UNIVERSITÀ DEGLI STUDI DI TORINO

MPM SPACE SCIENCES

MASTER MATHEMATICAL AND PHYSICAL METHODS FOR SPACE SCIENCES

Academic year 2019-2020

Courses and seminars

Courses

Analytical methods for the space
Astrophysics
Celestial mechanics and astrodynamics
Data analysis
Detectors and space equipment
Gravitational astronomy and metrology for astrophysics
Innovative mathematical methods for the space
Mission design
Relativistic mechanics

Seminars

A short overview of European Funding Landscape for Maths, Physics and Space Research
Artificial intelligence technology and applications
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Computing Systems and payloads in the cubeSat context
GAIA – Astrometric cosmology
Ground Station Services: the data path from space to cloud
Interferometry in space missions
Persistent homology applications to Complex networks and Neuroscience
Persistent homology of Phase transitions
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Statistical tools for GNSS clocks characterization
STOP (Structural, Thermal, Optical, Performance) Analysis for Euclid Mission
Time metrology and GNSS

Master MPM Space Sciences

Courses and seminars

Academic year 2019-2020

Analytical methods for the space

Susanna Terracini, *Department of Mathematics, Università di Torino*.
Giorgio Fasano, *Thales Alenia Space*.
Andrea Bacciotti.
4 CFU, Mandatory.

MODULUS 1 - Basics of Mathematical Control Theory with applications to orbital optimization

Objectives
This modulus is aimed at introducing the basic concepts mathematica optimal control, with a applications to orbital optimization. This task presents us with these mathematical issues: does an optimal control exist? How can we characterize an optimal control mathematically? How can we construct an optimal control?

Contents
1. Introduction to the mathematical control theory: controllability, bang-bang principle, dynamic programming
2. Examples and applications concerning the control of attitude of satellites and orbital transfer.

References

[1] Lawrence C. Evans, Introduction to Mathematical Optimal Control Theory, Lecture notes, Berkeley Math. 1983

[2] B. Bonnard, L. Faubourg, E. Tré lat, Mé canique cé leste et controle de systè mes spatiaux, Math. & Appl., Vol. 51, Springer Verlag, 2006

MODULUS 2 - Mathematical Modeling & Optimization

Objectives
This modulus is aimed to introduce various topics in space engineering applications, requiring the solution of increasingly hard optimization problems: among the various optimization issues object packing and loading problems and the general spacecraft control dispatch problem are considered. As far as object packing and loading problems are concerned, Operations Research and Computational Geometry perspectives are introduced. In this context of the general spacecraft control dispatch problem a dedicated controller has the task of determining the overall control action, aimed at

achieving (step-by-step) the desired system attitude. A number of thrusters are available to exert the overall force and torque, as required. The positions and orientations of the thrusters have to be optimized, in order to minimize the propellant consumption of the entire mission.

Contents

1. Optimization issues arising in space engineering. Fundamentals of optimization
2. Packing optimization in space: an overall global optimization (GO) approach, based on mixed integer linear and mixed integer nonlinear programming (MIP and MINLP)
3. Control dispatch optimization
4. Applications

References

[1] Becerra, V.M. (2008): Optimal control. Scholarpedia 3(1), 5354

[2] Betts, J.T. (2010): Practical Methods for Optimal Control and Estimation Using Nonlinear Programming. SIAM, Philadelphia

[3] Ciriani, T.A., Fasano, G., Gliozzi, S., Tadei, R. Eds. (2003) Operations Research in Space and Air. Kluwer, Dordrecht

[4] Colasurdo, G., Casalino, L. (2013): Indirect methods for the optimization of spacecraft trajectories. In: Fasano, G., Pintér, J.D. (eds.) Modeling and Optimization in Space Engineering. Springer, New York

[5] Fasano, G. and Pintér, J.D., Eds. (2013) Modeling and Optimization in Space Engineering. Springer New York

[6] Fasano, G. and Pintér, J.D., Eds. (2016) Space Engineering - Modeling and Optimization with Case Studies. Springer, New York

[7] Fasano, G. and Pintér, J.D., Eds. (2019) Modeling and Optimization in Space Engineering - State of the Art and New Challenges. Springer, New York

[8] Floudas, C.A. (2000): Deterministic Global Optimization: Theory, Methods, and Applications. Kluwer, Dordrecht

[9] Floudas, C.A., Gounaris, C.E. (2009): A review of recent advances in global optimization. J. Global Optim. 45, 3-38

