APPLICATION FORM – Internet Version (issued January 2000)

NATO SCIENCE PROGRAMME
Cooperative Science and Technology Sub-Programme
COLLABORATIVE LINKAGE GRANT
NATO Scientific Affairs Division, Bd. Leopold III, B-1110 Brussels, Belgium
fax +32 2 707 4232 : e-mail science@hq.nato.int

Enter Scientific Area - PST  LST  EST  or  SST  : (See Notes for Applicants paragraph 22)

1. PROJECT TITLE (maximum ten words): Orthogonal Polynomials: Theory, Applications, and Generalizations

2. PRINCIPAL INVESTIGATORS* (curriculum vitae to be provided for each one - see attached form)

(i) Project Coordinator from a NATO country:
Surname/First Names(s)/Title: Geronimo, Jeffrey/Professor of Mathematics
Institute and Address: School of Mathematics, Georgia Institute of Technology, Atlanta, GA 30332-0160 USA
Telephone/Fax/E-mail: (404)894-4747/(404)894-4409/geronimo@math.gatech.edu

(ii) Project Coordinator from a Partner country:
Surname/First Name(s)/Title: Aptekarev, Alexandre/Professor, Doctor of Physics and Mathematics Sc.
Institute and Address: Keldysh Institute of Applied Mathematics, RAS, Miusskaya Pl. 4, Moscow 125047, Russia
Telephone/Fax/E-mail: 7-095-2507856/7-095-9729737/aptekaa@keldysh.ru

(iii) Other Principal Investigators if any (list group leaders of any other collaborating teams)
Surname   First Name(s)    Title    Institute and Address    Telephone/Fax/E-mail
Van Assche, Walter.  Dr.  Katholieke Universiteit Leuven, Celestijnenlaan 200 B
Celetijnienlaan 200 B
B-3001 Leuven, Belgium 32-16327051/32-16327998
walter@wis.kuleuven.ac.be

Lopez-Lagomasino, Guillermo Dr.  Universidad Carlos III de Madrid
C/ Universidad, 30, 28911 Legan'es-Madrid, Spain 34-916249097 / 34-916249129
lago@math.uc3m.es

Golinskii, Leonid Dr.  Inst. of Low Temperature, UAS
47 Lenin Ave., Kharkov 61103, Ukraine (380-572)308-566 / (380-572)335-593
golinskii@ilt.kharkov.ua

3. SCIENTIFIC CODES and Percentage of discipline content
(see classification of scientific subjects at Annex to Notes for Applicants)

<table>
<thead>
<tr>
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<th>02</th>
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</table>

4. PROJECT KEYWORDS (maximum 15) Orthogonal polynomial, Riemann-Hilbert technique, potential theory, turning point theory, rational approximation, integrable system, two variable polynomials

5. SUPPORT REQUESTED: (a) and (b) – for visits abroad (add separate page if necessary)  

<table>
<thead>
<tr>
<th>Enter Names, Destinations and Duration of Visits of all Investigators</th>
<th>(a) Travel</th>
<th>(b) Living</th>
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<tr>
<td>J. Geronimo: to Belgium, Spain, Russia, duration 2 weeks</td>
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<td>A. Aptekarev: to USA, duration 2 weeks</td>
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<td>500</td>
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<tr>
<td>W. Van Assche: to USA, duration 2 weeks</td>
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<td>500</td>
</tr>
<tr>
<td>G. Lopez-Lagomasino: to USA, duration 2 weeks</td>
<td>1,100</td>
<td>500</td>
</tr>
<tr>
<td>L. Golinskii: to USA, duration 2 weeks</td>
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<td>500</td>
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<tr>
<td>See separate sheet</td>
<td>11,400</td>
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<td>Sub-Total</td>
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<td>(b) 8,000</td>
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<th>(a) Travel</th>
<th>(b) Living</th>
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</thead>
</table>

(c) Other Expenditure - Partner countries only  (See para. 18 of Notes for Applicants. Specify type and cost of any small scientific equipment, and justify its necessity to the project. Funding for computers and peripherals is not available.)

