

New Directions in Data Analysis

Research at Sannio and Salerno Universities

Innocenzo M. Pinto



The Waves Group



LIGO-G050036-00-Z



Plan

Current work

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Conclusions



Current work

Sequential detection

SIRP modeling of IFO noise

Signum-coded data



Sequential Detection

The Rationale:

Looking for *almost endless* signals (e.g., PSRs) with unknown strength, using *fixed size* data is *not* the best choice.

A. Wald, *Sequential Analysis*, Dover, NY, 1947.

A.G. Tartakovski, I.A. Ivanova, *Prob. Inf. Transm.*, **28**, 55, 1992

S. Marano, V. Matta, P. Willett, *IEEE Trans.* **SP-51**, 385, 2003.



Sequential Detection, contd.

-Define *current* log-likelihood ratio,

$$\Lambda_n = \Lambda_{n-1} + \ln \left(\frac{f(x_n | H_1)}{f(x_n | H_0)} \right), \quad \Lambda_0 = 0, \quad n = 0, 1, 2, \dots$$

PDF of n-sample,
signal ON (known)

PDF of n-sample,
signal OFF (known)

-Compare *current* log-likelihood ratio to *two* thresholds.

False-alarm prob.
(prescribed)

$$\gamma_0 = \ln \frac{\beta}{1-\alpha}, \quad \gamma_1 = \ln \frac{1-\beta}{\alpha}$$

False-dismissal
prob. (prescribed)

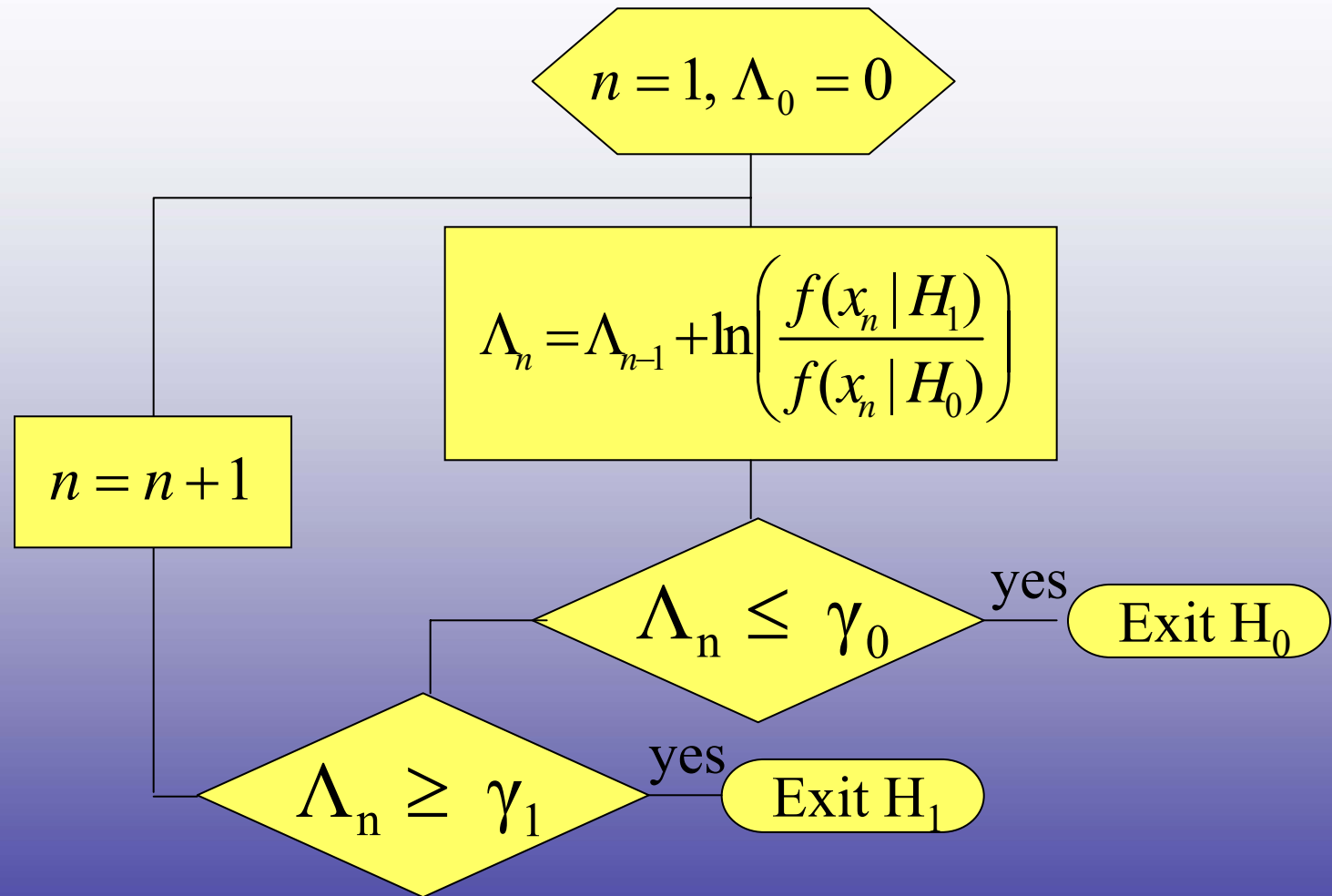
-Exit *iff* $\Lambda \leq \gamma_0$ ($\Rightarrow H_0$) or $\Lambda \geq \gamma_1$ ($\Rightarrow H_1$); otherwise *repeat*;

NO signal detected

signal detected



Sequential Detection, contd.



