INTERNATIONAL CONFERENCE ON LIBRATION POINT ORBITS AND APPLICATIONS

Parador d'Aiguablava
Begur, Girona, Spain
June 10–14, 2002

PROGRAM

Organizing committee:

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(http://www.ieec.fcr.es/libpoint/main.html)

Contents

CONFERENCE INFORMATION

PRESENTATION

The International Conference on Libration Point Orbits and Applications will be held at the Parador d'Aiguablava, on the Costa Brava of Girona (Spain) from 10 to 14, June 2002.

This Conference is the latest in a series of meetings, under the name of "Libration Point Mission Design Workshop", that have been organized the last 6 years by JPL in a more informal manner. For the first time, the Conference will be hosted in Europa, it will last one week and will gather people from Agencies, Companies, Universities and Research Centers, involved in libration missions and/or in related problems in Celestial Mechanics. As the previous meetings, the Conference will be devoted to the study of libration orbits and applications for space missions and astronomical problems. The overarching theme will be the use of modern mathematical techniques combined with the state of the art computational methods and tools.

The main topics to be considered are:

- Libration Orbit Missions: Mission analysis and operations. Contingency plans. New challenges.
- Dynamics Around the Libration Points: The phase space. Navigation. Transfer and station keeping.
- Software Tools: Mission analysis design tools.
- Applications of Libration Orbits and its Manifolds: New mission concepts. Solar system dynamics.

One of the goals of the Conference is to define the State of the Art of the field of libration point orbits and their applications. With this idea, we plan to publish a book to survey various topics related to libration point orbits. Under the light of the new mission concepts and applications, we want also to collect the most challenging new problems in the field. For this purpose, in addition to the regular presentations, all conference attendees are invited to participate in the two round tables that we have planned for Tuesday 6/11 and Thursday 6/13 at the end of each day.

INVITED SPEAKERS

Gerald L. Condon	Johnson Space Center, NASA, USA
David W. Dunham	Johns Hopkins University, USA
Natan Eismont	Space Research Institute, IKI, Russia
David C. Folta	Goddard Space Flight Center, NASA, USA
Martin Hechler	European Space Operations Center, ESA, Germany
Kathleen C. Howell	Purdue University, USA
Wang-Sang Koon	California Institute of Technology, USA
Daniel J. Scheeres	University of Michigan, USA
Carles Simó	Universitat de Barcelona, Spain
Roby S. Wilson	NASA-Jet Propulsion Laboratory, Caltech, USA

DAILY TOPIC SESSIONS

- Monday. Past and future missions: Mission analysis and operations.
- Tuesday. Dynamics around the libration points: the phase space.
- Wednesday. Software tools.
- Thursday. Dynamics around the libration points: transfer, navigation and station keeping.
- Friday. Applications of libration point orbits and its manifolds: New mission concepts. Solar system dynamics.

PROCEEDINGS

Proceedings, organized around the contents of the invited lectures, will will be published after the conference, containing the communications and extended abstracts of the posters. In addition, as mentioned earlier, we plan to publish a separate book surveying the various topics related to libration point orbits.

Manuscript submission

Papers should be submitted to the Conference organizers for review and acceptance before September 15, 2002. The papers should be submitted electronically in any standard word-processing program (LATEX files are prefered) to the following address: lagrange@maia.ub.es. A hardcopy version should also be sent to:

Libration Point Orbits and Applications
Institut d'Estudis Espacials de Catalunya (IEEC)
Edifici Nexus, Despatx 201
Gran Capità, 2-4
08034 Barcelona, Spain

All the figures should also be sent in separare files in EPS or PDF format. The full address (including e-mail) of the authors must appear on the title page in a format similar to the one that appears in the abstracts of the present booklet. The corresponding author should be clearly displayed. A template for the paper format will be sent to the corresponding author.

REGISTRATION

A Registration fee of 300 Euros (approximately $250) will be in effect for the Conference. It should be payed in cash the first days of the meeting at the registration desk, that will be open Sunday 6/9, from 6:00 PM to 8:00 PM and Monday 6/10, from 8:00 AM to 9:00 AM. The Registration fee includes participation in the Conference sessions, two coffee breaks daily, Wednesday trip and banquet and a copy of the Conference proceedings.

CATALONIA, THE COSTA BRAVA AND BEGUR

Catalonia is a small country of six million inhabitants, but it has more than a thousand years of history and a culture and language of its own which have forged its character. Today Catalonia is an Autonomous Community within Spain an occupies an area of 31,930 square kilometers.

The small vilage of Begur, is located in the Costa Brava (the “Rugged Coast”) in one of the regions of Girona called Baix Empordà. In the Costa Brava, a few kilometers to the north of Begur, we find the archeological ruins of Empúries, the first vilage of the classical Greece in our country. The Greek colonizers, and their Roman successors, left behind a rich collection of sculptures and ceramics and just a short distance away from Begur is the iberian settlement of Ullastret with its ancient towering walls.

The personality of Catalonia was formed in the Middle Ages. This is why there are so many ancient civil and religious buildings, dating from the 9th to the 14th century in Romanesque and Gothic style. Among the most remarkable are the monastery of Sant Pere de Rodes, overlooking the sea on the Costa Brava and, farther inland, the monastery of Santa Maria de Ripoll and the three Cistercian monasteries of Santa Maria de Poblet, Santes Creus and Vallbona de les Monges, all important centres of culture and art in the Middle Ages.

Many cities, such as Girona, Vic, Barcelona, Tarragona, Tortosa and Lleida, have magnificent cathedrals. Girona cathedral is famous for its single nave - the widest Gothic nave in Europe. Other handsome medieval buildings are the current, or former, homes of government institutions. Examples are the Paeria in Lleida and the Palace of the Generalitat in Barcelona, which is the seat of the present-day Catalan government. All these ancient stones could tell tales of days gone by when Catalan merchants sailed all over the Mediterranean and catalan men-of-arms controlled many places around its shores.

At the turn of the 20th century, many buildings where designed in Modernist style, the characteristically Catalan version of Art Nouveau, which was all the vogue in Europe. It is particularly intriguing to see how many Modernist-style wine cellars –also known as “wine cathedrals”– were built in the rural areas, and to discover the Modernist-style factories which bear witness to the industrial strength of Catalonia in the wake of the Industrial Revolution. Barcelona has more Art Nouveau buildings than any other city in the world, no wonder it was the birthplacei, 150 years ago, of Antoni Gaudí.

