generation Interferometric Gravitational Wave Detector,*" Nature Astron., 3 (2019) 35
https://doi.org/10.1038/s41550-018-0658-y

- V. Pierro, I.M. Pinto et al., "*On the Performance Limits of Coatings for Gravitational Wave Detectors made of Alternating Layers of two Materials,*" Opt. Mater. 96 (2019) 109269.
https://doi.org/10.1016/j.optmat.2019.109269

- E. Mejuto-Villa, L. Troiano, I.M. Pinto, "*On the Application of T-norms to Gravitational Wave Data Fusion: a Confirmatory Study,*" Int. J. Approx. Reasoning, 113 (2019) 372
https://doi.org/10.1016/j.ijar.2019.07.013

Selected Papers (last 10 years), contd.

- A. Fusco, I.M. Pinto e al., "*Glitch Entomology,*" Proc 14th Marcel Grossman Meeting on Recent Developments in Theoretical and Experimental General Relativity, M. Bianchi et al., Eds., World Scientific (2018) 3645.
https://doi.org/10.1142/9789813226609_0474
- M.L. Gorodetsky, Y. Levin, I.M. Pinto, S.P. Vyatchanin, "*In Memoriam Vladimir Borisovich Braginsky,*" Phys. Lett. A382 (2018) 2157 (Editorial)
https://doi.org/10.1016/j.physleta.2018.05.025
- M. Magnozzi, I.M. Pinto et al., "*Optical Properties of Amorphous SiO_2-TiO_2 Multi-Nanolayered Coatings for 1064-nm Mirror Technology,*" Opt. Mat. 75 (2018) 94
https://doi.org/10.1016/j.optmat.2017.09.043
- The LIGO and Virgo Collaborations, including I.M. Pinto, "*GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral,*" Phys. Rev. Lett. 119 (2017) 161101
https://doi.org/10.1103/PhysRevLett.119.161101
- M. Principe and I.M. Pinto, "*Locally-Optimum Network Detectors of Unmodeled Gravitational Wave Bursts in Glitch Noise,*" Phys. Rev. D 95 (2017) 082006
https://doi.org/10.1103/PhysRevD.95.082006
- D.V. Martynov, I.M. Pinto et al., "*Sensitivity of the Advanced LIGO Detectors at the Beginning of Gravitational Wave Astronomy,*" Phys. Rev. D 93 (2017) 112004
https://doi.org/10.1103/PhysRevD.93.112004
- V. Fiumara, I.M. Pinto, et al., "*Free-Space Antenna Pattern Retrieval in Nonideal Reverberation Chambers,*" IEEE Trans. EMC-58 (2016) 673.
https://doi.org/10.1109/TEMC.2016.2539351

Selected Papers (last 10 years), contd.

- M. Principe, I.M. Pinto et al., "*Material Loss Angles from Direct Measurements of Broadband Thermal Noise,*" Phys. Rev. D 91 (2015) 022005. https://doi.org/10.1103/PhysRevD.91.022005
- The LIGO and Virgo Collaborations, "*Observation of Gravitational Waves from a Binary Black Hole Merger,*" Phys. Rev. Lett. 116 (2016) 061102 https://doi.org/10.1103/PhysRevLett.116.061102
- P. Addesso, I.M. Pinto et al., "*Sparsifying Time-Frequency Distributions for Gravitational Wave Data Analysis,*" Proc. 3rd International Workshop on Compressed Sensing Theory and its Applications (2015) https://doi.org/10.1109/CoSeRa.2015.7330283
- V. Pierro, A. DeVita, R.P. Croce, I.M. Pinto et al.,"*Membrane Heating in Living Tissues Exposed to Nonthermal Pulsed EM Fields,*" IEEE Trans. PS-42 (2014) 2236 https://doi.org/10.1109/TPS.2014.2342492
- G. Castaldi, V. Gald, I.M. Pinto, "*Short-Pulsed Wavepacket Propagation in Ray-Chaotic Enclosures,*" IEEE Trans. AP-60 (2012) 3027 https://doi.org/10.1109/TAP.2012.2201126
- R.P Croce, I.M. Pinto et al., "*Robust Gravitational Wave Burst Detection and Source Localization in a Network of Interferometers using Cross-Wigner Spectra,*" Class. Quantum Grav. 29 (2012) 045001 https://doi.org/10.1088/0264-9381/29/4/045001

Selected Papers (last 10 years), contd.

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