<table>
<thead>
<tr>
<th></th>
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</thead>
</table>

(c) 5,400

Total (a) (b) (c) 25,000

* Please note that names, affiliations and e-mail addresses may be published by NATO in the context of providing information on the Science Programme. Inclusion of these details here implies authorisation for their use for this purpose.
<table>
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<td>E. Rakhmanov</td>
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<td>600</td>
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<tr>
<td>K. T. McLaughlin</td>
<td>Belgium, Russia</td>
<td>2 weeks</td>
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<td>600</td>
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<tr>
<td>D. Lubinsky</td>
<td>Russia, Ukraine</td>
<td>2 weeks</td>
<td>1,200</td>
<td>600</td>
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<td>H. Woerdeman</td>
<td>Belgium, Spain</td>
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<td>1,200</td>
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</tr>
<tr>
<td>J. S. Dehesa</td>
<td>USA</td>
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<td>1,100</td>
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<tr>
<td>A. Duran</td>
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<td>F. Marcellan</td>
<td>USA</td>
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<td>A. Martinez</td>
<td>USA</td>
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<td>A. Kuijlaars</td>
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<tr>
<td>V. Kaliagin</td>
<td>USA</td>
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<td>Sub-Totals</td>
<td></td>
<td>(a) 11,400</td>
<td>(b) 5,400</td>
<td></td>
</tr>
</tbody>
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6. **RESEARCH PLAN** Describe the current state-of-the-art, outline objectives and methods of investigation, and give relevant references

a. Please provide a summary of about 200 words

The purpose of the NATO project is to bring together expert researchers in the United States, Western Europe, and the Partner countries of Russia and Ukraine some of whom are already collaborating within the framework of a large INTAS project. The backbone of the project is the development of the asymptotical theory of orthogonal polynomials, as well as their generalizations, such as multiple orthogonal polynomials, Sobolev orthogonal polynomials, and multivariable orthogonal polynomials. Important tools for the development of this asymptotical theory are the Riemann-Hilbert method, the turning point method, logarithmic potential theory, and the spectral theory for difference equations. Most of the international experts in these areas are members of the project. One of the main objectives is the application of the above theory to random matrices, integrable systems, rational approximants, and quantum mechanical systems.

b. Please provide a full description – (no more than 2 additional pages may be used)

**Current State-of-the-Art**

The asymptotic theory of orthogonal polynomials is an important and powerful tool in modern analysis. Several applications of this tool have recently received world wide attention since they have been used to solve some long standing problems, see P. Deift's recent contribution "Integrable systems and combinatorial theory.” Notices AMS vol. 47N6, 2000, pp. 631-640 and his invited lecture “Uniform asymptotics for orthogonal polynomials” for the International Congress of Mathematicians in Berlin (1998). In the last decade this theory has been reinvigorated by completely novel techniques as well as the advancement of existing techniques, namely the Matrix Riemann-Hilbert approach, the Szegö-Bernstein approach, the turning point method, trajectories of Abelian quadratic differentials on Riemann surfaces and extremal problems of Logarithmic Potential Theory. Also important are the generalizations associated with these techniques such as Vector Potentials, equilibrium under constraints and external fields, and applications to diverse areas such as random matrix theory, number theory, integrable systems, and rational approximation. Thus the project has scientific significance due to recent international interest. It should be noted that all the European and partner countries investigators are currently supported by a large INTAS grant (number INTAS 00-272) which has resulted in more than 60 publications in top quality journals. This NATO grant would allow that collaboration to continue as well as add an American component. Results in the areas described below have been the work of many people, however, due to lack of space we shall mainly emphasize the work of the grant participants.

