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Astrodynamics Network AstroNet-II

The Final Conference

Springer

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Preface

From June 15 to June 19, 2015, the *AstroNet-II International Final Conference* was held in Tossa de Mar. This conference was one of the last milestones of the Marie-Curie Research Training Network on Astrodynamics "AstroNet-II" that was funded by the European Commission under the Seventh Framework Programme. The network put together mathematicians, engineers and astronomers from European universities, governmental agencies and industry with the objective of training through research activities.

The AstroNet-II training programme focused on projects for early-stage researchers (ESRs) and experienced researchers (ERs) that crossed the traditional boundaries between mathematics, engineering and industry, ensuring that they obtained an interdisciplinary and multi-sectorial overview of the field. This was supported by an extensive programme of schools, workshops, tutorials and internships and by a close collaboration between academia and space companies. In this framework, the main goals to be achieved were:

- To introduce the fellows of the network to a range of astrodynamic concepts and problems, as well as to the relevant new mathematical theories and techniques
- To develop their technical expertise and to train them to conduct research, to collaborate and to communicate their results
- To deepen and broaden the knowledge and skills of the fellows working in the areas of astrodynamics, dynamical systems, control theory and numerical methods
- To offer in the fellows' project opportunities for doing research in private companies, international organisations and academia
- To provide them also with the complementary communications and project management skills that are needed for a successful career

Nowadays space missions are being required to fulfil many different types of functions and, as a consequence, are becoming increasingly more complex. Furthermore, a number of different spacecraft architectures, such as constellations, formations, tethered spacecraft or solar sails, have been proposed for some specific objectives. To achieve their functions and goals, future missions sometimes require

new, faster and unusual kinds of trajectories. They are very often also merged with precise attitude control dynamics whose determination, in many cases, raises new major dynamics and control questions.

A broad range of mathematical objects, theories and techniques are needed for these new concepts and applications. The research topics of the network included innovative new methods for designing spacecraft trajectories and controlling their dynamics. The scientific programme, centred on a number of key astrodynamical objectives of current interest to space agencies and industry but also of innovative mathematical interest, was mainly divided in three sections: Trajectory Design and Control, Attitude Control and Structural Flexibility of Spacecraft and Formation Flying. Particular emphasis was placed on optimising trajectories and control to minimise fuel usage to extend mission ranges. Many times this is achieved by maximising the use of "natural dynamics" and employing ideas and techniques from dynamical systems theory.

Since January 2012, 18 young researchers were involved in the network, working on the above-mentioned astrodynamic problems and the interface between mathematics and astrodynamics which provided an exciting research arena from the point of view of both applications and mathematics. When the network came to its end, it was time to communicate to an international specialised audience some of the work carried out during those four years. Together with the presentations of the fellows, we had also the opportunity to hear about the work of other young scientists in the field, as well as a number of invited talks delivered by relevant people in astrodynamics. This present book of proceedings contains some of the contributions in the conference, and it is intended to be a summary for young scientists and researchers interested in the field.

We would like to thank all the people who made the network, the conference and this book possible, starting from the ESR and ER fellows: Albert Caubet, Marta Ceccaroni, Luca de Filipis, Mohammad M. Gomroki, Elisabetta Iorfida, Pawel Kicman, Junquan Li, Pedro J. Llanos, Zubin P. Olikara, Rocío I. Páez, Fabrizio Paita, Claudiu-Lucian Prioroc, Leon Simpson, Stefania Soldini, Andrea Turconi, Willem van der Weg, Alexander Wittig and Mattia Zamaro. Next are their scientist in charge and associated partners: Franco Bernelli (Politecnico di Milano), James Biggs (Strathclyde University), Juan Luís Cano (Elecnor Deimos), Alessandra Celetti (Universita di Roma Tor Vergatta), Jordi Fondecaba (Thales-Alenia Space), Jesús Gil (GMV), Mariela Graziano (GMV), Steve Greenland (Clyde Space), Steve Kemble (Astrium Limited Satellites), Ugo Locatelli (Universita di Roma Tor Vergatta), Andrzej Maciejewski (University of Zielona Gora), Vincent Martinot (Thales-Alenia Space), Seppo Mikola (University of Turku), Phil Palmer (University of Surrey), Maria Przybylska (University of Zielona Gora), Mark Roberts (University of Surrey), Mariano Sánchez (Elecnor Deimos), Johannes Shoenmakers (ESA/ESOC) and Ozan Tekinalp (Middle East Technical University). Last but not the least are the other invited speakers who also participated in this final conference: Miguel Belló (Elecnor Deimos), Fabrizio Bernardi (SpaceDyS), Franco Boldrini (Selex ES), Kathleen Howell and Natasha Bosanac (Purdue University), Chris Brunskill (Catapult Satellite Applications), Mateo Ceriotti (University of

