

Weakly Nonlocal Solitary Waves and Beyond-All-Orders Asymptotics

Generalized Solitons and
Hyperasymptotic Perturbation Theory

by

John P. Boyd

*University of Michigan,
Ann Arbor, Michigan, U.S.A.*



KLUWER ACADEMIC PUBLISHERS
DORDRECHT / BOSTON / LONDON

CONTENTS

PREFACE	xvii
Part I OVERVIEW	1
1 INTRODUCTION	3
1.1 The (Classical) Solitary Wave	3
1.2 Weakly Nonlocal Solitary Waves	7
1.3 Definitions	10
1.4 Fifth-Order Korteweg-deVries Eq.	14
1.5 Far Field Analysis: Linearity and the Phase Factor	15
1.6 Phase-Speed Matching and Resonance	18
1.7 Exponential Smallness	21
1.8 Perturbation Methods	22
1.9 Connections	25
1.10 Summary	26
Part II ANALYTICAL METHODS	29
2 THE METHOD OF MULTIPLE SCALES AND THE ϵ-POWER SERIES	31
2.1 Introduction	31
2.2 A Model Problem	32
2.3 The Method of Multiple Scales	33
2.4 Divergence of Multiple Scales	34
2.5 Forced Linear Model: Exact Solutions	37
2.6 The Exponential Smallness of the Radiation Coefficient	38
2.7 The Factorial Rate of Divergence	40

2.8	Divergence As a Function of Wavenumber	41
2.9	Sensitivity to Perturbations	44
2.10	Padé Approximants and Other Summability Methods	44
2.11	Summary	45
3	HYPERASYMPTOTIC PERTURBATION THEORY	48
3.1	Introduction: Superasymptotics, Optimal Truncation and All That	48
3.2	Optimal Truncation and Superasymptotics for the Stieltjes Function	51
3.3	Hyperasymptotics for the Stieltjes Function	54
3.4	Soliton Hyperasymptotics: Outline of Procedure	57
3.5	Hyperasymptotics for Solitons: An Overview	58
3.6	Superasymptotic Assertion	60
3.7	Newton's Iteration	62
3.8	Solving a Forced, Constant Coefficient ODE	64
3.9	Simplifying the Residual: Rearrangement	66
3.10	Simplifying the Residual: Approximations	69
3.11	Extrapolation: ν_0	73
3.12	Optimal Truncation	75
3.13	Extrapolation: ν_1	77
3.14	Summary	78
4	MATCHED ASYMPTOTIC EXPANSIONS IN THE COMPLEX PLANE	80
4.1	Perturbation Theory “Beyond All Orders”	80
4.2	A Primer of Matched Asymptotic Expansions	81
4.3	Exponentially Small Reflections	82
4.4	Forced Linear BVP	89
4.5	Borel-Logarithm Function	93
4.6	General Singularities	94
4.7	Nonlinearity	96
4.8	Critique: Complex Plane-Matched Asymptotics	100

5	STOKES' EXPANSION, RESONANCE & POLYCNOIDAL WAVES	106
5.1	Introduction: Solitons from Sine Waves	106
5.2	Stokes' Expansions	108
5.3	Stokes' Expansion: Radius of Convergence	112
5.4	Stokes' Expansion: Accuracy	114
5.5	Resonant Stokes' Expansion	116
5.6	Regimes of the FKdV Cnoidal Wave	122
5.7	Polycnoidal waves and resonance	127
6	THEOREMS AND PROOFS: EXISTENCE NON-EXISTENCE & SYMMETRY	132
6.1	Introduction	132
6.2	Formal Methods: Perturbation Theory and Numerical Methods	133
6.3	Nonexistence Theorems and Other Negative Results	133
6.4	Existence of Nanopterons	135
6.5	Symmetry	136
Part III NUMERICAL METHODS		139
7	PSEUDOSPECTRAL AND GALERKIN METHODS	141
7.1	Introduction	141
7.2	Choice of Basis Set	145
7.3	Multidimensional Basis Sets	149
7.4	Accuracy: Geometric and Subgeometric	150
7.5	Iteration	155
7.6	Partial Summation and the Fast Fourier Transform	157
7.7	Embedding Pseudospectral Algorithms in Finite Difference or Finite Element Codes	159
7.8	Parity and Other Discrete Symmetries	159
7.9	Continuous Symmetries: Translation and Dilation	161
7.10	A Worked Example	164
7.11	Travelling Kinks and Solitary Waves That Asymptote to Constants	167