Sequential Detection, contd.

- Test ends at some (*random*) $n=N$ (stopping time);
- CDF of N is known [Tartakovski & Ivanova, 1992];

-Key features:

MF=matched filter

$$E_{0,1}(N) < N_{MF}, \text{ for the same } d, e;$$

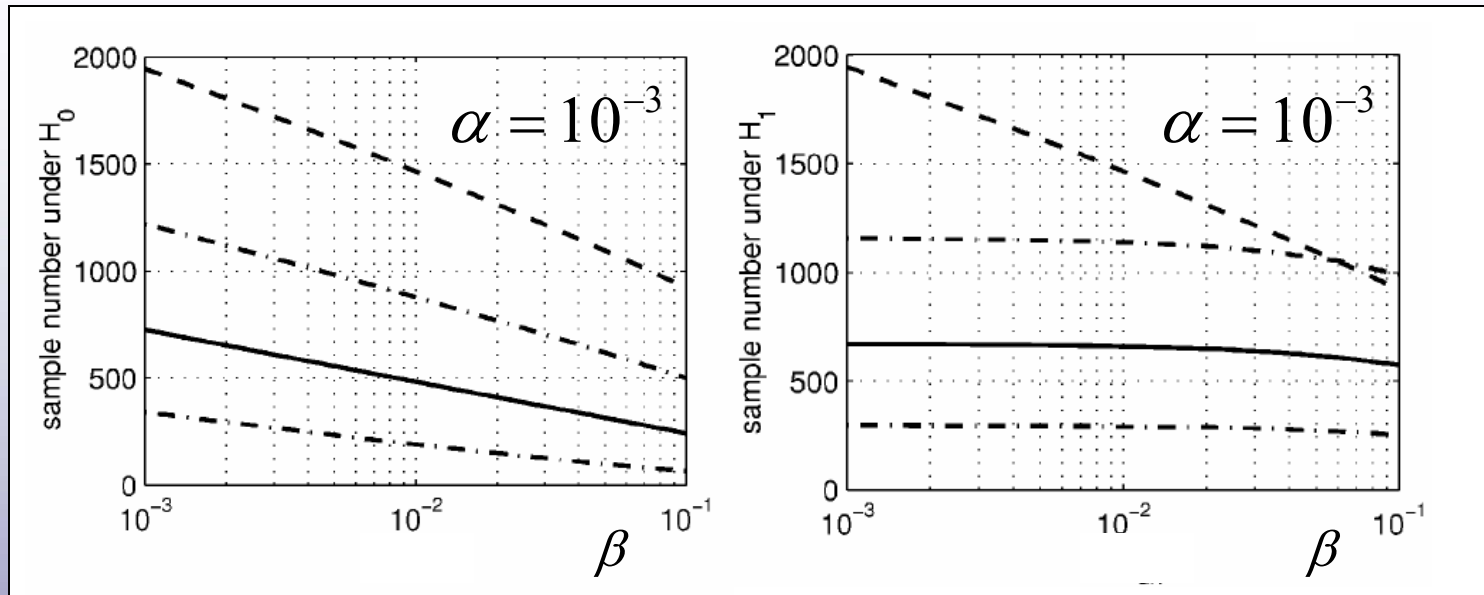
$$VAR_{0,1}(N) \sim \gamma_{0,1} \frac{VAR_{0,1}(a)}{E_{0,1}^3(a)}, \quad a = \ln \left(\frac{f(x|H_1)}{f(x|H_0)} \right)$$

benefits

- Shorter ave. time required for H_0/H_1 decision;
- Dynamic re-allocation of computational resources allowed in template-bank (ML) search;
- Straightforward implementation



Sequential Detection, contd.



Shorter ave. time required for H_0/H_1 decision

Dashed line: std. MF; solid line: average ST stopping time;

Dashed-dotted line: ST stopping time 10th and 90th percentiles.

S. Marano, V. Matta, P. Willett, IEEE Trans. **SP-51**, 385, 2003.



Sequential Detection, contd.