The Baix Empordà

The “Baix Empordà” occupies the centre of the Costa Brava and offers a sizeable array of cultural, geographic, culinary and commercial offerings. Sites that are truly ”must-sees” include the Medes islands, located just off the coast across from the Montgrí massif, the coves of Begur, Calella de Palafrugell and the Sant Sebastià lighthouse, in addition to the remains of the Iberian settlement at Ullastret and the medieval villages of Pals and Peratallada.

The capital of the region is La Bisbal d’Empordà, a town with a longstanding pottery tradition that has been kept alive thanks to the activity of a good number of master craftsmen. The history and evolution of the pottery tradition is reflected in the recently inaugurated Terracotta-Pottery Museum of La Bisbal. The streets of the old quarter lead to the Plaça Major, or central square, the erstwhile parade grounds of he Episcopal castle. Built in the mid-11th century, the castle is considered one of the most important examples of the Catalan civil Romanesque style.

The Baix Empordà coastline presents innumerable coves and inlets where sand and water combine to offer up one of the main natural attractions of the Costa Brava. The Fornells, Aiguablava, Sa Tuna, Aiguafreda, Cap Sa Sal and Sa Riera inlets in Begur, or the Aigua-xelida, Tamariu, Llafranc and Calella inlets in Palafrugell, together with the beaches of L’Estartit, Pals, Sant Antoni de Calonge, Palamós, Platja d’Aro, Santa Cristina d’Aro and Sant Feliu de Guíxols, are noted for the beauty of their surroundings. In the summer months, these and many other coastal towns celebrate an infinity of festive events, most notably the Torroella de Montgrí Music Festival and the traditional ”Habaneras” festival in Calella de Palafrugell, held each year on the first Saturday in July.

An panoramic view of the region is provided from the Sant Sebastià lighthouse at Calella de Palafrugell. At the Cap Roig Botanical Gardens, we can find the most important species of flora in the Mediterranean. The Palafrugell Cork Museum, which shows the cork transformation processes and machinery used in this industry’s past, constitutes another of the area’s interesting sites.

One of the Baix Empordà’s greatest ecological treasures is the Medes islands, a tiny archipelago located just off the coast of L’Estartit formed by seven islets characterised by the lavishness of its marine ecosystem. The proximity of the coast and of the mouth of the Ter river allow the Medes to nurture their unique flora and fauna with abundant amounts of organic matter. Noteworthy examples of this unique seascape include the flocks of seagulls, banks of posidonia algae and myriad coral forms.

The Baix Empordà boasts another major natural site: the Gavarres massif, with its forests of holm oaks and cork oaks and typical Mediterranean fauna. The massif contains an important legacy of megalithic funerary monuments, in addition to large medieval defensive constructions and Pre-Romanesque and Romanesque religious buildings. One of the area's main attractions is the Cova d'en Daina dolmen, located in the municipality of Romanyà de la Selva.

Another of the Baix Empordà's major attractions is the Iberian settlement at Ullastret. The museum of this site shows the Iberians' legacy in the region during the heyday of their settlement in the 7th century B.C.

Medieval architecture endures in all its splendour in the Benedictine monastery at Sant Feliu de Guíxols, the historic site of Peratallada and the old quarter of Pals. The fortified enclosure of Peratallada is characterised by its keep and the palace it shelters. The town streets preserve a typically medieval urban layout, with most of them emerging onto the main square. The most distinguished sites in Pals include the Torre de les Hores, a magnificent circular Romanesque tower, and the church of Sant Pere, which presents a unique succession of styles from the Romanesque up to the 18th century. Another must visit is the Pedró lookout point, which offers splendid views of the Medes islands, the Montgrí massif, the Canigó peak and the Albera mountain range. The towns of Cruïlles and Monells constitute two more excellent examples of the region's most characteristic medieval heritage.

The Costa Brava

The Costa Brava's 200 km of coastline are a mosaic of Mediterranean villages like L'Escala, Palamós and Sant Feliu de Guíxols, with their rooftops washed by the sun and their feet in the sand, draped in rocky outcroppings and green pines to meet the golden waters of the Mediterranean. The uniqueness of this moving and sudden encounter between mountain and sea is what led the journalist Ferran Agulló to define this coast as the Costa Brava, the "Rugged Coast"

As most of the regions of Girona, the word that best defines it is diversity. Don't expect to find one landscape, one light, one vegetation... what you will find is a multitude of changing landscapes, evolving as you advance in one direction or another.

There are a lot of recommended places to visit: the Cap de Creus Natural Park, whose landscape suggests what the earth must have been like in its origins, the marshes of the Aiguamolls de l'Empordà, the Medes islands (in L'Estartit), the coves and inlets of Begur and Palafrugell, the citadel of Roses, the Greek and Roman ruins of Empúries (in L'Escala), the medieval villages of Pals and Peratallada, the Iberian remains of Ullastret, the old town of Tossa de Mar and the beautiful botanical gardens of Blanes and Lloret de Mar. At the Costa Brava, you can probably enjoy the biggest concentration of enchanting sights and experiences in the shortest possible distance.

Monuments

- *Romanesque:* Visitors are offered the essence of a millenary past, taking them into a magical world of unique religious, civil and military constructions. Visitors should not miss visiting the monasteries of Sant Pere de Rodes, Sant Joan de les Abadesses, Santa Maria de Ripoll and Sant Feliu de Guxols, the church of Sant Cristòfor in Beget, and the churches of Llanars, Molló, Santa Maria de Porqueres and Santa Maria de Vilabertran. Not to forget the historic centres of Girona, Santa Pau and Besalú.

- *Gothique:* The thread of history goes on to offer us a valuable legacy in the shape of remarkable buildings such as the church of Santa Maria, in Castelló d'Empúries, known as the "Empordà cathedral"; the convent of Sant Domènec, the cathedral and some of the buildings in the old quarter of Girona, the castle and the Carmelite convent in Peralada; the parish church and Montgrí castle, in Torroella de Montgrí, and the town centres of Pals, Peratallada and Sant Martí d'Empúries, amongst many others.

- *Baroque:* This artistic current bears witness to the exquisite sensibility of the society from which it arose, with examples in some of the altarpieces in Girona cathedral and the parish churches of Cadaqués, Palamós and Lloret de Mar; then there are imposing buildings such as the Roses citadel or the Carmelite convent and the Hospital of Sant Jaume in Olot, to name just a few examples.