[10] Grossmann, I.E. Ed. (1996): Global Optimization in Engineering Design. Kluwer, Dordrecht

[11] Hillier, F.J., Lieberman, G.J. (2005): Introduction to Operations Research, 8th edn. McGraw-Hill, New York

[12] Horst, R., Pardalos, P.M. Eds. (1995): Handbook of Global Optimization, vol. 1. Kluwer, Dordrecht

[13] INFORMS Computing Society (2012). Mathematical Programming Glossary. http://glossary.computing.society.informs.org/

[14] Kirk, D.E. (2004): Optimal Control Theory: An Introduction. Dover, Mineola

[15] Lebedev, L.P., Cloud, M.J. (2003): The Calculus of Variations and Functional Analysis with Optimal Control and Applications in Mechanics. World Scientific, Singapore

[16] Liberti, L., Maculan, N. Eds (2005): Global Optimization: From Theory to Implementation. Springer, New York

[17] Minoux, M. (1986): Mathematical Programming. Theory and Algorithms, Wiley, New York.

[18] Nemhauser, G.L. and Wolsey, L.A. (1988) Integer and Combinatorial Optimization, Wiley, New York

[19] Nocedal, J., Wright, S.J. (2006): Numerical Optimization, 2nd edn. Springer, New York

[20] Pardalos, P.M., Romeijn, H.E. Eds. (2002): Handbook of Global Optimization, vol. 2. Kluwer, Dordrecht

[21] Pintér, J.D. Ed. (2006): Global Optimization: Scientific and Engineering Case Studies. Springer, New York

[22] Williams, H.P. (2013): Model Building in Mathematical Programming, 5th edn. Wiley, Chichester

MODULUS 3 - Optimal control

Objectives

Optimal control is a useful tool in many aeronautic and aerospace applications (transfer of orbit, landing, travel planning and any problem where saving time or energy is a valuable goal).

The objective of this course is to introduce the basic elements of optimal control theory, in the case where the dynamical model is defined by a system of time-invariant, finite dimensional ordinary differential equations.

The main achievements of this theory, the dynamical programming principle and the Pontrjagin maximum principle, are presented. Two representative classical applications are discussed and solved: the linear quadratic regulation problem (on the infinite horizon) and the linear time optimal problem. Preliminary, we recall the fundamental notions and results of the classical calculus of variations, with some extensions. The relationship between the variational approach to the optimization problem and the control theory point of view is studied with some details.

Contents

1. Classical problems of the Calculus of variations. Fundamental Lemma. Euler-Lagrange equation. Legendre transform, Hamiltonian form. Constrained problems (holonomic and nonholonomic constraints). Convex functionals. Free boundary problems and transversality condition
2. Introduction to Control theory for ODE. Reachable set, controllability
3. Formulation of the Optimal control problem. Dynamic programming principle and Pontrjagin maximum principle. Comparison between the Euler-Lagrange equation and the PMP
4. Linear systems: the quadratic regulator problem and the time optimal problem

References

[1] A. Bacciotti, Teoria Matematica dei Controlli, Celid (reduced version available on-line)

[2] U. Boscain, B. Piccoli, Optimal Syntheses for control systems, Springer (reduced version available on-line)

[3] D. Burghes, A. Graham, Introduction to control theory, Ellis Horwood

[4] Lee E.B., L. Markus, Foundations of Optimal Control Theory

[5] R. Brockett, Finite dimensional control systems

[6] L. Pontriaguine (et al.), Théorie mathématique des processus optimaux, MIR

Astrophysics

Alessandro Bemporad, *INAF-OATO*.
Stefano Camera, *Department of Physics*, Università di Torino.
Alberto Cellino, *INAF-OATO*.
Silvano Fineschi, *INAF-OATO*.
Davide Gandolfi, *Department of Physics*, Università di Torino.
Francesco Massaro, *Department of Physics*, Università di Torino.
4 CFU.

Objectives
Provide the students with the basics knowledge of astrophysics required to understand the motivation for scientific space missions.