All-sky, all-frequency PSR search

Extended ML philosophy:

-All correlators implemented *sequentially*;

Decision rule:

- H_1 : *one* correlator exits with H_1

- H_0 : *all* correlators exit with H_0

As test goes on, more correlators exit with H_0

→ computational resources dynamically re-allocated

Preliminary formulation

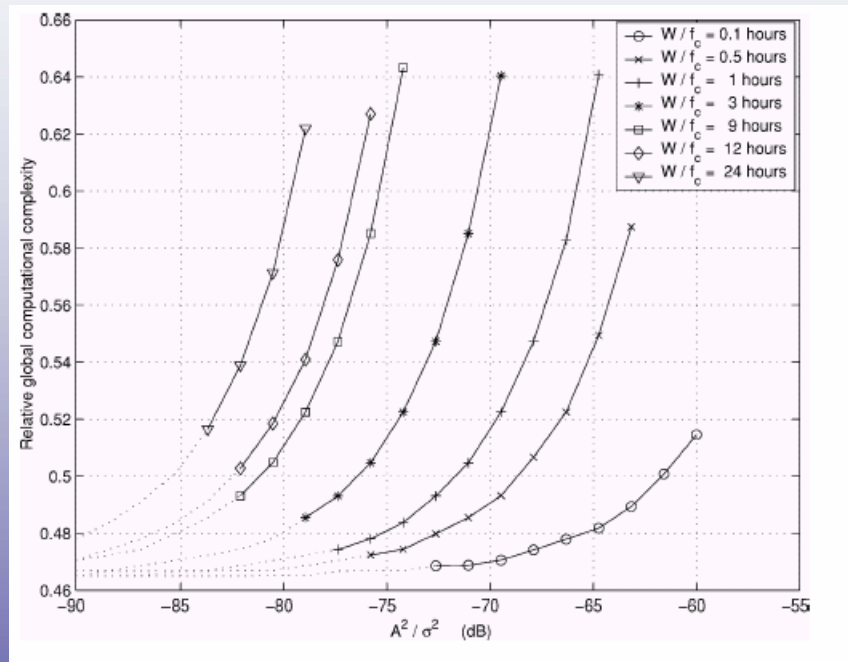
V. Matta, thesis, University of Salerno, 2001;

S. Marano, V. Matta, P. Willett, IEEE Trans. **SP-51**, 385, 2003.



Sequential Detection, contd.

All-sky, all-frequency PSR search



Detection statistic from incoherently combined STF (various sizes shown).

Comput. cost reduction sequential vs MF bank as a function of local (single STF) SNR.

continuous lines become dashed at $T=5$ years

V. Matta, thesis, University of Salerno, 2001;

S. Marano, V. Matta, P. Willett, IEEE Trans. **SP-51**, 385, 2003.



SIRP Modeling of IFO noise

Motivation

Real-world IFO noises non-stationary/non-gaussian;

Noise models needed to formulate (locally) optimum detection strategies [B. Allen et al., Phys. Rev. D65 122002 (2002); ibid. D67 122002 (2003)];

SIRP noise models [A.M. Vershik, Th. Prob. And its Appl., 9, 353, 1964 (in russian)] describe a wide class of NS/NG noises [D. Middleton, IEEE Tr. EMC-14, 12, 1972. M. Rangaswamy, et al., IEEE Tr. AES-29, 111, 1993];

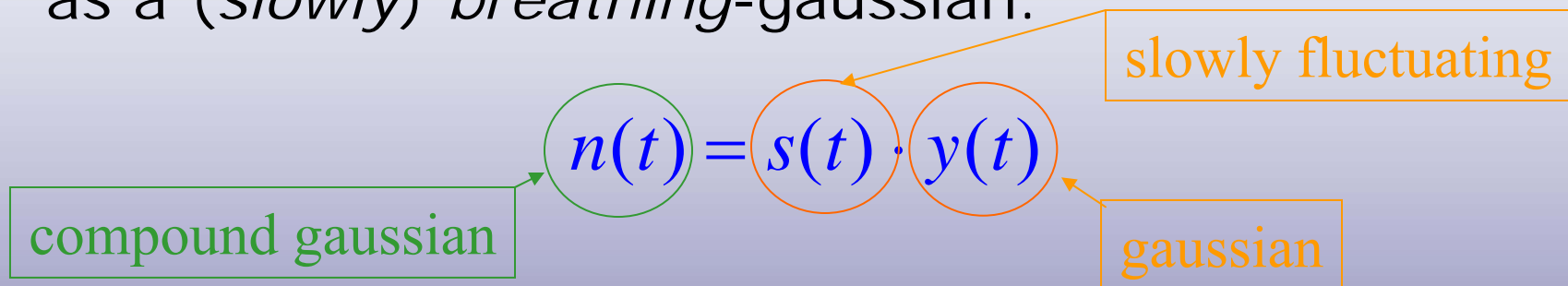
Structure of (locally) optimum detector in SIRP is known. [E. Conte et al., IEEE Trans. COM-43, 47, 1995.]



SIRP Modeling of IFO noise, cont.d

Facts

IFO noises (power lines & clicks removed) looks as a (*slowly*) *breathing*-gaussian:



- *Short data chunks* are still gaussian. *But* variance fluctuates randomly among different chunks (*stationarity lost*).
- *Long series* *not* gaussian (*gaussianity lost, but eventually stationarity recovered*).