- *Modernism:* One of the jewels of Catalan architecture, which in the Girona province can offer buildings as noteworthy as the Cusí and Salleras houses in Figueres, the Serinyena house in Cadaqués, the Casino dels Nois in Sant Feliu de Guíxols, the Armstrong cork factory in Palafrugell, the Masramon and Solà-Morales houses in Olot, the Masó and Ensesa houses and the La Punxa building in Girona, the Vichy Catalán spa in Caldes de Malavella, the Bonada and Sant Miquel de la Roqueta houses in Ripoll, and the Casal in Camprodon.

Cuisine

Catalan cooking of the Costa Brava and the Pyrenees has a strong popular accent, even in restaurants. Nevertheless, we are talking about an historic and cultured style of cooking which is more than 1000 years old.

Empordà (the sea) and Cerdanya (the mountains) even today use products that were introduced or described by the Greeks and the Romans. Afterwards, the Arabs in the Early Middle Ages brought us ingredients (such as sugar, rice, artichokes ...) which were unknown to the rest of Europe at that time. And in the Late Middle Ages our national cuisine had such fame (including dishes and sauces which, miraculously, still exist today) that the sophisticated Italians of the Renaissance affirmed that the Catalan chefs (amongst them Robert de Nola) were the best in Europe. Literary chefs (Sent Soví, Robert de Nola), dieticians and distillers (Arnau de Vilanova) and gastronomers and theoreticians (Francesc Eiximenis) give an air of nobility to our cuisine whether it be popular or refined, town or country, or even ecclesiastical. Continuing this historical saga, without leaving these regions, we also have important culinary documents of later periods. Fra Sever, of Olot, wrote the "Llibre de Pail de Quynar" ("The art of cooking") in 1787 whose recipes we still use today (stuffed pigs' trotters, stuffed aubergines, stuffed and roasted chicken ...). The very same Ferran Agulló, the journalist who "invented" the name "Costa Brava" wrote about its cuisine in the thirties giving it a role within the framework of the national cuisine of Catalonia. Later, came the writer/journalist Josep Pla, who in the years after the Spanish Civil War created the gastronomic literature of this part of the world. Still talking about cooks, we should mention his friend Josep Mercader, from the Empordà region, who fixed the ground rules for today's modern creative cuisine, and to all those who continue to keep its fame to the forefront.

However, there is one thing you should never pass up: the bounty of our restaurants, the so-called "mar i muntanya" cuisine, a sublime combination of the fruits of the sea with the meats and vegetables of the mountains and plains. Specialities like the suquet de peix (fish stew), cuttlefish and peas, chicken with crayfish, meatballs with prawns, or rice casserole will fill your album of mementoes, pictures which will come fondly back to mind when reminiscing about your stay in Catalonia.

You can find more information in http://www.costabrava.org/.

PROGRAM SUMMARY

Monday, June 10

08:00 – 08:30	**Registration**
08:30 – 09:00	**Opening Session**
09:00 – 09:45	**Martin Hechler:** HERSCHEL, PLANK and GAIA Orbit Design
09:45 – 10:30	**Roby S. Wilson:** The Genesis Mission: Mission Design and Operations
10:30 – 11:00	POSTERS and COFFEE BREAK
11:00 – 11:30	**Craig E. Roberts:** The SOHO Mission Halo Orbit Recovery from the Attitude Control Anomalies of 1998
11:30 – 12:00	**Martin B. Houghton:** Getting to L_1 the Hard Way: TRIANA's Launch Options
12:00 – 12:30	**Jean Kechichian, E. Campell, M. Werner & E. Robinson:** Solar Surveillance Zone Population Strategies with Picosatellites Using Halo and Distant Retrograde Orbits
12:30 – 13:00	**Alexander Sukhanov:** Possible Orbits for the First Russian/Brazilian Space Mission
13:00 – 15:00	LUNCH
15:15 – 16:00	**Gerald L. Condon, Christopher L. Ranieri & Cesar Ocampo:** Earth-Moon Libration Point (L_1) Gateway Station. Lunar Transfer Vehicle Kickstage Disposal Options
16:00 – 16:30	**Iwona Gacka:** The Halo Orbits in the Sun-Mars System
16:30 – 17:00	POSTERS and COFFEE BREAK
17:00 – 17:30	**Natalia Titova & Valentin N. Tkhai:** The Reversible System with Two Degrees of Freedom. Existence of Periodic Solutions in Non-Robust Cases
17:30 – 18:00	**Aexey E. Rosaev:** The Investigation of Stationary Points in Central Configuration Dynamics
18:00 – 18:45	**Gerard Gómez, Josep J. Masdemont & José M. Mondelo:** Libration Point Orbits: A Survey from the Dynamical Point of View

Tuesday, June 11

09:00 – 09:45	**Carles Simó:** The Dynamics of the RTBP in the Vicinity of the Secondary Including Collinear Points
09:45 – 10:30	**Wang Sang Koon:** Invariant Manifolds, the Spatial Three-Body Problem and Space Mission Design
10:30 – 11:00	POSTERS and COFFEE BREAK
11:00 – 11:30	**Gerard Gómez, Josep J. Masdemont & José M. Mondelo:** Dynamical Substitutes of the Libration Points for Simplified Solar System Models
11:30 – 12:00	**Alexander Sukhanov & Natan Eismont:** Low Thrust Transfer to Sun-Earth L_1 and L_2 Points with a Constraint on the Thrust Direction
12:00 – 12:30	**Regina Martínez & Carles Simó:** Periodic Orbits in the 3D Hill Problem
12:30 – 13:00	**Aexey E. Rosaev:** One Kind of Orbit of Collision Related with Lagrangian Libration Points
13:00 – 15:15	LUNCH
15:15 – 16:00	**Kathleen C. Howell:** Transfers to L_1 and L_2 Orbits that Include Lunar Encounters
16:00 – 16:30	**Miquel Àngel Andreu:** New Results on Computation of Translunar Halo Orbits of the Real Earth-Moon System
16:30 – 17:00	POSTERS and COFFEE BREAK
17:00 – 17:30	**Regina Martínez & Anna Samà:** On the Neighbourhood of Collinear Points in the Planar Three Body Problem
17:30 – 18:00	**Andrew D. Burbanks:** Normal Form Methods Applied to L_1, L_2
18:30 – 19:30	ROUND TABLE