Contents
1. Solar System: current knowledge of the physical properties of the solar system bodies, derived by remote observations and in-situ exploration
2. The Sun: basics of the physics of the Sun interior, solar dynamo and solar atmosphere
3. Exoplanets: basic properties of transiting planets and their atmosphere and how these properties are derived
4. High-energy Astrophysics: description of the main radiative processes producing X- and gamma-ray emission and overview of their astrophysical sources
5. Cosmology: observational probes of the existence and properties of dark energy and dark matter: galaxy clustering and weak lensing cosmic shear

References

[1] Bertotti, Farinella and Vokrouhlicky, Physics of the Solar System, Kluwer academic Publishers, 2003

[2] Landi Degl'Innocenti, Fisica Solare, Springer (2008)

[3] Ferrari, Stelle, galassie e universo. Fondamenti di astrofisica, Springer

[4] Rybicki and Lightman, Radiative Processes, WILEY-VCH Verlag GmbH & Co. KGaA

[5] Shapiro and Teukolsky, Black Holes, White Dwarfs, Neutron Stars, WILEY-VCH Verlag GmbH & Co. KGaA

[6] Frank, King and Raine. Accretion Power in Astrophysics, Cambridge University Press

Celestial mechanics and astrodynamics

Vivina Barutello, *Department of Mathematics*, Università di Torino.

Alberto Boscaggin, *Department of Mathematics*, Università di Torino.

Alessandro Portaluri, *DISAFA*, Università di Torino.

Camilla Colombo, *Department of Aerospace Sciences and Technologies*, Politecnico di Milano.

Marco Sansottera, *Department of Mathematics*, Università di Milano.

Giovanni Gronchi, *Department of Mathematics*, Università di Pisa.

Martins Sudars, *Thales Alenia Space*.

4 CFU, Mandatory.

MODULUS 1 - Classical equations of celestial mechanics

Objectives

Provide the basic theory of ODEs and the classical equations of celestial mechanics.

Contents

1. Review on basic notions of ODEs and dynamical systems
2. Basic equations of celestial mechanics: Kepler's laws and the 2-body problem, restricted 3-body problem, N-body problem

References

[1] R. Fitzpatrick, An Introduction to Celestial Mechanics, Cambridge University Press, Cambridge, 2012.

[2] K. Meyer, G. Hall, D. Offin, Introduction to Hamiltonian Dynamical Systems and the N-body problem, Springer, New York 2009.

[3] R. Ortega, A. Ureña, Introdución a la Mecanica Celeste, Editorial Universidad de Granada, Granada, 2010.

[4] H. Pollard, Celestial Mechanics, Mathematical Association of America, Washington D.C., 1976.

MODULUS 2 - Astrodynamics

Objectives

This modulus is concerned with the basics of orbital mechanics and applications, from orbital manoeuvres to gravitational motions and to space debris.

Contents

1. References systems in space
2. Orbital manoeuvres
3. Gravitational motion and interplanetary trajectories
4. Orbit perturbation modelling and applications
5. Application to planetary protection and defence
6. Space debris

References

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MODULUS 3- Stability of planetaries systems

Objectives

The modulus id concerned with the long-standing problem of stability of a planetary system, focusing on the Kolmogorov-Arnold-Moser theory (KAM Theory) on persistence of invariant tori in near to integrable Hamiltonian systems and including a short discussion of some recent results based on computer assisted methods.

Contents

1. Hamiltonian formalism: a short introduction. Dynamical variables, first integrals and canonical transformations. Integrable systems: Liouville-Arnold-Jost theorem. The general problem of the dynamics: Poincaré's theorem on the nonexistence of first integrals
2. Persistence of invariant tori: the Kolmogorov's normal form. Statement of the KAM theorem and main ideas behind it. Near the identity canonical transformations via Lie series: formal introduction and Cauchy's estimates
3. Kolmogorov's normal form: formal scheme and quantitative estimates. The accumulation of small divisors and the problem of convergence
4. The KAM theorem: a comparison between the classical and the quadratic methods. The game of small divisors
5. KAM in Celestial Mechanics: a short and partial overview of the state-of-the-art in the scientific literature

References

[1] V.I. Arnold, Proof of a theorem of A. N. Kolmogorov on the invariance of quasi-periodic motions under small perturbations of the Hamiltonian, Usp. Mat. Nauk, 18, 1963

[2] V.I. Arnold, Mathematical Methods of Classical Mechanics, Graduate Texts in Math., Vol. 60, Springer-Verlag, New York and Berlin, 1978

[3] A. Giorgilli, U. Locatelli, A classical self-contained proof of Kolmogorov's theorem on invariant tori, in Proceedings of the NATO ASI school "Hamiltonian systems with three or more degrees of freedom", NATO ASI series, Math. Phys. Sci., Vol. 533, Kluwer Academic Publishers, Dordrecht-Boston-London, 1999

[4] A.N. Kolmogorov, Preservation of conditionally periodic movements with small change in the Hamilton function, Dokl. Akad. Nauk SSSR, 98, 1954

[5] J. Moser, On invariant curves of area-preserving mappings of an annulus, Nachr. Akad. Wiss. Gott,. II Math. Phys. Kl 1962

[6] J. Moser, Convergent series expansions for quasi-periodic motions, Math. Ann., 169, 1967

MODULUS 4 - Orbit determination

Objectives

The modulus is concerned with the orbit determination: the purpose is to introduce the students to the basics of the classical orbit determination methods and to show some of the most recent results to deal with cutting-edge problems in this field.