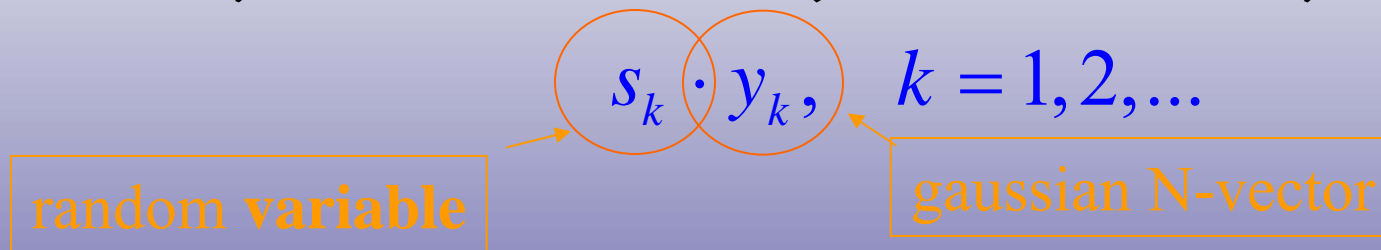


SIRP Modeling of IFO noise, cont.d

SIRP defined

Assume noise variance does *not* fluctuate across a typical time span T .

Each and any chunk of data with size N (i.e., duration T) can be written (k =chunk index)



SIRP noise: chunks can be regarded as different *realizations* corresponding to *different values* of s drawn from *the same* distribution.



SIRP Modeling of IFO noise, cont.d

Assume sought signals *shorter* than T (fluctuation scale of noise variance)

Possible Strategies

Adopt std. MF, and compute *threshold* from *locally estimated* noise variance (**heuristic**)

Neyman Pearson strategy: *condition* likelihood ratio under H_0 and H_1 w.r.t. to random s , and *weight* resulting *detection statistic* using known PDF of s (SIRP).

Resulting detector is **canonical** and **CFAR optimum** [Conte et al., IEEE Trans CT-43, 47 (1995)]



SIRP Modeling of IFO noise, cont.d

Testing & characterizing (white) SIRPs

SIRP noise m -tuples ($m \leq N$) share the following unique properties :

- The related m -tuples $\xi_m = \mathbf{g} / |\mathbf{x}_m|$ fill *uniformly* the unit-radius m -sphere;

- The related m -tuples $\rho_m = |\mathbf{x}_m|$ are distributed according to

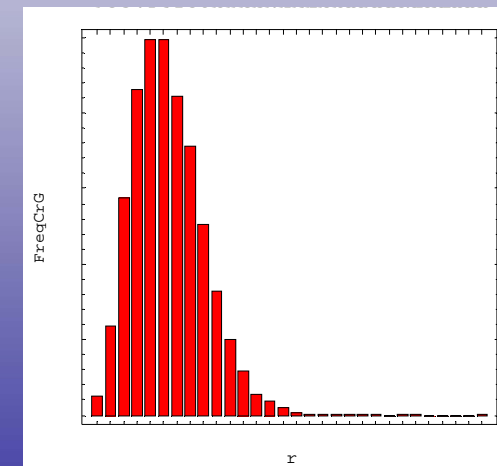
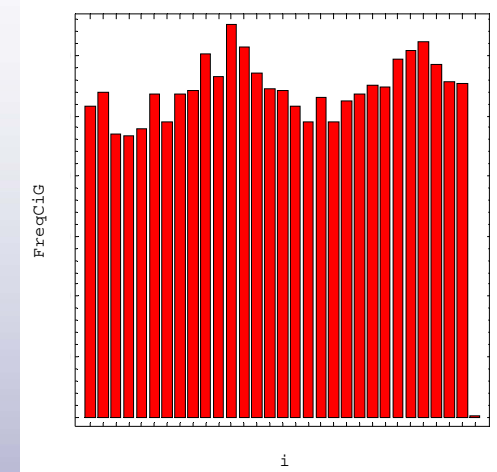
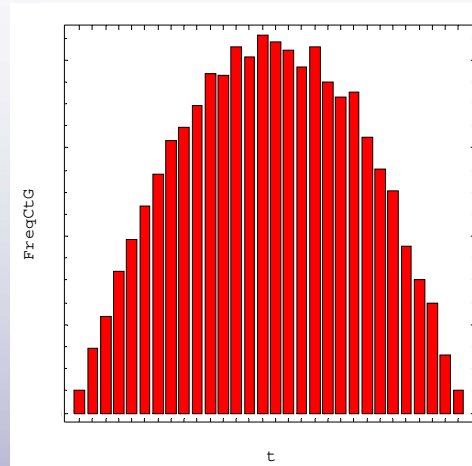
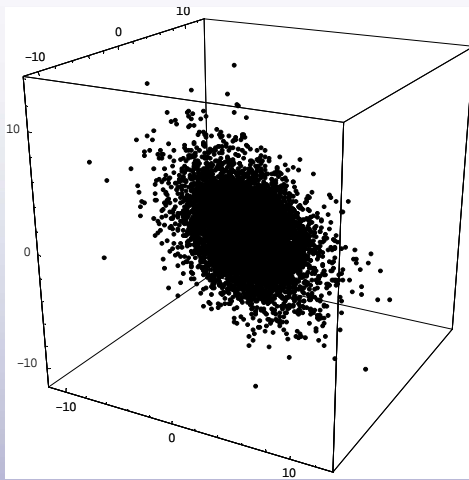
$$f_\rho(\rho) = \frac{2^{1-m/2} \rho^{m-1}}{\Gamma(m/2)} \int_0^\infty s^{-N} \exp\left(-\frac{\rho^2}{2\lambda^2}\right) f_s(s) ds$$