The Matrix Riemann-Hilbert approach has had wide success in obtaining a complete asymptotic development uniformly in the complex plane for orthogonal polynomials whose weight function is given by \(\exp(-Q_{2m}(x))\). Here \(Q_{2m}\) is a polynomial of degree \(2m\) in \(x\). McLaughlin has been a pioneer in this area. For instance, besides the above problem McLaughlin and coworkers have applied this technique to obtain asymptotics for polynomials orthogonal with respect to non-analytic weights given by \(\exp(-|x|^\alpha)\), while Kuijlaars, McLaughlin, Van Assche and coworkers have obtained strong asymptotics uniformly in the complex plane for analytic perturbations of Jacobi weights. An important problem that will be considered by the group is how to extend Riemann-Hilbert techniques to obtain asymptotics for polynomials orthogonal with respect to discrete weights. The Riemann-Hilbert technique has been extended to multiple orthogonal polynomials and to complex weights by Van Assche, Geronimo, Kuijlaars, and Aptekarev. Intimately linked to the asymptotics obtained by the Riemann-Hilbert approach is the theory of logarithmic potentials with external fields. One of the pioneers in this area is Rakhmanov. Work is being carried out (Aptekarev, Rakhmanov, Martinez) to extend this area to vector potentials with external fields so that it may be applied to multiple orthogonal polynomials. Important in the area of multiple orthogonal polynomials is to determine when the orthogonality relations give a unique solution. Such systems are called normal and work is continuing (Rakhmanov, Lopez) in this area. Extensions of the classical approach of Szegö-Bernstein have been developed by Lubinsky and coworkers so that now asymptotics and bounds for a very general class of orthogonal polynomials are available. An important property of orthogonal polynomials is the electrostatic interpretation of their zeros. This is being pursued by Marcellan, Martinez, and Rakhmanov. Polynomials orthogonal on the real line also satisfy a three term recurrence formula and the coefficients in the recurrence formula determine the polynomials and their weight function. Aptekarev, Duran, Geronimo, Kaliagin, and Van Assche have been active in obtaining results in this direction even when coefficients are complex, matrices, or operators. Important new developments have been obtained by the group around Barry Simon and these need to be developed and extended. Recently a turning point theory for difference equations analogous to that of differential equations has been developed. This allows (Geronimo, Van Assche) a development of strong asymptotics for orthogonal polynomials with unbounded recurrence coefficients. In particular asymptotics for classes of polynomials orthogonal with respect to discrete weights can now be obtained.

Polynomials orthogonal on the unit circle continue to be an area of investigation (Geronimo, Golinskii, Lopez). Investigations are continuing into the relation between properties of the recurrence coefficients and the orthogonality measure, in particular how to characterize and obtain bounds on the discrete component of the measure beginning with the recurrence coefficients. Also important here is the description of the support of the orthogonality measure.

Work will continue on two variable polynomials orthogonal on the bicircle. (Geronimo, Woerdeman) Recent results have lead to the first non-trivial extension of the celebrated Fejer-Riesz lemma on the factorization of positive one variable trigonometric polynomials. With these results lies the possibility of extending the Riemann-Hilbert technique to two variables. An important aspect in the above development is the emphasis on the connection between certain classes of two variable polynomials and Matrix Orthogonal polynomials on the unit circle. Experts on matrix
It is important to apply and extend the above results to polynomials orthogonal with respect to varying weights (Aptekarev, Kuijlaars, Lopez, McLaughlin, Van Assche). These results have application to the theory of random matrices (McLaughlin, Kuijlaars). Another interesting extension is to polynomials orthogonal with respect to varying recurrence coefficients (Aptekarev, Geronimo, Kuijlaars, Van Assche). A generalization of the above is to polynomials orthogonal with respect to Sobolev norms (Aptekarev, Marcellan, Martinez, Van Assche). In particular it might be possible to use these polynomials and the method of intertwining multiresolution analysis to construct smooth compactly supported wavelets that are orthogonal in the Sobolev norm (Geronimo, Marcellan).

A useful application to quantum physics is the computation of entropy associated with orthogonal polynomials (Aptekarev, Dehesa, Martinez, Van Assche).

Other applications that have been pursued are to apply the techniques of orthogonal polynomials to study integrable systems such as the Toda lattice (Aptekarev, Van Assche), two dimensional autoregressive models (Geronimo, Woerdeman), and Rational and Pade approximation (Aptekarev, Kaliagin, Lopez Lagomasino, Martinez, Rakhmanov).