Wednesday, June 12

09:00 – 09:45	**David Dunham:** Libration-Point Missions 1978-2000
09:45 – 10:30	**David Folta & Mark Beckman:** Libration Orbit Mission Design: Applications of Numerical and Dynamical Methods
10:30 – 11:00	POSTERS and COFFEE BREAK
11:00 – 11:30	**Juan Bastante, Augusto Caramagno, Luís Peñín & José Rodríguez-Canabal:** Satellites Formation Transfer to Libration Points
11:30 – 12:00	**John Carrico & Emmet Fletcher:** Software Architecture and Use of Satellite Tool Kits Astrogator Module for Libration Point Orbit Missions
12:00 – 12:30	**Martin W. Lo & Roby S. Wilson:** The LTool Astrodynamic Problem Solving Environment
12:30 – 13:00	**Cesar Ocampo:** COPERNICUS: A Trajectory Design and Optimization System
13:00 – 13:30	**Donald J. Dichmann, Eusebius Doedel & Randy Paffenroth:** AUTO2000 and the Computation of Periodic Solutions of the 3-Body Problem
13:30 – 15:15	LUNCH
15:30 – 20:00	VISIT TO GIRONA
21:00	BANQUET

Thursday, June 13

09:00 – 09:45	**Natan Eismont & Alexander Sukhanov:** Technical Constraints Impact on Mission Design to the Collinear Sun-Earth Libration Points
09:45 – 10:30	**Daniel J. Scheeres:** Orbit Determination and Control of a Spacecraft in a Libration Point Orbit
10:30 – 11:00	POSTERS and COFFEE BREAK
11:00 – 11:30	**Mark Beckman:** Orbit Determination Issues for Libration Point Orbits
11:30 – 12:00	**Gerard Gómez, Manuel Marcote & Josep J. Masdemont:** Trajectory Correction Maneuvers in the Transfer to Libration Point Orbits
12:00 – 12:30	**Antonio F. Bertachini:** Space Trajectories Between the Lagrangian Points and the Primaries in the Sun-Earth System
12:30 – 13:00	**Jordi Cobos & Josep J. Masdemont:** Astrodynamical Applications of Invariant Manifolds Associated with Collinear Lissajous Libration Orbits
13:00 – 15:15	LUNCH
15:15 – 16:00	**Martin W. Lo:** The InterPlanetary Superhighway and the Development of Space
16:00 – 16:30	**Turgay Uzer:** Phase-Space Transition States
16:30 – 17:00	POSTERS and COFFEE BREAK
17:00 – 17:30	**Shane Ross:** A Statistical Semi-Analytical Theory of Transport Rates
17:30 – 18:00	**Charles Jaffe:** Statistical Theory of Asteroid Escape Rates
18:00 – 18:30	**Charalampos Skokos:** Smaller Alignments Index Determining the Ordered or Chaotic Nature of Orbits in Conservative Dynamical Systems
18:30 – 19:30	ROUND TABLE

Friday, June 14

09:00 – 09:45	**Jacques Henrard:** The Trojan Web
09:45 – 10:30	**Enric Castellà & Àngel Jorba:** Dynamics Near the Lagrangian Points of the Real Earth-Moon System
10:30 – 11:00	POSTERS and COFFEE BREAK
11:00 – 11:30	**Frederic Gabern & Àngel Jorba:** Restricted Four and Five Body Problems in the Solar System
11:30 – 12:00	**Closing Session**
13:00 – 15:00	LUNCH

DAILY SESSIONS

Monday, June 10, 2002

09:00 AM – 13:00 PM and 15:15 PM – 19:30 PM

Session Room: Bahía
Session Title: Mission Analysis and Operations
Session Chair: Gerard Gómez

08:30 **Opening Session**

09:00 **HERSCHEL, PLANCK and GAIA Orbit Design.**
Martin Hechler (European Space Operations Center).

HERSCHEL/PLANCK (double launch in 2007 on ARIANE) and GAIA (launch in 2010 on SOYUZ/FREGAT) are Astronomy missions in the ESA Scientific Program with different objectives but with quite common requirements of a highly stable thermal environment and sky viewing conditions unobstructed by Earth and sun. A class of orbits near the L_2 libration point (outside Earth) in the sun-Earth system has been selected for these projects.

Not differentiating in the conventional way between Halo or Lissajous orbits, a family of non-escape orbits around L_2 has been classified solely by their property of neither falling towards the Earth nor to the sun within the limits of numerical precision of the initial conditions. This limit is defined by a bisection method and forward integration over e.g. 400 days starting from any point in the orbit.

The stable manifolds of some of the Lissajous orbits in this family (generally with large amplitudes) touch perigee conditions which can be naturally injected into by a launcher with maximum launch mass performance, e.g. fixed low perigee altitude, and specifically for ARIANE low inclination to equator, and a prescribed relation between argument of perigee and inclination. Thus a 'free' transfer to some of these orbits which requires no manoeuvres after perigee, except stochastic orbit corrections, exists.

Starting from the free transfers to the large amplitude non-escape orbits, transfers to small amplitude (e.g. maximum sun-spacecraft-earth angle below 10^o) have been constructed combining the linear theory for orbits in the restricted circular three body problem with the numerical algorithm. The linear theory defines directions of escape (e+8t-term) and non-escape in the velocity subspace. Manoeuvres along the non-escape direction which are optimum in the linear theory to change the orbit amplitude, are numerically corrected along the escape direction.

By the same approach also optimum eclipse avoidance strategies could be derived, which guarantee a mission of at least 6 years without eclipse with a manoeuvre of typically 15 m/s. The eclipse avoidance manoeuvres are performed during the last revolution before the eclipse occurs near one of the maximum amplitudes, and essentially revert the track of the motion in the plane orthogonal to the sun Earth line.

Launch windows and propellant allocations were derived for different given project specific constraints on the launcher ascent (e.g. sun aspect angle conditions), on the transfer (e.g. eclipse conditions), and on the final orbit (mainly amplitudes). Herschel and Planck will share a launcher, either an ARIANE 5 ESV (upper stage with delayed ignition after coast arc) or an ARIANE 5 ECA (cryogenic upper stage) launched from Kourou. HERSCHEL will remain on the large amplitude orbit to which the launcher naturally delivers, whereas PLANCK will perform an amplitude reduction manoeuvre. GAIA will be launched by a Soyuz/Fregat launch from Baikonur, with or without lunar gravity assists and the necessary phasing orbits. In all cases the combination of the orbit amplitudes (in ecliptic and orthogonal to it) for a given size (maximum sun-spacecraft-Earth angle) and the initial phase in the orbit will depend on the launch date.

Finally the navigation and orbit maintenance aspects of the mission have been studied for the transfer and for the phase in the Lissajous orbit comparing several maintenance strategies. The preferred strategy is using a constant manoeuvre direction (along the escape line in the linear theory) which allows a dedicated spacecraft design.

09:45 **The Genesis Mission: Mission Design and Operations.**
Roby S. Wilson (NASA Jet Propulsion Laboratory-Caltech).