$f_s(s)$ bein the PDF of the *breathing factor* s



SIRP Modeling of IFO noise, cont.d

EVIDENCE (TAMA300 DT2-R012)



Top left: 3D scatter plot (data triples);

Top mid & right: distribution (histogram) of polar angles t and i (spherically uniform, SIRP hallmark);

Bottom right: distribution (histogram) of polar radius r . Should be Rayleigh if noise were gaussian.



Signum-Coded (1 bit) data

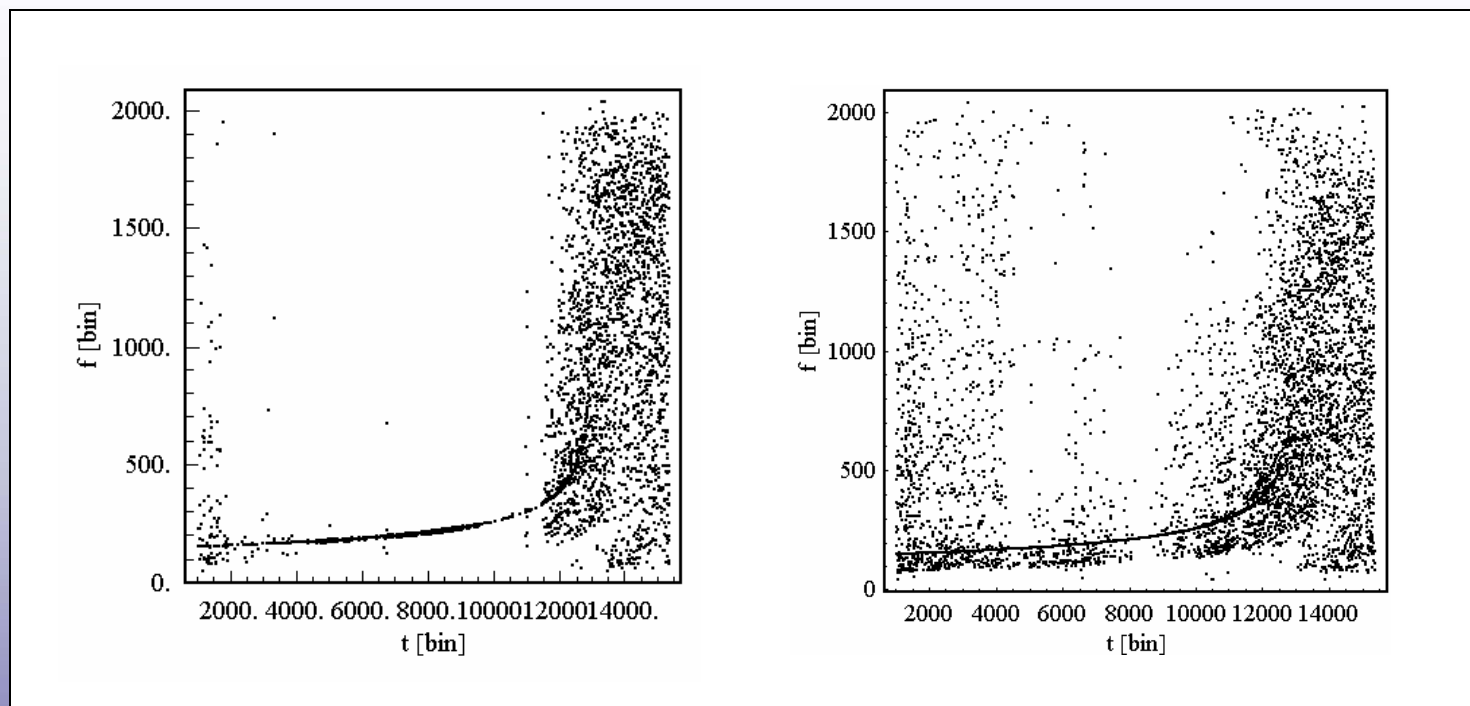
1-bit data coding (signum-coding) entails huge savings in storage and CPU budget.

Performance degradation predicted and observed
[J.H. Miller, J.B. Thomas, IEEE Tr. **COM-25**,
687, 1977.]

Trades off with improved robustness w.r.t. poorly modeled noise features [S.A. Kassam, IEEE Tr. **IT-22**, 22, 1976]



Signum-Coded data, contd.



Thresholded equalized Wigner-Ville t-f image.
2PN (MACHO) chirp in TAMA-DT2 noise, $d=24$.
Left: full data; right: signum-coded (1 bit) data
[R.P. Croce, PhD thesis, Univ. of Salerno, 2001]



Signum-Coded data, contd.