Contents

1. The classical orbit determination methods by Laplace and Gauss
2. The problem of alternative solutions: a geometric characterization of the number of preliminary solutions due to Charlier, and a recent generalization
3. The least squares method and the computation of orbits
4. Observations with modern telescopes and the identification problem: innovative methods to compute preliminary orbits

References

[1] C.V.L. Charlier, On Multiple Solutions in the Determination of Orbits from three Observation, MNRAS 71, 1910

[2] C.V.L. Charlier, Second Note on Multiple Solutions in the Determination of Orbits from three Observation, MNRAS 71, 1911

[3] C.F. Gauss, Theoria motus corporum coelestium in sectionibus conicis Solem ambientium (1809), Theory of the Motion of the Heavenly Bodies Moving about the Sun in Conic Section', reprinted by Dover publications, 1963

[4] G.F. Gronchi, Multiple Solutions in Preliminary Orbit Determination from Three Observations, CMDA 103/4, 2009

[5] G.F. Gronchi, G. Baù , S. Marò , Orbit determination with the two-body integrals. III, CMDA 123, 2015

[6] G.F. Gronchi, G. Baù , A. Milani, Keplerian integrals, elimination theory and identification of very short arcs in a large database of optical observations, CMDA 127/2, 2017

[7] P.S. Laplace, Mém. Acad. R. Sci. Paris, in Laplace's collected works 10, 1780

[8] A. Milani, The Asteroid Identification Problem I: recovery of lost asteroids, Icarus 137, 1999

[9] A. Milani, G.F. Gronchi The theory of orbit determinatio, Cambridge University press, 2010

[10] L.G. Taff, D.L. Hall, The use of angles and angular rates. I - Initial orbit determination, CMDA 16, 1977

MODULUS 5 - Re-entry Trajectories

Objectives

The modulus objective is to introduce the aspects of the flight mechanics applicable to the re-entry vehicle flights mechanics and mission analysis discipline.

Contents

1. Introduction to the re-entry vehicle main characteristics and trajectories
2. Types of trajectories and re-entry flight mechanics problems
3. Re-entry events and performance parameters
4. Reference frames and equations of motion
5. Modelling of the vehicle and environment

6. Setting up and structuring a simulator tool

Data analysis

Cristina Zucca, *Department of Mathematics*, Università di Torino.
Francesco Massaro, *Department of Physics*, Università di Torino.
6 CFU, Mandatory.

MODULUS 1 - Statistical analysis

Objectives
The modulus aims to give an introduction to some statistical techniques useful in astronomical fields. Some prerequisites are required (basics of probability and statistics). The theoretical lectures will be completed by pratical lessons using the R software.

Contents
1. Introduction to statistics for astronomical data
2. Regression: linear models and linear models with mixed effects models
3. Time series analysis: ARMA and ARIMA models, time domain and frequency domain

MODULUS 2 - Software packages for observed data

Objectives
The second modulus provides basis details on how to handle different software packages developed to reduce and analyze observations carried out by high energy satellites launched by ESA and NASA, such as XMM-Newton, SWIFT, Fermi. We expect to show how basic commands and pipelines for different facilities can work and we can eventually plan to have a dedicated special hands-on session. This will also provide a few examples on how problems occurring after the launch of a satellite, if present, can be solved a posteriori using astronomical software.

Contents
1. Review of some basic concepts of statistical analysis necessary to interpret the high energy data in the X-ray and in the gamma-ray band
2. Reducing and analyzing datasets of three astrophysical sources observed with three different satellites: the spectral analysis of a point like source seen with XMM-Newton; X-ray photometry of a crowded field observed with SWIFT; investigation of the gamma-ray light curve of a variable source in the Fermi archive

References

[1] `https://www.cosmos.esa.int/web/xmm-newton/sas`

[2] `https://heasarc.gsfc.nasa.gov/docs/software.html`

[3] `https://fermi.gsfc.nasa.gov/ssc/data/analysis/software`

Detectors and space equipment

Mario Bertaina, *Department of Physics*, Università di Torino.
Raffaella Bonino, *Department of Physics*, Università di Torino.
Luca Latronico, *INFN*.
4 CFU, Mandatory.