The Genesis mission was successfully launched on August 8, 2001 on its journey to the Sun-Earth L_1 libration point. The ojective of the Genesis mission is to collect solar wind samples in a large amplitude Lissajous for approximately 2.5 years and then safely return them to Earth for analysis. This talk will explain the processes used to generate the Genesis trajectory and the design changes required to accommodate spacecraft capabilities and constraints, as well as the redesign for the launch slip from February to August 2001. The operational aspects of the mission will also be discussed, including redesigning the stationkeeping biases to simplify operations, planning for contingencies, and the upcoming tasks necessary to return the spacecraft safely back to a predefined landing area in Utah.

11:00 **The SOHO Mission Halo Orbit Recovery From the Attitude Control Anomalies of 1998.**
Craig E. Roberts (Computer Sciences Corporation).

The joint ESA-NASA spacecraft called the Solar and Heliospheric Observatory (SOHO) is historically the second of five deep-space missions to be operated at one of the Sun-Earth collinear libration points by the NASA Goddard Space Flight Center (GSFC). SOHO, launched in December 1995 with a goal of revolutionizing solar science, has flown in a halo orbit around the Sun-ward L_1 point continuously since March 1996. This billion-dollar mission had an intended two-year minimum lifetime to be followed by an extended mission phase of at least four years.

However in 1998 SOHO's life was nearly cut short twice by two separate, very different on-board anomalies of the severest natures. Both times SOHO was rescued, but only after immense and extraordinary struggles. The first mishap, which occurred in late June of 1998, saw SOHO lose 3-axis attitude control, with the resulting tumble severing communications with Earth. The loss of communications lasted until early August when radar signals re-discovered the de-powered, frozen spacecraft, slowly spinning about its major axis of inertia. By chance, SOHO's geometrical circumstances were then becoming such that the solar panels would soon be receiving some sunlight despite its spinning, non-nominal attitude. This good fortune provided the opportunity for a rescue, and a strategy was developed for slowly and carefully re-powering and thawing the spacecraft. The rescue effort conducted over several weeks was successful, and by late September the spacecraft itself was functioning nearly normally (though not yet the science instruments).

Recovery operations including a series of delta-V maneuvers to restore the halo orbit continued during the autumn of 1998, and optimism was high until the last of the gyroscopes failed just before Christmas. This event did not lead to loss of the Sun-pointing attitude control, but did lead to an automatic fail-over of attitude control from the gyros and momentum wheels to the spacecraft's thrusters. The problem was that, without the gyroscopes, there was no way to return attitude control to the reaction wheels and to cease the attitude thruster firing that was imparting a net delta-V in the Sun-ward direction. The continual thrusting posed a dual threat. Not only would SOHO eventually run out of fuel, but the cumulative delta-V imparted to the halo orbit as much as 0.4 m/sec per day threatened to push SOHO away from the L_1 region and into an independent and useless solar orbit. The mission appeared doomed, but after a months-long fight to rescue it a second time, SOHO was once again saved.

The aspects of the rescues that this communication will address concern the halo orbit. Halo orbits are not only extraordinarily sensitive to perturbations, but by their nature the delta-V costs to correct the orbit grow exponentially with the time elapsed from experiencing the perturbation. Due to the perturbations involved, both of the SOHO accidents threatened escape from the L_1 region. Hence, the mission could still have been lost despite all other efforts to re-establish control of the spacecraft's attitude and on-board functions, had personnel at GSFC's Flight Dynamics Facility (FDF) not found ways to restore the orbit while contending with numerous adverse circumstances arising from the accidents. Among the problems was broken on-board, closed-loop maneuver control, and orbit determination degraded to the point of uselessness. In response, a number of critical improvisations were devised. The most important of these, developed following the second mishap, was a technique for correcting orbital energy via a time-staggered series of counter-active delta-V maneuvers while modeling the propagation of the trajectory as a continuous low-thrust mission, which it essentially was for a period of 40 straight days. This was a feat never before performed with a halo orbit mission.

11:30 **Getting to L_1 the Hard Way: Triana's Launch Options.**
Martin B. Houghton (NASA's Goddard Space Flight Center).

Over the past four years, NASA s Goddard Space Flight Center has built and tested the Triana observatory, which will be the first Earth observing science satellite to take advantage of the unique perspective offered by a Lissajous orbit about the first Earth-Sun Lagrange Point (L_1). Triana was originally meant to fly on the U.S. Space Transportation System (a.k.a. the Space Shuttle), but complications with the shuttle manifest have forced Triana into a "wait and see" attitude. The observatory is currently being stored at NASA s Goddard Space Flight Center, where it waits for an appropriate launch opportunity to surface. To that end, several possible alternatives have been considered, including variations on the nominal shuttle deployment scenario, a high inclination Delta-type launch from Vandenberg Air Force Base, a Tsyklon class vehicle launched from Baikonur, Kazakhstan, and a ride on a French Ariane vehicle out of French Guiana into a somewhat arbitrary geostationary transfer orbit (GTO). This paper chronicles and outlines the pros and cons of how each of these opportunities could be used to send Triana on its way to L_1.

12:00 **Solar Surveillance Zone Population Strategies with Picosatellites Using Halo and Distant Retrograde Orbits.**
Jean A. Kechichian, Eric T. Campbell, Michael F. Werner and Ernest Y. Robinson (The Aerospace Corporation).

Solar surveillance missions that provide ample warning time of impending solar storms to satellite users in earth orbit are naturally designed to allow the weather forecasting spacecraft to wander as far away from the earth as possible, in the direction of the sun. Vehicles positioned on the L_1 halo orbits do not provide more than an hour of warning time due to the fact that the L_1 equilibrium point of the sun-earth system is located at some 1.5 million km from the earth. In order to increase this warning time by a factor of two or more, use is made in this paper of distant retrograde orbits (Ref.1), which remain in the vicinity of the earth but at substantially larger distances from it than the L_1 point. However the spacecraft transits only for a limited time inside the surveillance zone centered on the sun-earth axis, such that a certain number of such vehicles in the form of inexpensive picosatellites is needed for continuous surveillance capability. Alternatively, and in a different scheme, picosatellites are released from their parking halo orbit to travel on that halo orbit invariant unstable manifold (Ref. 2), in succession and thereby wander farther away from the earth for increased warning time. This paper shows several picosatellite release strategies and their associated trajectories for both the distant retrograde orbit and the halo orbit cases mentioned above. It also provides an estimate of the minimum number of picosatellites needed for continuous coverage for a given time span.