Objectives and Methods of Investigation

a) Asymptotics and bounds for orthogonal polynomials. This will be the backbone of the project. To obtain new results here we will extend the classical Bernstein-Szegö approach and develop new techniques, namely the Riemann-Hilbert approach from complex analysis of matrix-valued analytic functions and Turning point theory (from the asymptotic theory of differential equations). Special attention will be paid to polynomials orthogonal with respect to varying weights and complex weights. Also to be considered are orthogonal polynomials obtained by varying recurrence coefficients.

Tasks (see description and abbreviations for the teams in Section 7 below)

a.1 To obtain strong asymptotic formulas for polynomials orthogonal with respect to discrete weight using the Riemann-Hilbert technique [teams A, B, C].

a.2 To obtain strong asymptotics for solutions of second order difference equations using turning point theory [teams A, B, C].

a.3 To obtain a connection between varying weights and varying recurrence coefficients. To give conditions on the recurrence coefficients that allows the existence of limits of varying weights [teams A, B, C].

a.4 Use the Szegö-Bernstein approach to obtain bounds for orthogonal polynomials on the real line and on the circle [teams A, B, E]

b) Generalizations of orthogonal polynomials. The theory of Multiple Orthogonal Polynomials (or so called Hermite-Pade polynomials) will be studied with emphasis on developing the Riemann-Hilbert approach for Multiple Orthogonal polynomials and vector potentials with external fields. Another generalization will be the study of several variable orthogonal polynomials. In particular our interests are the algebraic and analytic properties of these types of polynomials and their connection with matrix orthogonal polynomials and two variable Riemann-Hilbert problems. We will also investigate polynomials orthogonal with respect to a Sobolev inner product with attention to applications to wavelets and zero distribution.

Tasks

b.1 Prove existence of solutions of extremal problems for vector potentials with external fields obtained from multiple orthogonal polynomials. Prove normality for various systems of multiple orthogonal polynomials [teams A, B, C, D].

b.2 Construct wavelets based on Sobolev orthogonal polynomials [teams A, D].

b.3 To determine the relation between the reflection coefficient of matrix polynomials orthogonal on the unit circle and the reflective coefficients of the associated two variable orthogonal polynomial [teams A, D, E].

c) Applications. One of the main objectives is to develop applications of the above theory. Important applications of the asymptotic theory of orthogonal polynomials are to the study of random matrices and integrable systems. Rational and Pade approximants have a classical as well as modern connection with the theory of orthogonal polynomials. Other areas of application are spectral theory and scattering for difference operators, numerical analysis, number theory, and special functions.

Tasks

c.1 Compute the entropy associated with various classes of orthogonal polynomials [B, C, D].

c.2 Compute the Fredholm determinant for random matrices associated with Jacobi weights [A, C].

c.3 To obtain the asymptotic series for the rate of convergence of best rational approximants for an analytic function [teams A, B, C, D].

Scientific references (selected)

7. INTERNATIONAL COOPERATION Describe the roles to be played by each research team. State the importance of this cooperation for the project and justify the visits to be made by each scientist.

1. One of the objectives of the project is to bring the USA team together with 4 European teams (two from Western Europe and two from Eastern Europe) who already have an intensive international collaboration within the framework of a large scale INTAS project 2000-272.

2. Teams description. Justification of the visits

A. The USA research team has strong expertise in developing modern methods of investigation of asymptotics for Orthogonal Polynomials and Applications. J. Geronimo (he participates in tasks a.2, a.3, b.2, b.3) is a leading expert in "turning point methods" for analysis of asymptotics for solutions difference equations, including Orthogonal Polynomials. K. McLaughlin (he participates in tasks a.1, c.2) is a leading expert in "Riemann-Hilbert methods for asymptotics of orthogonal polynomials and applications to "random matrix theory". E. Rakhmanov (he participates in tasks a.3, b.1, c.1, c.3) is a leading expert in "potential theory approach" to asymptotical theory, including modern extensions like matrix potentials, external fields and constraints. D. Lubinsky (he participates in tasks a.4, b.3) is a leading expert in modern extensions of the classical "Bernstein-Szegő theory." H. Woerdeman (he participates in tasks a.4, b.3) is a leading expert in applications to several variables orthogonality and multi-variable factorization.