Objectives
The objectives of this course are to provide basic knowledge of detectors and instruments developed for scientific payloads of space missions. The course will illustrate design elements and operational constraints of specific example observatories, as determined by the required scientific performance.

Contents
1. Instruments and detection principles which include: a) interaction between matter and radiation; b) detection technologies; c) space equipments and instrumentation
2. Cosmic radiation: experiments and results. This module will include also multi messenger studies with networks of observatories
3. Space environment and space debris

References

[1] Slides and material presented during the classes

Gravitational astronomy and metrology for astrophysics

Mariateresa Crosta, *INAF-OATO*.
Mario Lattanzi, *INAF-OATO*.
4 CFU, Mandatory.

Objectives
The course focuses on the methods of gravitational astronomy and relativistic metrology and their applications to astrophysical investigations, especially in respect to the new generation of space mission operating in the weak gravitational field of the Solar System. The lectures will illustrate also the role of fundamental astronomy for the calibration of models for stellar astrophysics and in the latest investigations on formation, structure and evolution of the Milky Way, with implications for current cosmological theories (local cosmology).

Contents
1. General Relativity (GR) and Space Sciences: fundamentals of the theory of measurements in weakly curved space-time. Time transformations in GR
2. Reference Frames for Space Sciences: construction and materialization of celestial reference systems and coordinate frames: the ICRS/F, BCRS, and GCRS
3. The measurement/observation protocol in GR: photon paths (relativistic observables from within the gravitational field of the Solar System, inverse ray-tracing methods, astrometric lensing and GWs effects)
4. The observer (relativistic observers in space, relativistic satellite attitude)
5. Relativistic observation equations: the O-C equations. S/N of the instrumentation aboard satellites: optics, detectors, and their calibrations. Mathematical methods for the solution of large least squares problems
6. Relations between quantum and relativistic metrology: physical and coordinate time, clocks on board and on Earth

References

[1] Gravity: Newtonian, Post-Newtonian, Relativistic, by Eric Poisson and Clifford Will, Cambridge University Press, 2014

[2] Classical Measurements in Curved Space-Times, by Fernando de Felice and Donato Bini, Cambridge University Press, 2010 ESA Gaia Documentation (technical notes)

[3] The global sphere reconstruction (GSR). Demonstrating an independent implementation of the astrometric core solution for Gaia, Vecchiato et al., 2018A&A...620A..40V

[4] Application of time transfer functions to Gaia's global astrometry. Validation on DPAC simulated Gaia-like observations, Bertone at al., 2017A&A...608A..83B

[5] Orbiting frames and satellite attitudes in relativistic astrometry, Bini et al., 2003CQGra..20.4695B

[6] Gaia relativistic astrometric models. I. Proper stellar direction and aberration, Crosta et al. 2010A&A...509A..37C

[7] General relativistic observable for gravitational astrometry in the context of the Gaia mission and beyond, Crosta et al. 2017PhRvD..96j4030C

Innovative mathematical methods for the space

Davide Ferrario, *Department of Mathematics and Applications*, Università di Milano Bicocca.

Aalessandra De Rossi, *Department of Mathematics*, Università di Torino.

Piergiorgio Lanza, *Thales Alenia Space*.

4 CFU.

MODULUS 1 - Computational algebraic topology

Objectives

The modulus gives an introduction to recent applications of computational algebraic topology to nonlinear and data analysis. The aim is to illustrate some of the directions that ideas and techniques are being taken to, with a hands-on approach. The activity is hence structured as a series of introductory lectures immediately followed by a practical workshop.

Contents

1. Basic elements of combinatorial and simplicial topology
2. Singular and simplicial homology theory
3. Computational and persistent homology
4. Applications: topological data analsys and nonlinear analysis

References

[1] T. Kaczynski, K. Mischaikow and M. Mrozek. Computational homology. Vol. 157. Springer Science & Business Media, 2006

[2] D.L. Ferrario and R.A. Piccinini. Simplicial structures in topology. Springer Science & Business Media, 2010

[3] N. Otter, M.A. Porter, U. Tillmann, P.Grindrod and H.A. Harrington. A roadmap for the computation of persistent homology. EPJ Data Science 6, 2017

MODULUS 2 - Numerical methods for scattered data

Objectives

The second modulus aims to introduce numerical methods to approximate functions on the sphere, which can be applied to high-dimensional approximation of scattered data (for example, in geophysical and meteorological problems) and to modelling partial differential equations.