7.12	Modons and Peakons	169
7.13	Summary	170
8	NONLINEAR ALGEBRAIC EQUATIONS	172
8.1	Introduction: Initialize, Continue, Iterate	172
8.2	A Tale of Two Flows: the Davidenko Predictor and the Newton Corrector	175
8.3	Initialization	177
8.4	Continuation	182
8.5	Branch-Crossing and Fold Points	189
8.6	Newton's Iteration: Basic Properties	195
8.7	Minimizing Residual Norm	197
8.8	The Geometry of Phase Space	197
8.9	Newton's Iteration: Underrelaxation	198
8.10	Tunneling Away from a Minimum of the Residual Norm	203
8.11	Quasi-Newton Methods	208
8.12	Non-Newtonian Iterations	212
8.13	Direct Methods for Special Low Order Systems	219
8.14	Summary	222
9	SPECIAL ALGORITHMS FOR EXPONENTIALLY SMALL PHENOMENA	224
9.1	Introduction	224
9.2	Fourier methods	225
9.3	Infinite interval, I: The triumph and folly of pure rational Chebyshev basis	229
9.4	Infinite interval, II: The radiation basis function	232
9.5	Infinite interval, III: Cnoidal matching	235
9.6	Sensitivity	238
9.7	Summary	239
Part IV	APPLICATIONS	241
10	WATER WAVES: FIFTH-ORDER KORTEWEG-DEVRIES EQUATION	243
10.1	Introduction	243

10.2	A generic derivation and scaling of the FKdV equation	246
10.3	Multiple Scales Perturbation Theory	250
10.4	Parameters: ϵ , Phase Speed and Φ	255
10.5	Eigenfunctions and resonant phase shifts	257
10.6	Symmetry	262
10.7	Complex Plane Matched Asymptotics	264
10.8	Numerical Solutions: FKdV	265
10.9	Radiatively Decaying FKdV Solitons	268
10.10	Bound States of Solitons	269
10.11	Water Waves	271
11	ROSSBY & INTERNAL GRAVITY WAVES: NONLOCAL HIGHER MODES	279
11.1	Introduction	279
11.2	Model Equations	283
11.3	Eigenfunction Expansions, the Method of Multiple Scales, and the KdV Equation	285
11.4	Two-Mode (Coupled-KdV) Model	289
11.5	Improved Single-Mode Model: The Korteweg-deVries Equation with Mixed Cubic and Quadratic Nonlinearity	292
11.6	Variations on a Theme: One-Mode & Two-Mode Models for Equatorial Rossby Waves	294
11.7	Modified Korteweg-deVries Equation	297
11.8	Magnetic Modons in a Shear Flow	301
11.9	Observations of Nonlocal Gravity and Rossby Waves	302
11.10	Theoretical and Numerical Studies	304
12	THE ϕ^4 BREATHER	306
12.1	Introduction	306
12.2	The Multiple Scales Series	310
12.3	Far Field Analysis	314
12.4	Eigenfunctions	316
12.5	Numerical calculations of the nanopteron and nanopteroidal wave	318
12.6	Radiative Decay of a Localized Initial Condition	321
12.7	Summary	323

13 ENVELOPE SOLITARY WAVES: THIRD ORDER NONLINEAR SCHROEDINGER EQUATION AND THE KLEIN-GORDON EQUATION	325
13.1 Introduction	325
13.2 Optical Solitons	329
13.3 TNLS Equation: An Overview	331
13.4 TNLS Equation: Scaling and Parameters	333
13.5 The TNLS Equation: Perturbation Theory	337
13.6 Periodic Solutions	339
13.7 Eigenfunctions	341
13.8 Numerical calculations of nanopterons	344
13.9 Bions	348
13.10 Radiative Decay in the TNLS Equation	349
13.11 Direct Approach to Envelope Solitons: KG Eq.	352
13.12 The Cubic Klein-Gordon Equation: Special Properties	353
13.13 The Fourier Method in Group and Carrier Coordinates	355
13.14 KG Eq.: Far Field & Phase Condition	357
13.15 Klein-Gordon numerical solutions	360
13.16 Summary	363
14 TEMPORAL ANALOGUES: SEPARATRIX SPLITTING & THE SLOW MANIFOLD	366
14.1 Introduction	366
14.2 Separatrix Splitting for the Perturbed Pendulum	368
14.3 The Slow Manifold: Background	373
14.4 Simplest Model of the Slow Manifold: The LK Quintet	375
14.5 The Slow Manifold: The Method of Multiple Scales & Ambiguity	379
14.6 Dynamical Systems Theory	383
14.7 The Slow Manifold: Summary	384
15 MICROPTERONS	387
15.1 Introduction	387
15.2 The Rotation-Modified Korteweg-deVries (RMKdV) Equation: a One-Dimensional Micropteron	389