Glasgow), Pierluigi di Lizia (Politecnico di Milano), Elena Fantino (Universitat Politècnica de Catalunya), Ariadna Farrés (Universitat de Barcelona), Elisabet Herrera-Sucarrat (Mathworks), Tomasz Kwiatkowski (University of Zielona Gora), Martin Lara (Universidad de La Rioja), Thomas Peters (GMV), Marco Sansottera (University of Milan), Hanspeter Schaub (University of Colorado) and Francesco Topputo (Politecnico di Milano). Finally we want also to thank Pilar Montes, Anna Bertolin and Eva Notario (Institut d'Estudis Espacials de Catalunya) for their administrative support and the care they had managing all the events.

During the conference, we also wanted to pay tribute to the astrodynamicist José Rodríguez-Canabal who died aged 68 in 2013. For their contribution to this special session, we want to thank his family, Eugenia, Marta, Pablo and Adrián, and also friends who approached us to his scientific and personal career: Walter Flury (ESA/ESOC), Miguel Belló (Elecnor Deimos), Vicente Companys (ESA/ESOC), Guy Janin (ESA/ESOC), Javier Jiméenez (Univ. Politécnica de Madrid), Jaume Pagès (Universia) and Carles Simó (University of Barcelona) who chaired the session. The reader will also find a summary of their presentations to the special session edited in the header of the present book.

Barcelona, Spain — Gerard Gómez
Barcelona, Spain — Josep J. Masdemont

Contents

José Rodríguez-Canabal Memorial (1945–2013)

Gerard Gómez and Josep J. Masdemont

1 Introduction

Dr. José Rodíguez-Canabal was an aerospace engineer that graduated at E.T.S.I. Aeronáuticos of the Universidad Politécnica de Madrid. In 1972, he finished his Ph.D. in control theory at the University of Southern California under the supervision of Prof. R.S. Bucy. After completing his PhD, he moved to Toulouse, where he worked at the Laboratoirte d'Automatique et ses Applications Spatiales of the CNRS during a short period of time; in 1973 he got a position at ESOC, from which he retired in 2010.

During almost 37 years of his professional career at ESOC, Dr. Rodríguez-Canabal worked in the mission analysis of many of the most relevant missions launched or participated by ESA, including Exosat, Cluster II, Double Star, Giotto, Lisa, Rosetta, SOHO and Venus Express.

The AstroNet-II International Final Conference devoted a special session to his memory, where there took part, together with his closest family and some of his best friends and colleagues at ESOC. All of them recalled not only his high professionalism but also his kindness and friendly personality. The memorial included the following lectures:

- Walter Flury (ESA/ESOC): "35 years of mission analysis at ESOC"
- Miguel Belló (Elecnor Deimos): "Lessons learned"
- Vicente Companys (ESA/ESOC): "The Rosetta mission: Flight operations"
- Guy Janin (ESA/ESOC): "The office no. 411"
- Javier Jiménez (Univ. Politécnica Madrid): "José Rodríguez-Canabal: The early years"
- Jaume Pagès (Universia): "José Rodríguez-Canabal: A personal approach"
- Johannes Schoenmaekers (ESA/ESOC): "Interplanetary trajectory design for Rosetta and Solar Orbiter"

This paper is a short summary on the contents of the above lectures in the memorial and has been prepared by the editors of the present book. Although it is difficult

to separate the human aspects from the professional side, especially in a such rich personality like the one of José, for this note we have preferred to do so, in order to highlight some of his many qualities.

2 The Human Approach

Pepe, which is how all his friends called him, was born in 1945 in Plasencia, a beautiful city in western Spain. It was in the midst of the post-civil war era, during a period of autocracy with very few foreign relations. He was the fourth son of a family of five (four boys and a girl).

He was an intelligent man with great intellectual curiosity, especially in the areas of technology where he had truly unique skills. He enjoyed a brilliant academic career; according to one of his professors, Dr. A. Liñan, and his Ph.D. supervisor, Dr. Richard S. Bucy, this was due to his dedication, curiosity, open mind and desire to learn, which all of them are required qualities to succeed in science.