Gaussian noise *mixture*

$$n(t) = \alpha n_1(t) + (1 - \alpha) n_2(t),$$

$$n_i(t) = N(0, \sigma_i^2), \quad 0 \leq \alpha \leq 1$$

Detection statistics

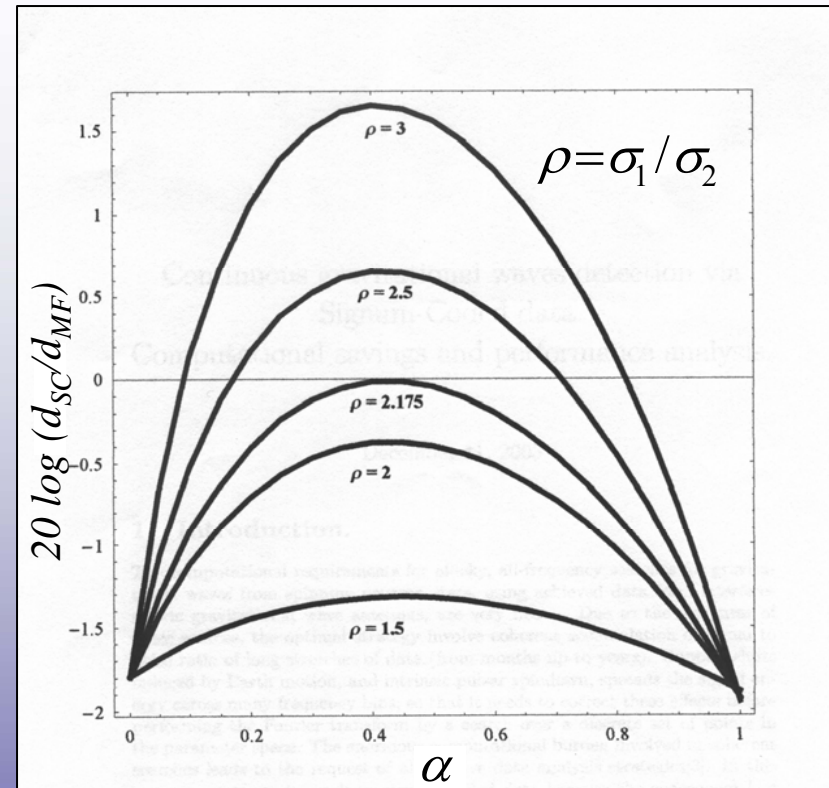
$$S_{MF} = \sum_k y_k s_k$$

y_k
s_k
template
data

$$S_{SC} = \sum_k \text{sgn}(y_k) \text{sgn}(s_k)$$

Performance-index:

$$d = \frac{\mu_S(H_1) - \mu_S(H_0)}{\sqrt{[\sigma_S^2(H_1) + \sigma_S^2(H_0)]/2}}$$



Signum coded detector vs. standard. Matched-Filter
In additive gaussian mixture.
[R.P. Croce et al., in progress].



Past work

Correlator bank economization

Tanaka-Tagoshi chirp parameterization

Cumulative distribution of bank supremum

Binary stars with large eccentricity

Symmetry-breaking based detectors

Time-frequency data analysis

Radiation-pressure driven chaos in MPFP

GW-related, last 10 years



Past work

Correlator bank economization

Main results: *explicit correlator-interpolation formula using close-to-theoretical minimum number of correlators for a miscribed minimal match.*

R. P. Croce, Th. Demma, V. Pierro, I. M. Pinto, D. Churches, B. S. Sathyaprakash, "*Gravitational wave chirp search: Economization of post-Newtonian matched filter bank via cardinal interpolation*", Phys. Rev. **D62**, 121101R (2000).

R. P. Croce, Th. Demma, V. Pierro, and I. M. Pinto, F. Postiglione, "*Nearly Minimum redundant correlator interpolation formula for gravitational wave chirp detection*", Phys. Rev. **D62**, 124020 (2000).



Past work

Tanaka-Tagoshi chirp parameterization

Main results: recipe for constructing uniform & Minimally sparse PN – 2 order template lattice for *any* prescribed minimal match.

R. P. Croce, Th. Demma, V. Pierro, I. M. Pinto, "*Tanaka-Tagoshi parameterization of post-1PN spin-free gravitational wave chirps: Equispaced and cardinal interpolated lattices for first generation interferometric antennas*", Phys. Rev. **D64**, 042005 (2001).

R. P. Croce, Th. Demma, V. Pierro, I. M. Pinto, "*More on the Tanaka-Tagoshi parameterization of post-1PN spin-free gravitational wave chirps: Equispaced and cardinal interpolated lattices*", Phys. Rev. **D64**, 087101 (2001).

R. P. Croce, Th. Demma, V. Pierro, I. M. Pinto, "*Optimum placement of post-1PN gravitational wave chirp templates made simple at any match level via Tanaka-Tagoshi coordinates*", Phys. Rev. **D65**, 102003 (2002).



Past work

Cumulative distribution of correlator bank supremum (ML detection statistic).