12:30 **Possible Orbits for the First Russian/Brazilian Space Mission.**
A. Sukhanov (Space Research Institute (IKI) of Russian Academy of Sciences).

At present a first Russian/Brazilian space mission is being developed. The main mission goal is space weather monitoring and study of the solar wind interaction with the Earth magnetosphere. A Russian satellite is to be inserted into a highly eccentric Earth orbit with apogee of about 400,000 km. Brazil intends to participate in the mission with its own satellite whose orbit is not defined yet. One of the options being considered is piggybacking the satellite with the Russian one and then launching it from the Russian satellite orbit to the Sun-Earth L_1 point and possibly L_2 point. Several possible orbits for the Brazilian satellite were found. All of them are ballistic, i.e. do not include any active maneuvers except launch from the parking orbit and possibly insertion into a halo orbit (if it is included in the option). There are both direct transfers and using Moon swingby ones among the orbits. The orbits can be conventionally divided into the following groups:

- Insertion into L_1 halo orbit;
- Insertion into a quasi-periodic orbit approaching L_1 point and returning to Earth;
- Flying by the L_1 point and subsequent transfer to L_2 point with possible insertion into a halo orbit around the point;
- Insertion into a quasi-periodic orbit approaching L_1 and L_2 points in turn.

The orbits are shown and described in details in the paper.

References:

(a) Ocampo, C, *Trajectory Optimization for Distant Earth Satellites and Satellite Constellations,* PhD Thesis, University of Colorado, Department of Aerospace Engineering Sciences, 1996.

(b) Howell, K.C, B.T. Barden, and M.W. Lo, *Application of Dynamical Systems Theory to Trajectory Design for a Libration Point Mission,* The Journal of the Astronautical Sciences, Vol.45, No.2, April-June 1997, pp. 161-178.

15:15 **Earth-Moon Libration Point (L_1) Gateway Station. Lunar Transfer Vehicle Kickstage Disposal Options.**

Gerald L. Condon (NASA Johnson Space Center), Christopher L. Ranieri (NASA Johnson Space Center) and Cesar Ocampo (The University of Texas at Austin).

The notion of human missions to libration points has been proposed for more than a generation. A human-tended Earth-Moon libration point (L_1) Gateway Station could support an infrastructure expanding human presence beyond low Earth orbit and serve as a staging location for human missions to the lunar surface, Mars, asteroids, and other libration point locations. Human occupation of the Gateway Station requires a human transfer system in the form of a Lunar Transfer Vehicle (LTV) designed to ferry the crew between low Earth orbit and the Gateway Station. A key element of such a system is the proper and safe disposal of the LTV kickstage. Another important element addresses potential unplanned or undesired return of either the Gateway Station or associated support spacecraft to Earth. This report addresses several potential options for post-trans L_1 injection LTV kickstage disposal including: return to Earth (ocean impact), lunar surface impact, lunar fly-by to escape from Earth-Moon system, and insertion into a long-life parking orbit. In addition, the report examines the orbit lifetime for a (compromised) vehicle or the Gateway Station, located at Earth-Moon L_1, which does not perform required station-keeping maneuvers. Orbit lifetimes are also determined for a vehicle at L_1 that experiences a parametric scan of impulsive ΔVs of varying magnitudes and directions.

Session Room:	Bahía
Session Title:	Dynamics Around the Libration Points
Session Chair:	Kathleen C. Howell

16:00 **The Halo Orbits in the Sun-Mars System.**

Iwona Gacka (Astronomical Observatory of Wrocław University).

This paper shows a families of halo orbits in the Sun-Mars system. It has been computed numerically. The method of numerical improvement of initial conditions was used to calculate a periodic orbit around collinear points L_1 and L_2. Then the program follows along the path of vector of initial conditions to get a family of these orbits. The set of the differential equations of motion and the variational equations was integrated using Bulirsch-Stoer method. We study the stability of periodic orbits in the circular restricted three-body problem with respect to some perturbations. In this work was included the disturbance from Earth as well as Jupiter. It was used the JPL Ephemerides which gave the position and velocity of this planets. The influence of radiation pressure is discussed too. There are shown the stable orbits, for which the stability parameters perform

the condition $|p| < 2$ and $|q| < 2$.

17:00 **The Reversible System With Two Degrees of Freedom. Existence of Periodic Solutions in Non-Robust Cases.**

Natalia N. Titova (A.A. Dorodnitsyn Computing Center of Russian Academy of Sciences) and Valentin N. Tkhai (Moscow State Academy of Instrument Making and Computer Science).

In this work we consider the reversible mechanical system with two degrees of freedom. For this system the non-robust case of existence the families of symmetric periodic solutions in the neighborhood of equilibrium is investigated. We mean the case when the characteristic equation of the linearized perturbed system in a neighborhood of equilibrium admits a zero root.

With these assumptions the necessary conditions of existence of such families are obtained. We have used the Poincare s method modified for reversible system.

The theoretical results are used for the investigation of existence of symmetric periodic orbits in a neighborhood of libration points in the restricted photo-gravitational three-body problem for non-robust cases.

17:30 **The Investigation of Stationary Points in Central Configuration Dynamics.**

Aexey E. Rosaev (FGUP NPC "NEDRA").

A system of N points, each having m mass, and a central mass M, forming a planar central configuration, is considered. The motion equations for a testing particle are given. Different forms of motion equations are compared. The linearization of equations is applied.

The main target of this work is to determine the stationary solution (libration points) coordinates in considered system, and then to study their behavior in dependence of different parameters -masses, number of points, etc.

It is shown, that the stationary solution (libration points) in considered system may be determined from algebraic equation of 5-th degree. It is obtained, that at large mass of particles outside libration point disappear. For inner libration points the limit minimal distance l was detected. In case small m / M solution for libration points in the considered problem have as a limit similar solution for 3-body collinear points. The stability of founded solution (in linear approach) is investigated.

The next step of our investigation is to construct another central configuration of 2N+1 body, where N new particles, each having m1 mass, different from m, are placed to the libration point of our first system. The possibility of the generalization to a system kN+1 body is discussed.

The main analytic results of this work verified with Maple symbolic computation system.

18:00 **Libration Point Orbits: A Survey from the Dynamical Point of View.**

Gerard Gómez (Universitat de Barcelona), Josep J. Masdemont (Universitat Politècnica de Catalunya) and José M. Mondelo (Universitat Politècnica de Catalunya).

The aim of this paper is to provide the state of the art on libration point orbits. We will focus in the Dynamical Systems approach to the problem, since we believe that it provides the most global picture and, at the same time, allows to do the best choice of both strategy and parameters in several mission analysis aspects.