Contents

1. Approximation methods for the sphere: spherical harmonics, zonal kernels, optimal nodes on the sphere
2. Fast algorithms for satellite data approximation
3. An overview of applications in spherical geometries: CAGD, Shallow water flows (numerical weather prediction), Mantle convection (Rayleigh-Bénard convection) and Vector fields on the sphere

References

[1] W. Freeden, T. Gervens and Schreiner. Constructive Approximation on the Sphere with Applications to Geomathematics, Clarendon Press, Oxford, 1998

[2] W. Freeden and M. Schreiner, Spherical functions of Mathematical Geosciences. A Scalar, Vectorial, and Tensorial Setup, Springer, 2009

MODULUS 3 - Image Processing for Space Applications

Objectives

The modulus gives a general overview of image processing algorithms and problems specifically coped in space environment, with the aim of understanding the difference between human vision and Image Processing carried out by a computer: understanding the fundamentals of digital image treatment (pixel, layers, colors); applying basic concepts of filtering, restoring, etc; using Multi Spectrum Camera why?; applying basic concepts of simple object detection in Deep Learning.

Contents

1. Fundamentals of digital image treatment
2. Image Enhancement in Spatial domain
3. Color Image Processing and Image Compression
4. A quick sight on the future: Deep Learning approach

References

[1] Digital Image Processing, 3rd edition Rafael Gonzalez, Richard Woods ISBN number 9780131687288 Publisher: Prentice Hall © 2008

[2] Image Processing with Images, 2nd edition Jurjen Broeke, Jose Maria Mateos Perez, Javier Pascau Publisher: Packt Publishing (March 2015)

[3] Digital Image Processing, 2nd edition Rafael Gonzalez, Richard Woods ISBN number 978-0201180756 Publisher: Prentice Hall © 2002

Mission design

Luca Derosa, *iMEX.A.*

4 CFU, Mandatory.

Objectives

The course covers the fundamental aspects of manned/unmanned space missions design, analyzing in particular the design of interstellar missions and space missions at relativistic speed.

It is aimed at young professionals and scientists, with a background in engineering sciences, math or physics, who need to acquire skills and knowledge in space mission design and at experienced engineers, specialized in one particular area of expertise, who need to acquire a system level understanding of the overall advanced space missions.

Contents

1. Introduction to space engineering and space mission design
2. The space environment (solar system and interstellar medium): hazards and effects
3. Human factors in Astronautics, with focus on long duration space missions: physiological/physical, psychological, habitability
4. Thermal control: fundamentals and technology options
5. Environmental Control & Life Support System (ECLSS): fundamentals and examples of systems to provide a safe & comfortable place for humans in deep space missions
6. Elements of astrodynamics and space trajectories, space structures & mechanisms, attitude determination and control
7. Elements of special relativity and astronautical applications: relativistic rocket equation, relativity and mechanics, relativity and thermodynamics, relativistic spaceflight profiles, effects of space environment at relativistic speeds, etc
8. Space propulsion systems: cold gas, chemical (solid, liquid, hybrid), electric (electrothermal, electrostatic, electromagnetic), and focus on advanced (sails, energetic beams, radiations, nuclear, antimatter, ramjet, exotics solutions)
9. Electrical power system: power source, energy storage, power management & distribution
10. Characteristics and main elements of the ground segment: support to space mission communications and operations
11. Data handling and communications architecture, with focus on solutions for deep space communications: gravitational lenses, data compression with KLT, etc
12. Payload and experiments: elements of design and examples
13. Risk management and reliability for space missions.

References

[1] J. R. Wertz, W. J. Larson, Space Mission Analysis and Design, Microcosm Press & Kluwer Academic Publishers, 1999

[2] R. F. Tinder, Relativistic Flight Mechanics and Space Travel, Morgan & Claypool Publishers, 2007

[3] K. F. Long, Deep Space Propulsion – A Roadmap to Interstellar Flight, Springer, 2012

[4] M. G. Millis, E. W. Davis, Frontiers of Propulsion Science, AIAA, 2009

Relativistic mechanics

Lorenzo Fatibene, *Department of Mathematics*, Università di Torino.

4 CFU, Mandatory.

Objectives

The aim is to provide a general framework for describing the motion of objects in a gravitational field and its relation to newtonian and post newtonian physics.