Exploring new possibilities was something Pepe did his whole life, both alone and in company, to face amazing challenges and intergalactic dreams. He was musically gifted; when he was young, he used to play the harmonica by ear and as an adult he took clarinet lectures. He also explored gardening, art, cooking, organising parties and trips, librarianship, document management and sailing, although after a trip from Barcelona to Mallorca by boat the captain diploma ended up in a drawer (Fig. 1).

Fig. 1 Exploring new possibilities was something Pepe did his whole life

Fig. 2 His relationship with Eugenia was the most important thing in his life

In 1963, he moved to Madrid to study aeronautical engineering. This was a very significant event for Pepe with consequences throughout his life: he found Eugenia there. They met, fell in love, got married and left to the USA. His relationship with Eugenia was the most important thing in his life. As one would expect, the initial partnership of Eugenia and Pepe grew. Their daughter Marta was born in California and their son Pablo in Germany. His grandchildren, Adrián, Nicolás and Hernán, undoubtedly gave him the greatest pleasure over the last few years (Fig. 2).

Pepe wanted to share his life and interests with many friends, and especially with ESOC fellows and young people, to which he delivered help, support and guidance. He always listened to their concerns and he did everything in his hands to be there for them and to help in key moments. He was always there to share their worries, either at the office or at home. Together with Eugenia, they worked for many years to improve schooling and to help the children of immigrants to go to a gymnasium. Every year, he organised a group day out with the ESOC students, which ended with a barbecue at his house, all with the aim of socialising together and gaining their trust. He did this with his utmost and absolute conviction and devotion (Fig. 3).

And as a last personal trait, Pepe was a committed pro-European. The idea won him over and he was convinced that today's generations have a huge responsibility to build Europe as a place to share and where the errors of the not-so-distant past shall not be repeated. He was proud to have done his bit working with a European transnational organisation. He rejected offers to move to the USA on a number of occasions, and one of the underlying reasons for these decisions was the personal connection he had built with the idea of Europe.

Fig. 3 Pepe shared his life and interests with many friends, ESOC students and young people

3 The Professional Approach

As it has already been mentioned, during his professional career, José took part in the mission analysis of many of the most relevant missions launched or participated by ESA. Here we just remember some of his contributions to SOHO, LISA, Cluster and Rosetta and what we all learned from his approach (Figs. 4 and 5).

Launched in December 1995, the SOHO mission is a joint ESA/NASA project to monitor the solar activity from a halo orbit in the L_1 libration point of the Earth-Sun system. The main activities of José for SOHO were the mission analysis, the definition and computation of the nominal trajectory and the definition and design of the orbit maintenance. José developed a very clever way to numerically generate an accurate nominal halo orbit. He used Richardson theory to obtain a first approximation together with very small velocity manoeuvres at the ecliptic plane crossings. He also implemented a cheap and efficient station-keeping procedure for this new kind of unstable orbits. As Guy Janin recalled during the memorial, all these novel questions could only be solved in a so imaginative and brilliant way by the occupant of the office no. 411 of ESOC.

The Laser Interferometer Space Antenna (LISA) mission is a joint ESA/NASA project to develop and operate a space-based gravitational wave detector by laser interferometry. For this purpose, a fleet of three probes are located at the vertex of a triangle in an Earth-like orbit with 20° phase delay and 60° inclined with respect to the ecliptic. The transfer of the three satellites to a trailing orbit, 20° behind the Earth and targeting the LISA operational configuration (with a distance between satellites of 5×10^6 km), is not an easy problem. It was solved as an optimal control problem, after iteratively computing several optimal solutions in a sequential process and augmenting at each step the complexity of the problem (Fig. 6).