This does not mean at all that other approaches, form a more engineering point of view and that have been widely used in the past, are not useful for the analysis of a particular mission. Many of them only provide single solutions (corresponding to some local extrema) but they do not give too much insight about the underlying questions relevant to the problem. The Dynamical Systems approach gives a greater flexibility and offers more options to the mission analysis.

Tuesday, June 11, 2002
09:00 AM – 13:00 PM and 15:15 PM – 18:30 PM

Session Room: Bahía
Session Title: Dynamics Around the Libration Points
Session Chair: Martin W. Lo

09:00 **The Dynamics of the RTBP in a Vicinity of the Secondary Including Collinear Points.**
Carles Simó (Universitat de Barcelona).

The RTBP can be considered as a mild perturbation of Kepler's problem around the primary except in a vicinity of the secondary. Most of the interesting dynamics taking place in short time scales occurs in a ball of size $O(\mu^{1/3})$ around the secondary. The goal of the lecture is to describe the main objects in that region of the phase space.

First the available results for Hill's problem will be reviewed, stressing on the multiple homoclinic and heteroclinic connections which have been found.

Then we shall pass to the RTBP. The changes in the behavior as a function of the mass parameter μ will be considered.

The key idea is to offer a description of the possibilities for space missions and the ways to go in and out from that region.

09:45 **Invariant Manifolds, the Spatial Three-Body Problem and Space Mission Design.**
Wang Sang Koon (California Institute of Technology).

The invariant manifold structures of the collinear libration points for the spatial restricted three-body problem provide the framework for understanding complex dynamical phenomena from a geometric point of view. In particular, the stable and unstable invariant manifold "tubes" associated to libration point orbits are the phase space structures that provide a conduit for orbits between primary bodies for separate three-body systems. These invariant manifold tubes can be used to construct new spacecraft trajectories, such as a "Petit Grand Tour" of the moons of Jupiter. Previous work focused on the planar circular restricted three-body problem. The current work extends the results to the spatial case.

This is a joint work with Gerard Gómez, Martin Lo, Jerrold Marsden, Josep J. Masdemont and Shane Ross.

11:00 **Dynamical Substitutes of the Libration Points for Simplified Solar System Models.**
Gerard Gómez (Universitat de Barcelona), José María Mondelo and Josep J. Masdemont (Universitat Politècnica de Catalunya).

In this communication we will present methodology to generate simplified models suitable for the analysis of the motion of a small particle, such as a spacecraft or an asteroid, in the Solar System. The procedure is based on applying refined Fourier analysis methods to the time–dependent functions that appear in the differential equations of the problem. The equations of the models obtained are quasi–periodic perturbations of the Restricted Three Body Problem that depend explicitly on natural frequencies of the Solar System. Some examples of these new models are given and compared with other ones found in the literature. For one of these new models, close to the Earth–Moon system, we compute the dynamical substitutes of the collinear libration points.

11:30 **Low Thrust Transfer to Sun-Earth L_1 and L_2 Points With a Constraint on the Thrust Direction.**
Alexander Sukhanov and Natan Eismont (Space Research Institute (IKI) of Russian Academy of Sciences).

Low thrust transfer from a low Earth circular orbit (LEO) to Sun-Earth L_1 and then L_2 points is

analyzed in the paper. A spin-stabilized spacecraft of 290-kg wet mass equipped with the Russian D-38 thrusters of the TAL type is considered. The spacecraft solar arrays form a cylindrical surface whose axis coincides with the spin axis. The thrusters provide jet acceleration along the spin axis in both directions. The spin axis is orthogonal to the Sun direction in order to provide maximum afflux of the solar energy. Thus, the thrust also is always orthogonal to the Sun direction.

The spiral ascent of the spacecraft from LEO is considered first. Each orbit of the spiral has two thrust arcs and two coast ones. The thrust arcs are compromising the maximum ascent rate and a loss due to the non-optimal thrust direction. Then the spacecraft is inserted into an L_1 halo orbit in the ecliptic plane. The total characteristic velocity for the Earth-to-halo transfer is 7.1 km/s, the propellant consumption is about 80 kg. The Earth-to-halo transfer duration is 14 months.

After the research program in L_1 is completed the spacecraft moves to an L_2 halo orbit. Three transfer options are considered: with zero, one, and two complete orbits around the Earth. The transfer trajectories include three thrust arcs, such as follows: launch from the L_1 halo, a mid-course maneuver, and insertion into the L_2 halo. However, a completely ballistic transfer including only the launch and insertion maneuvers is also possible in the case of two complete orbits around the Earth. The propellant consumptions in the considered transfers are 2.9, 2.2, and 0.7-0.8 kg for the zero, one, and two complete orbits around the Earth respectively. The transfer durations are 6, 8.5, and 10.5 months respectively. The amplitudes of the halo orbits and transfer parameters can be varied by means of changing the low thrust maneuver values and locations.

Thus, the paper demonstrates that the Earth-to-halo and halo-to-halo transfers can be performed by means of the low thrust orthogonal to the Sun direction. This constraint significantly simplifies the spacecraft design. At the same time the propellant consumption and transfer duration are quite acceptable.

12:00 **Periodic Orbits in the 3D Hill Problem.**
Regina Martínez (Universitat Autònoma de Barcelona) and Carles Simó (Universitat de Barcelona).

The Hill problem provides a good approximation of the restricted three body problem near the secondary. We give a description of different families of periodic orbits of the 3–dimensional Hill problem as well as their stability parameters. The Lyapunov and vertical periodic orbits born at the equilibrium points and the direct and retrograde periodic orbits can be seen as main symmetrical families in this problem. From these families many bifurcations are found. Some families have periodic orbits passing through collision so, the numerical continuation is done using the regularization of binary collisions. The existence of heteroclinic connections between periodic orbits of different families is also studied.

12:30 **One Kind of Orbit of Collision Related with Lagrangian Libration Points.**
Aexey E. Rosaev (FGUP NPC "NEDRA").

In the context of the asteroid's danger problem, the determination of potentially the most dangerous orbits - the orbits of collision with the Earth has a significant interest.

One kind of orbit of collision related with lagrangian libration solution for the three body problem. It is known, that possible (temporary) capture to a satellite orbit from orbit near libration point. In case captured orbit have large inclination, it has very fast eccentricity evolution (increasing), leads to inevitable collision.

It is not excepted, that object, caused ecological catastrophe 40 mln. years ago, and object push with the Earth on the border Mesozoic and Cenozoic era before the collision were move on of the Earth's satellite orbit.