Main results: accurate approximate representation of whole-bank supremum CDF including covariance among nearby correlators;

R. P. Croce, Th. Demma, M. Longo, S. Marano, V. Matta, V. Pierro, I.M. Pinto, *"Gravitational wave chirp search: no-signal cumulative distribution of the maximum likelihood detection statistic"*, CQG, **20**, S803 (2003).

R. P. Croce, Th. Demma, M. Longo, S. Marano, V. Matta, V. Pierro, I.M. Pinto, *"How many templates for GW chirp detection? The minimal-match issue revisited"*, CQG, **21**, 4995 (2004).

R. P. Croce, Th. Demma, M. Longo, S. Marano, V. Matta, V. Pierro, and I.M. Pinto, *"Correlator bank detection of gravitational wave chirps: False-alarm probability, template density, and thresholds: Behind and beyond the minimal-match issue"*, Phys. Rev. **D70**, 122001 (2004).



Binary stars with large eccentricity **Past work, contd.**

Main results: fast/accurate GW waveform representations from highly elliptical binaries, including spectral truncation error formulae;

V. Pierro and I.M. Pinto, *"Exact solution of Peters Mathews equations for any orbital eccentricity"*, Nuovo Cimento **B111**, 631, 1996.

V. Pierro and I.M. Pinto, *"Steady state population statistics of compact binary stars"*, Astrophys. J., **469**, 272, 1996.

V. Pierro, I. M. Pinto, A. D. Spallicci, E. Laserra and F. Recano, *"Fast and accurate computational tools for gravitational waveforms from binary stars with any orbital eccentricity"*, MNRAS, **325**, 358 (2001).



Past work, contd.

Symmetry-breaking based detectors

[Stochastic Resonance etc]

Main results: performance never better than std. MF, but much cheaper and robust; wider class of SBB detectors (Kac polys) under investigation;

R. P. Croce, Th. Demma, V. Galdi, V. Pierro, and I. M. Pinto, F. Postiglione, *"Rejection properties of stochastic-resonance-based detectors of weak harmonic signals"*, Phys. Rev. **E69**, 062104 (2004).

V. Galdi, V. Pierro, and I. M. Pinto, *"Evaluation of stochastic-resonance based detectors of weak harmonic signals in additive white Gaussian noise"*, Phys. Rev. **E57**, 6470 (1998).



Past work, contd.

Time-frequency data analysis

Main results: parametric (chirps, Hough-Radon estimator) and non-parametric (bursts, Kolmogorov-Smirnov test) data sieving, based on Wigner-Ville time-frequency representation.

M. Feo, V. Pierro, I.M. Pinto, M. Ricciardi, *"Efficient GW chirp detection and estimation via time-frequency analysis and edge detection"*, Proceedings MG- VII, T. Jantzen et al. Eds., World Scientific, 1994, pp. 1986-1090.

M. Feo, V. Pierro, I.M. Pinto, M. Ricciardi, *"Efficient GW chirp estimation via Wigner-Ville representation and generalized Hough transform"*, in Gravitational Waves, F. Fiducaro ed., World Scientific, 1997, pp. 291-294.

...work done in the perspective of Eternity...



Past work, contd.

Radiation-pressure driven chaos in Multi-Pendular Fabry-Perots

Main results: Chaotic dynamics and multistability of freely swinging multipendular FP due to radiation Pressure nonlinearity w. mirror position

V. Pierro, I.M. Pinto, *"Radiation pressure induced chaos in multipendular Fabry-Perot resonators"*, Phys. Lett. **A185**, 14 (1994); *ibid.* **A193**, 493 (1994).



More about us

Faculty:

Innocenzo M. Pinto (professor, Sannio U.)
Maurizio Longo (professor, Salerno U.)
Vincenzo Pierro (associate prof., Sannio U.)
Vincenzo Galdi (associate prof., Sannio U.)
Stefano Marano (assistant prof., Salerno U.)
Vincenzo Matta (assistant prof., Salerno U.)

PostDoc

Rocco P. Croce (Sannio U.)
Theo Demma (Sannio U.)



www.thewavesgroup.unisannio.it

Pierro



Galdi



Marano



Matta



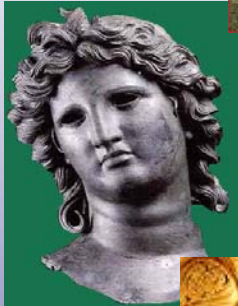
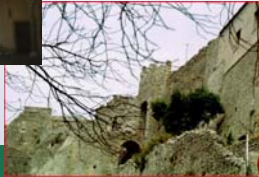
Croce