Fig. 4 José with Guy Janin and Walter Flury in the farewell of Dr. Lin (CNSA) in 1999

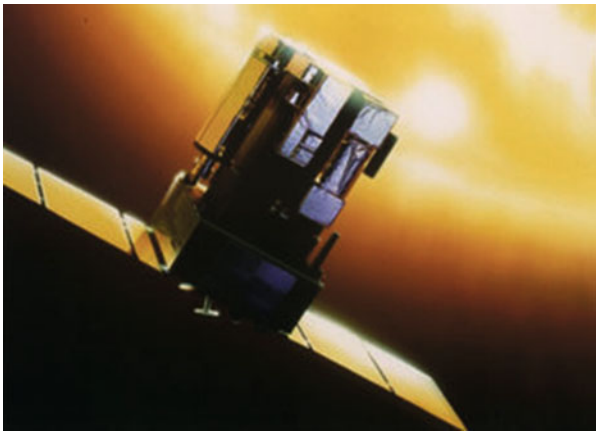


Fig. 5 Artist's impression of the Solar and Heliospheric Observatory (SOHO). Credit: ESA

From the approach used by José together with M. Bello for the LISA mission, one learns that in mission analysis, in general, there does not exist a simple optimal solution for a given problem. For most of them, a systematic search is needed to find all possible optimal candidates, and the solution of complex problems is usually obtained after the computation of a sequence of solutions of simpler problems with incremental level of difficulty.

The Cluster ESA mission is currently investigating the Earth's magnetic environment and its interaction with the solar wind in three dimensions. For this purpose, four satellites follow a high eccentric polar orbit. The four Cluster satellites must configure a tetrahedron with different prescribed distances, according to the region of the magnetosphere (North and South cusp, bow shock, magnetopause, etc.) to be analysed (Fig. 7).

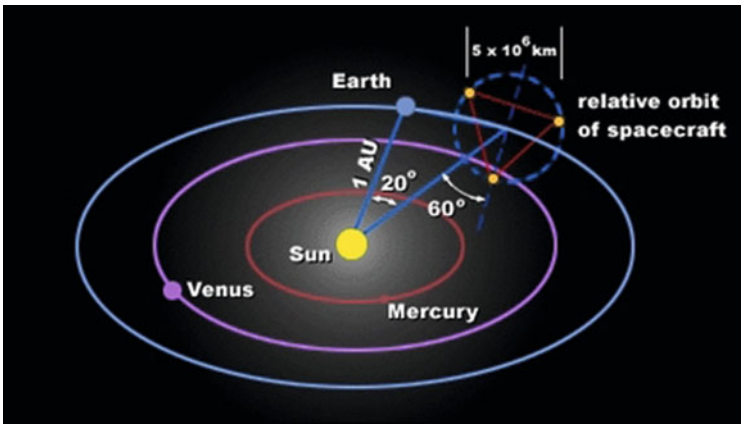


Fig. 6 A schematic diagram of the LISA spacecraft in formation as they orbit around the Sun. Credit: ESA

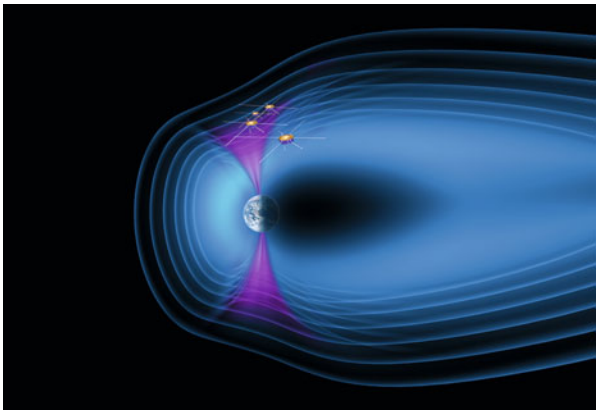


Fig. 7 Artist's impression of the Cluster spacecraft crossing the northern cusp of Earth's magnetosphere. Credit: ESA

Several problems were studied by José and M. Bello related to this mission. The first was the optimisation of the Cluster orbit injection strategy from its launcher delivery state. The second was the optimisation of the orbital manoeuvre sequence, in such a way that the required spacecraft configuration, with the required satellite distances, was achieved at each phase of the mission with a minimum cost in terms of Delta-v.

Miguel explained us that one of the most important things that he learned from José during the realisation of this project was how to behave in a very difficult and changing team environment of scientists, principal investigators, engineering and managers: always with respect for the work performed by others.