Contents

1. Geodesics in a spacetime. Lagrangian description, first integrals
2. Semi-analytical methods (Weierstrass equations)
3. Exact Kepler laws, their relation with weak field approximations and relativistic corrections
4. Strong field effects
5. Symplectic control methods applied to test particles

References

[1] S.Benenti, Hamiltonian Structures and Generating Families, Universitext (Springer-Verlag New York, 2011)

Seminars

A short overview of European Funding Landscape for Maths, Physics and Space Research

Serena Ballarin, CSTF - Common Strategic Task Force, Università di Torino
Stefano Chiadò , Vastalla
Raffaella Di Nardo, CSTF - Common Strategic Task Force, Università di Torino

The seminar will give an overview of European funds, focusing on partnership opportunities, consortium building and role of companies in R&I projects. Both the entrepreneur's view and the EU espert's view will be analized.

Artificial intelligence technology and applications

Stefano Chiadò , Vastalla

Artificial Intelligence is everywhere. But is it really so? Do we all agree on what Artificial Intelligence is? What is the state of the art in AI? What are Machine Learning and Deep Learning?
We will have a lot of questions to answer during the workshop, and we will also talk about efficiency and the importance of not reinventing the wheel making use of what is available on the market (i.e. Amazon Web Services tools, Google tools, etc.). We will also explore what are the possible applications of AI in Space sciences with some real world examples (i.e. Kepler exoplanet discovery).

Cognitive, psychological and neurophysiological effects of human space flight

Raffaella Ricci, Department of Psychology, Università di Torino

The seminars are concerned with the following topics.
Microgravity effects on human performance. It is known that cortical sensorimotor map and brain reorganization occur as an adaptive response to reduced gravitational input. Neurosensory and cognitive effects induced by microgravity may significantly affect the crew's performance during spaceflight. In addition, this adaptation may not be optimal upon return to Earth or operations on a planetary surface or in the case of an emergency landing. Neurosensory and cognitive effects induced by altered gravity on crew's performance need to be taken into account in the design of Human Machine Interfaces (HMI), Internet of Things (IoT) technologies and space habitat to ensure the success of future deep space missions (i.e. cislunar modules, Moon village, Mars, and beyond).
Crew members' psychological wellbeing. A manned mission into deep Space, beyond Low Earth Orbit (LEO) and cislunar Space, such as for example the journey to Mars, is one of the greatest psychological challenge that humans have ever faced. Several stressors might condition the astronauts' mental state and their impact is expected to augment in human long-duration missions. Life in isolated, confined, and extreme environments (ICE), with few other team members, for long duration periods, may lead to psychological (e.g. stress, anxiety, depression), interpersonal and communication issues among the crew members and/or between the crew and the terrestrial team. The identification of effective countermeasures, fostering human psychological wellbeing, will be crucial to the success of long-duration deep space missions.

Computing Systems and payloads in the cubeSat context

Ferdinando Ricchiuti, CSP innovazione nelle ICT

Candidates will have an overview of technological solution for onboard systems. They will understand the available capabilities in terms of computing and networking, facing the major challenges in critical systems such as reliability, redundancy, hardware acceleration and data storage. Furthermore, candidates will understand the standard form factor and payload's physical constraints, that are a major issue in designing the overall system. The adoption of an open computing platform, will be relevant to create an ecosystem, enabling the integration of third parties software components.

GAIA - Astrometric cosmology

Mario Lattanzi, INAF-OATO

Ground Station Services: the data path from space to cloud

Ferdinando Ricchiuti, CSP innovazione nelle ICT

Candidates will learn how Ground Station Service will be implemented and how data will be made available. They will also learn the kind of threats the data are exposed during transmission over the network and some technologies that can provide effective solution to these threats. Finally, they will learn some basic concepts of machine learning and what are the related services and solutions already available in the cloud.

Interferometry in space missions

Marco Pisani, INRIM

Laser interferometry is the chief method for any length measurement where extreme precision and accuracy are required. It has been used for decades in the nanometer range up to the kilometer range in a huge number of applications. Nevertheless, because of the complexity of the technique, space community is not keen to use it on board of satellites. Only in very recent times space missions foresee the use of interferometers in metrological demanding scientific missions. After an introduction about the principles of laser interferometry I will give an overview of the present and future applications of interferometry in space missions.

Persistent homology applications to Complex networks and Neuroscience

Francesco Vaccarino, Department of Mathematics, Politecnico di Torino

After recalling the main concept to be used in persistent homology we will show how it can be of use in analysing complex weighted networks with a special focus on the human brain functional connectome.