B. The Russian team has strong expertise in applications of modern asymptotical theory of orthogonal polynomials and solutions of difference equations. A. Aptekarev (he participates in tasks a.1, a.2, a.3, b.1, c.1, c.3) is a leading expert in approximation of analytic functions by rational functions ("best rational approximants, Hermite-Pade approximants"). V. Kaliagin (he participates in tasks a.2, a.4) is a leading expert in spectral theory of difference operators, including non-symmetrical operators.

C. The strength of the Belgium team is in the analytic theory of orthogonal polynomials, recurrence relations, special functions (in this topic W. Van Assche is a leading expert, he participates in tasks a.1, a.2, a.3, b.1, c.1) and complex
analysis, potential theory, and boundary value problems (in this topic A. Kuijlaars is a leading expert, he participates in
tasks a.1, b.1, c.2, c.3).

D. The Spanish team combines a group from Madrid and several Universities from south of Spain. The team has strong
expertise in developing generalization for orthogonal polynomials and applications. G. Lopez (he participates in tasks b.1, b.3, c.3) and A. Martinez (he participates in tasks b.3, b.1, c.1) are leading experts in complex analysis and
approximations. J. Dehesa (he participates in task c.1) is a leading expert in applications of orthogonal polynomials and
special functions to Quantum physics. For generalizations of Orthogonal Polynomials - F. Marecellan (he participates in
task b.2) is a leading expert in “Sobolev orthogonality” and A. Duran (he participates in task b.3) is a leading expert in
“matrix orthogonal polynomials.”

E. The Ukranian team from Kharkov has a strong tradition of research of Orthogonal Polynomials going back to S. Bernstein
works. L. Golinskii (he participates in tasks a.4, b.3) is a leading expert in “Orthogonal polynomials on the unit circle,” in
particular the operator theoretic approach (spectral theory).

3. As noted in the research description there is much overlap in the interests of the various groups and it is important to allow
visits of one to two weeks to encourage coordination and cooperation among the various groups.

4. At the end of the project we are planning to organize a NATO-workshop in Spain (Madrid) to discuss the results obtained during
the project.

8.EXPECTED DURATION OF THE COLLABORATION  (see paragraph 14 of Notes for Applicants)

<table>
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<th>ONE YEAR</th>
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### INVESTIGATORS
(a) Provide below the names of the other Investigators participating in the project who will benefit from NATO funding under this CLG.

<table>
<thead>
<tr>
<th>Name</th>
<th>Discipline</th>
<th>Highest Degree</th>
<th>Affiliation</th>
<th>of time to be spent on project</th>
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<tr>
<td>Duran, Antonio J.</td>
<td>Mathematics</td>
<td>PhD</td>
<td>Universidad de Sevilla, Spain</td>
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<td>Kaliaguine, Valeri</td>
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<td>PhD</td>
<td>The College of William &amp; Mary, USA</td>
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</tbody>
</table>

(b) Have the Project Coordinators or any of the other Principal Investigators or Investigators been supported in the past by a NATO grant? If Yes, give the name(s) and grant number(s)

YES: J. Geronimo and A. Aptekarev  
NATO PST/EV 978797

### REFEREES
Suggest three referees from NATO member countries other than those of Investigators, and provide their complete addresses. Referees should not be former research directors or associates, or postgraduate students of participants.

(a) Marcel de Bruin, Technical University Delft, Faculty of Information Technology and Systems, Department of Applied Mathematical Analysis, P. O. Box 5031, 2600 GA Delft, The Netherlands

(b) Vilmos Totik, Bolyai Institute, University of Szeged, Aradi Vertanuk tere 1, H-6720 Szeged, Hungary

(e) Christian Berg, Institute for Mathematical Sciences, University of Copenhagen, DK-2100 Copenhagen, Denmark  
Phone: (+45) 3532 0728, FAX: (+45) 3532 0704, email: berg@math.ku.dk

### COSTS
Give an estimate, in US$, of the total yearly cost for the research (excluding salaries and costs covered by NATO grant), and indicate sources of support (excluding NATO support).