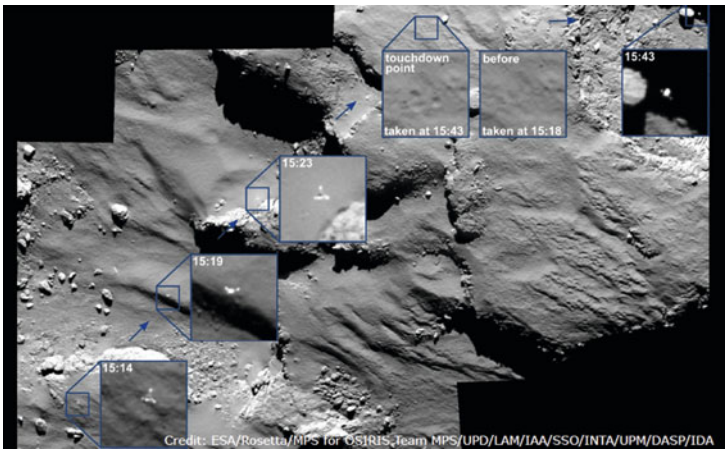


Fig. 8 The European Space Agency's Rosetta spacecraft captured these photos of the Philae lander descending towards, and then bouncing off, the surface of Comet 67P/Churyumov–Gerasimenko during its historic touchdown on Nov. 12, 2014. Credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA

Rosetta was one of the last missions that José took part. In this iconic ESA mission, the in situ analysis of a comet nucleus is done for the first time. For this mission, José participated in the mission analysis, the interplanetary trajectory generation, the interplanetary navigation, the near-comet operations, the comet outgassing model and the lander release strategy (Fig. 8).

As what V. Companys explained during his lecture, in 1998 a Rosetta meeting took place at ESOC involving members of the project group and of the ground segment. José was at the meeting in his function of mission analyst. The topic of the meeting was to explore potential measures for mass reduction: the spacecraft development had consumed mass margins and the fear was that the maximum Ariane V lift capability would be exceeded. Several options were explored, some of them involving spacecraft hardware modification. Also, the possibility to reduce propellant reserves (and hence available Delta-v) was considered. In particular, it was questioned whether the allocation of 185 m/s for launcher dispersion correction was adequate. Also, an allocation of 140 m/s for adjusting the time of asteroid Otawara and Siwa fly-bys was challenged. José fiercely defended the propellant budget and refused any reduction.

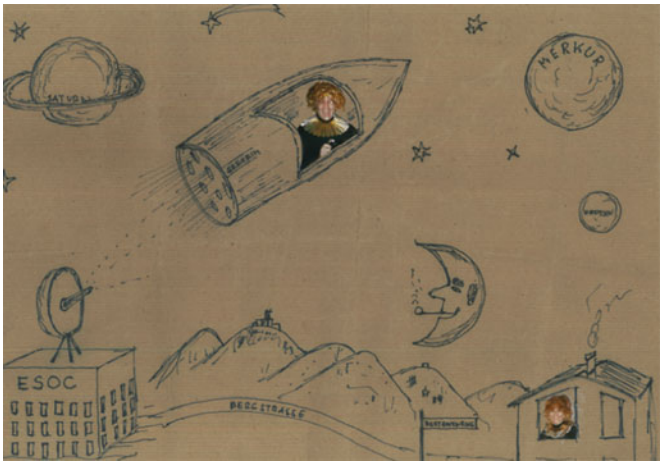
Due to the failed Ariane 157, the original Rosetta mission to comet 46P/Wirtanen could not be flown. The backup mission to 67P/Churyumov–Gerasimenko required 1770 m/s nominal cruise Delta-v instead of the 1550 m/s of the Wirtanen mission. The propulsion contingency in 2006 further degraded the propellant situation. People responsible of operations always take extreme care to preserve propellant resources. But if in 1998 José would not have managed to defend the propellant budget, the Rosetta spacecraft would not be today flying around Churyumov–Gerasimenko. The flight dynamics department of ESOC is very aware of this, and

with these lines, it wanted to give herewith credit to José for maybe one of his most remarkable contributions to ESA.

4 Summary

Several keywords, related to the personality and professionalism of José, often appeared during the memorial lectures. We think that they are a good summary of all it was said. So, we want to include them here just to remember what we learned from him:

- *Tolerance:* All ideas are respectable.
- *Justice:* Hate all type of injustices and help all affected groups.
- *Sense of humour:* Be always in a good mood.
- *Support:* Be always supportive for whenever need of a person.
- *Creativity:* In science and engineering, not all is invented; there is a lot of room for innovation.
- *Persistence:* Success is a 1 % inspiration and a 99 % transpiration.
- *Confidence:* Be confident in the work that we perform, not to be confused with arrogance.
- *Patience:* Results come if we put all means.



We all, friends and colleagues, are indebted to José that has gone but not forgotten