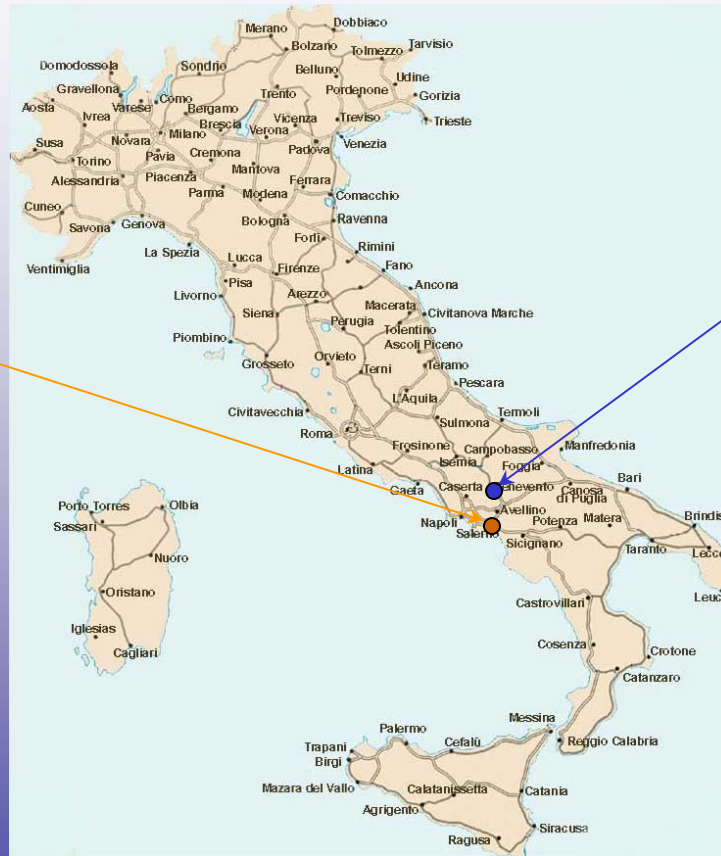
Demma



More about us, contd.



Salerno



Benevento



ASPEN 2005
GWADW

More about us, contd.



University of Salerno
www.unisa.it

40.000 students, 9 Faculties



Salerno University Campus



University of Sannio
at Benevento
www.unisannio.it

6.000 students, 4 Faculties



Sannio University Buildings



More about us, contd.

C. BRADASCHIA, R. DEL FABBRO, A. DI VIRGILIO, A. GIAZOTTO, H. KAUTZKY, V. MONTELATICI, D. PASSUELLO, A. BRILLET, O. CREGUT, P. HELLO, C.N. MAN, P.T. MANH, A. MARRAUD, D. SHOEMAKER, J.Y. VINET, F. BARONE, L. DI FIORE, L. MILANO, G. RUSSO, J.M. AGUIRREGABIRIA, H. BEL, J.P. DURUISSEAU, G. LE DENMAT, Ph. TOURRENC, M. CAPOZZI, M. LONGO, M. LOPS, I. PINTO, G. ROTOLI, T. DAMOUR, S. BONAZZOLA, J.A. MARCK, Y. GOURGHOULON, L.E. HOLLOWAY, F. FULIGNI, V. IAFOLLA, G. NATALE;

The Virgo project : a wide band antenna for gravitational wave detection.

Nuclear Instruments and Methods in Physics Research **A289**, pp 518-525, 1990



More about us, contd.



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".

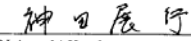
1. The TAMA Project, Japan, is a cooperation consisting among others of the following Institutions: National Astronomical Observatory (NAO); the Institute of Cosmic Ray Research (ICRR); The University of Tokyo, the Institute of Laser Science (ILS); the High Energy Accelerator Research Organization (KEK), 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 recombinant 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


Nobuyuki Kanda
TAMA Data Analysis Group Leader


Innocenzo M. Pinto
The Waves Group Principal Investigator

Date Feb. 9, 2000

Date 10 Feb. 2000



More about us, contd.

IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 53, NO. 2, FEBRUARY 2005

Ray-Chaotic Footprints in Deterministic Wave Dynamics: A Test Model With Coupled Floquet-Type and Ducted-Type Mode Characteristics

Giuseppe Castaldi, Vincenzo Fiumara, Vincenzo Galdi, *Member, IEEE*, Vincenzo Pierro, Innocenzo M. Pinto, *Member, IEEE*, and Leopold B. Felsen, *Life Fellow, IEEE*

IEEE TRANSACTIONS ON SIGNAL PROCESSING, VOL. 51, NO. 2, FEBRUARY 2003

Sequential Testing of Sorted and Transformed Data as an Efficient Way to Implement Long GLRTs

Stefano Marano, Peter Willett, *Senior Member, IEEE*, and Vincenzo Matta

IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 53, NO. 2, FEBRUARY 2005

Radiation Properties of Planar Antenna Arrays Based on Certain Categories of Aperiodic Tilings

Vincenzo Pierro, Vincenzo Galdi, *Member, IEEE*, Giuseppe Castaldi, Innocenzo M. Pinto, *Member, IEEE*, and Leopold B. Felsen, *Life Fellow, IEEE*



More about us, contd.

Dedicated Simulation Facilities

- 16xCPU PIII/1GHz, (1GBRAM+250GBHD)/node under LINUX/MOSIX;
- QUAD C6701 FP-DSP board+dev.kit;
- TMS XP-30 double-ASIC DSP-board (in progress).



Conclusions

Exploring *new strategies & sharpening old ones*

Experimental merging between physics and engineering cultures and communities;

*Heard melodies are sweet
but those unheard are sweeter*

[John Keats, 1795-1821]