Persistent Homology of Phase transitions

Francesco Vaccarino, Department of Mathematics, Politecnico di Torino

After introducing some basic concepts in the geometry of configuration spaces we will show how phase transitions are related to topological transition and we will shed some light on a method to find them via persistent homology.

Space mission management

Fumiyoshi Kajino, Konan University

Management of the space mission is very important to lead the mission to success, especially for large international groups. Based on the experience as an instrument manager of JEM-EUSO mission, we will talk about the mission management along the items of mission objectives, requirements, management tools, phases etc..

Statistical tools for GNSS clocks characterization

Valerio Formichella, INRIM

Atomic clocks flying on board the satellites of Global Navigation Satellite Systems (GNSS) must meet strong requirements in the terms of timing performance. Statistical tools typical of time metrology are therefore applied to characterize GNSS clocks. This tutorial will introduce some of these tools, among which: the Allan deviation, for the characterization of the clock's stability; detectors of clock anomalies, for detecting anomalous clock's behavior within the noise.

STOP (Structural, Thermal, Optical, Performance) Analysis for Euclid Mission

Alberto Anselmi, Thales Alenia Space

Euclid is the next cosmology mission of ESA, to be launched in 2022. The spacecraft is now under construction under the lead of Thales Alenia Space in Turin. The objective of the mission is to elucidate the dark matter and dark energy components of the current 'standard model of cosmology', as established over the last 20 years and consolidated by the Plank spacecraft, also built by Thales Alenia Space in France and Italy. Euclid will map the whole extragalactic sky in a wide bandwidth at high depth and sensitivity, using two instruments, an imager in the visible domain and a photo/spectrometer in the near infrared range, placed in the focal plane of a 1.2m diameter, wide-field (0.5 deg^2) Korsch telescope. The driving requirements for the spacecraft and telescope arise from the 'weak lensing' measurement, which demands exceptional dimensional stability of all parts of the observing instrument. The stability objective is met by a variety of means, such as placing the telescope in the shadow of a large sunshield, using highly insulating thermal covers, manufacturing all optical structures from high-stability ceramic materials, and placing rather narrow limits on the permitted incidence angle of the sun on the sunshield at any given epoch.

The design phase of the project has now been completed and manufacturing, assembly and test of the various parts in ongoing. In parallel, a detailed mathematical model of the spacecraft and instrument has been built and is being used to verify the correct operation of the mission as faithfully as possible in advance of the actual flight. The STOP analysis consists of a suite of test cases, reproducing the range of conditions the spacecraft will see in orbit in terms of attitude with respect to the sun, internal state of the spacecraft, performance of the materials, etc. The analysis begins with a very detailed finite-element thermal model, which produces a prediction of the temperature and temperature variation of each element, external and internal. The temperatures are then mapped onto a finite-element model of the structures, which is exercised to produce displacements and rotations of the elements making up the optical chain. Finally, an optical code calculates the perturbed image (the point-spread function), affected by tiny but crucial aberrations, in 9 points in the telescope field. Finally, the simulated image is processed to generate the optical figures of merit to be compared with the specifications.

The build-up and verification of the STOP code is in its final stages and numerous lessons have

already been learnt, leading, in some cases, to changing some details of the design. Despite the ceramic materials, with coefficients of thermal expansion well below 1 μm/m/K at the 140K operating temperature, and the super-insulation, the performance is shown to depend on keeping the temperature fluctuations in the sensitive parts of the telescope below about 50 mK on time scales of several hours, comprising several small attitude manoeuvres of the spacecraft. The results of the STOP analysis are being used to guide the testing of the telescope and system, which is a challenge in itself, given the smallness of the effects to be measured.
After a short introduction to the Euclid project and mission, the lecture will illustrate the principles, the modelling approach and techniques of the STOP analysis. The main results will be presented, including examples of potential weaknesses of the design which have been identified and corrected in the process. The approach to the verification will also be discussed, giving a preview of the predictions that are going to be put to the test in the next months.

Time metrology and GNSS

Ilaria Sesia, INRIM

Precise timekeeping is the heart of any Global Navigation Satellite System (GNSS), and atomic clocks are the fundamental technology for reaching the required level of timing accuracy. Applying time metrology to GNSS means to keep all the system's clocks synchronized, and to characterize and monitor the status of these clocks. This tutorial will introduce the key aspects of time metrology in GNSS, and will introduce the methodology applied for space clock metrological characterization.