15.3	Non-Hydrostatic Gravity Waves with Rotation in Two Horizontal Dimensions: RMKP Equation	396
15.4	The Morning Glory: Internal Gravity Solitons	399
15.5	Modons: Basic Theory for Dipolar Vortices	407
15.6	Tribbia-Verkley-Boyd Nonlocal Modons	412
15.7	Nonlocal Modons: One-Sided, East Wing-Only Vortex Pairs of Swaters	417
15.8	Monopole Vortices	421
15.9	Gulf Stream Rings	422
15.10	Equatorial Rossby: Leakage-to-Barotropic	427
15.11	Summary	429
Part V RADIATIVE DECAY & OTHER EXPONENTIALLY SMALL PHENOMENA		431
16	RADIATIVE DECAY OF WEAKLY NONLOCAL SOLITARY WAVES	433
16.1	Introduction	433
16.2	Perturbation Theory	435
16.3	Near-Soliton Initial Conditions: Analysis of Perturbative Wave Packets	438
16.4	Extensions: Linearity, Forcing, Transience and Breathers	440
16.5	Limitations: Dispersion versus Resonance	443
16.6	Subtleties	446
16.7	Multiple Scales in Time: Derivation of Model Equations for Radiative Damping	447
16.8	An ODE for the Decay of the Amplitude Due to Radiation	449
16.9	Multiple Scales in Time: Micropteron and the Morning Glory	451
16.10	Summary	454
17	NON-SOLITON EXPONENTIALLY SMALL PHENOMENA	455
17.1	Introduction	455
17.2	Dendritic Crystal Growth	455
17.3	Viscous Fingering in a Hele-Shaw Cell (Saffman-Taylor Problem)	459

17.4	Quantum Mechanics	461
17.5	Diffusion on Exponentially Long Time Scales	462
17.6	Steepest Descent: Asymptotic Expansions for Integrals	464
17.7	Numerical Analysis	468
17.8	Isolation of Exponential Smallness, I: Equatorial Kelvin Wave with Critical Latitude and Other Eigenproblems	471
17.9	Isolation of Exponential Smallness II: Laminar Flow in a Porous Pipe or Channel with Suction (Berman-Robinson and Terrill Problems)	476
17.10	Summary	478
18	THE FUTURE	479
A	IDENTITIES: TRIGONOMETRIC, SECH AND TANH	482
A.1	Differentiation Identities	482
A.2	Hyperbolic Identities	484
A.3	Trigonometric Identities	485
B	SECH/TANH PERTURBATION SERIES	486
B.1	Polynomialization	486
C	ELLIPTIC FUNCTIONS	489
C.1	Basic Properties	489
C.2	Elliptic Nome and Modulus	490
C.3	Series: Complete Elliptic Integral and Modulus	491
C.4	Elliptic Functions: Fourier & Imbricate Series	492
C.5	Elliptic Functions: Differentiation Identities	493
C.6	Elliptic Functions: Integration	493
D	SOLITONS AND CNOIDAL WAVES: KDV, MKDV, NLS, MIXED KDV/MKDV	494
D.1	Solitons	494
D.2	Spatially Periodic Solutions	496

E TIME INTEGRATION WITH THE FOURIER PSEUDOSPECTRAL ALGORITHM FOR WAVE EQUATIONS	500
E.1 Spectral Methods and Wave Equations	500
E.2 Time Integration Schemes	500
E.3 Pseudospectral Evaluation of the Right-Hand Side: The Fast Fourier Transform	502
E.4 Complication I: Library Fast Fourier Transform Software	505
E.5 Complication II: Differential Operators Acting on Time Derivatives as in the Regularized Long Wave and Quasi-Geostrophic Equations	506
GLOSSARY	508
REFERENCES	519
INDEX	582