$12,500

Date: Please ensure that both Project Coordinators sign on Page 1

Note that, for convenience, dollars have been requested for funding estimates in this application; however, the NATO awards are granted and guaranteed only in EURO.
SURNAME : GERONIMO  FIRST NAME(S) Jeffrey

Affiliation and official address: School of Mathematics
Georgia Institute of Technology
Atlanta, GA 30332
404 894 4747/geronimo@math.gatech.edu

Date and place of birth: February 25, 1949 Cairo, Egypt  Nationality: USA

Education (degrees, dates, universities)

Ph.D.  1977  The Rockefeller University
B.S.  1972  S.U.N.Y. at Albany

Career/Employment (employers, positions and dates)

School of Math., Georgia Institute of Technology, Visiting Asst. Prof.  1977-1978
Dept. of Biophysics, The Rockefeller University, Asst. Prof.  1978-1979
School of Mathematics, Georgia Institute of Technology, Visiting Asst. Prof.  1979-1983
Physique Theorique Centre d'Etudes, Nucleaires, Saclay, France,
Visiting Asst. Prof.  1982-1984
School of Math., Georgia Institute of Technology, Assistant Professor,  1986-1991
Physique Theorique Centre d'Etudes, Nucleaires, Saclay, France,
Visiting Prof.  1996—1997
University of Paris VI, Fulbright Scholar  1996-1997
School of Mathematics, Georgia Institute of Technology, Professor  1991-present

Specialization (specify)

(i)  main field  Analysis, complex and harmonic analysis
(ii)  other fields  Mathematical physics
(iii)  current research interest  Orthogonal polynomials in and and several variables

Honours, Awards, Fellowships, Membership of Professional Societies

Best Thesis Advisor, Georgia Tech 1996
Fulbright Scholarship  1996-1997
Latest NSF Grant: Some problems in Orthogonal polynomials and wavelets 1997-2001

Publications (list selected publications on page 2 of curriculum vitae)

- Number of papers in refereed journals: 60
- Number of communications to scientific meetings: 10
- Number of books: 0
Recent selected publications (additional pages should NOT be attached and reprints should not be enclosed)


SURNAME: APTEKAREV  FIRST NAME(S): Alexandre

Affiliation and official address: Keldysh Institute of Applied Mathematics
Russian Academy of Sciences
Miusskaya Sq. 4, Moscow 125047, Russian Federation
7-095-705-0341

Date and place of birth: 11 March 1955, St-Peterburg (Leningrad), Russia (USSR) Nationality: Russia

Education (degrees, dates, universities)
Diploma of Higher Education (M.A.) 25/1 1977 Moscow State University
Speciality: Physics. (1-1 N 326004, 25/1 1977)
Degree of Candidate of Phys. & Math. Sci. (Ph.D) 19/6 1981 Moscow State University
Diploma (1M N 014727, 25/11 1981)
Speciality: Mathematical Analysis
Degree of Doctor of Physics & Mathematics Sciences (Full D.Sc. Degree) 22/6 1989 Moscow State University
Diploma (1M N 005126) Specialty: Mathematical Analysis

Career/Employment (employers, positions and dates)
Keldysh Institute of Applied Mathematics Leading Scientist (since 1990) 1980-Present
of the Russian (USSR) Academy of Sciences
Moscow State University & Full Professor (since 1999) 1987-Present

Specialization (specify)
(i) main field Analysis – Complex analysis and approximation theory
(ii) other fields Mathematical physics
(iii) current research interest Number theory and dynamic systems

Honours, Awards, Fellowships, Membership of Professional Societies
2001 Prize-grant of Charity Foundation for support of Russian science
2000-2002 Award from the Russian President: "State stipendium for outstanding scientist"
2000-2001 Visiting research senior fellowship (F/99/009) Katolieke Universiteit Leuven, Belgium

Publications (list selected publications on page 2 of curriculum vitae)
- Number of papers in refereed journals: 30
- Number of communications to scientific meetings: 36
- Number of books: 1
Recent selected publications (additional pages should NOT be attached and reprints should not)