The example of this kind of orbit of collision is presented at this work.

15:15 **Transfers to L_1 and L_2 Orbits that Include Lunar Encounters.**
Kathleen C. Howell (Purdue University).

Consider the design of transfer trajectories to the vicinity of the Sun-Earth collinear libration points. Most qualitative analysis must be accomplished from the perspective of a model with, at least, three bodies. However, since motion in this Earth-Moon region is essentially a four-body problem, the behavior apparent in a Sun-Earth three-body model can be significantly influenced in some cases due to lunar perturbations. Alternatively, a transfer strategy to exploit the potential advantage of the Moon¡?PC850(146)¿s presence through gravitational encounters is difficult to implement within the context of either the CR3BP or a model that employs ephemeris information for the Sun and Earth locations. Some semi-analytical and numerical studies to examine this problem are to be presented.

16:00 **New Results on Computation of Translunar Halo Orbits of the Real Earth-Moon System.**
Miquel Àngel Andreu (Universitat de Barcelona).

The computation of translunar Halo orbits of the real Earth-Moon system (REMS) has been an open problem for a long time, but now, it is possible to compute Halo orbits of the REMS in a systematic way. In this paper, we describe the method used for the numerical computation of Halo orbits for a time span longer than 41 years. Halo orbits of the REMS are computed from quasi-periodic Halo orbits of the Quasi-bicircular Problem (QBCP). The QBCP is a model for the dynamics of a spacecraft in the Earth-Moon-Sun system. It is a Hamiltonian system with three degrees of freedom and depending periodically on time. In this model, Earth, Moon and Sun are moving in a self-consistent motion close to bicircular. The computed Halo orbits of the REMS are compared with the family of Halo orbits of the QBCP. The results show that the QBCP is a good model to understand the main features of the Halo family of the REMS. Most of the results shown in this communication can be found in http://www.ma.utexas.edu/mp_arc-bin/mpa?yn=01-351

17:00 **On the Neighbourhood of Collinear Points in the Planar Three Body Problem.**
Regina Martínez and Anna Samà (Universitat Autònoma de Barcelona).

The goal of this note is to study a neighborhood of the collinear points of the general planar three body problem.

There are two families of periodic orbits: the Lyapunov family and the family of homographic solutions. We shall study the second family. The stability parameters of these periodic orbits depend on a parameter β (which depends only on the masses and ranges in (0, 7)) and the eccentricity of the orbit e.

First, these stability parameters are studied analytically for $e \gtrsim 0$ and for $e \lesssim 1$. In the case $e \gtrsim 0$ some properties of the normal form of the variational equations along the homographic solutions are proved. For $e \lesssim 1$ some variables related to the blow-up ones, which appear in studies of triple collisions, are introduced.

Later on the stability parameters are computed numerically for the full range of (β, e) and the bifurcation diagram is obtained. Note that the ranges studied analytically have severe numerical difficulties. It is found that, in general, these periodic solutions are hyperbolic–elliptic, but there are regions where they are hyperbolic–hyperbolic.

The existence of invariant tori in a neighborhood of the collinear points is also studied. To this end, the Hamiltonian system is reduced to the 4D central manifold using a normal form. It is checked numerically that the non-degeneracy conditions of KAM theorem are satisfied for all positive masses, including the 2:1 resonance case.

17:30 **Normal Form Methods Applied to L_1, L_2.**
Andrew D. Burbanks (University of Bristol).

The normal form transformation is applied to the libration points L_1 and L_2 in the spatially restricted three body problem. We present computer visualisations of the various geometrical objects constructed in phase space and mapped back into physical space using the normal form transformation.

18:00 **Stability of the Stationary Collinear Solutions in the Generalized Three-Body Problem.**
Vadim Buchin (Dorodnicyn Computing Centre of the Russian Academy of Sciences).

In frame of generalized three-body problem, interaction between two bodies is replaced by arbitrary potential forces. Stationary collinear solutions are obtained. Sufficient and necessary conditions of stability are studied. The research was supported by the Russian Foundation for Basic Research (01-01-02001, 00-15-96150).

18:30 **ROUND TABLE**

Wednesday, June 12, 2002
09:00 AM – 13:00 PM

Session Room: Bahía
Session Title: Mission Analysis and Software tools
Session Chair: Josep J. Masdemont

09:00 **Libration-Point Missions 1978-2001.**
David Dunham (Johns Hopkins University).

This paper will present a history of the concepts that have enabled the libration-point missions of the past quarter century. Halo and Lissajous orbits about the collinear libration points were first developed in the late 1960's in preparation for a satellite that could have supported communication with an Apollo mission to the back side of the Moon. Halo orbit theory was developed extensively for the 3rd International Sun-Earth Explorer (ISEE-3) satellite, the first libration-point mission launched in 1978. ISEE-3 also demonstrated the practicality of another new concept, double-lunar swingby trajectories that, like libration-point orbits, also fixed the orbit in the rotating frame, but at lower altitudes, to achieve different scientific goals. The basic ideas pioneered by ISEE-3 were used for the trajectory designs of SOHO, WIND, and Genesis. The ISEE-3 heritage, and the trajectory similarities and differences of these later missions, will be discussed. The idea of a Lissajous orbit with in-plane amplitude decreased by use of a lunar swingby, used effectively by MAP, was even found during calculations for ISEE-3, although the full utility of such trajectories was not realized until a few years later, as published in Russian studies for the never-flown Relict-2 mission. The background for the first Lissajous orbit mission, ACE, will also be described. Application of these concepts, and possible future improvements for planned missions, will conclude the presentation.

09:45 **Libration Orbit Mission Design: Applications Numerical and Dynamical Methods.**
David Folta and Mark Beckman (NASA Goddard Space Flight Center).

Sun-Earth libration point orbits serve as excellent locations for scientific investigations. These orbits are often selected to minimize environmental disturbances and maximize observability. Trajectory design in support of such missions is increasingly challenging as more complex missions are envisioned in the next few decades. Trajectory design software must be further developed to incorporate better understanding of the libration orbit solution space and thus improve the efficiency and expand the capabilities of current approaches.

The Goddard Space Flight Center (GSFC) is currently supporting multiple libration missions. This support includes mission operations, trajectory design, algorithm and software development and application of that software to real-time mission support. GSFC's software support of these mission consists of three programs: Swingby - a GSFC developed analysis tool using numerical integration and differential corrections, Astrogator - a COTS tool from Analytical Graphics Inc. using numerical integration and forward targeting, and Generator - an analysis tool developed by Purdue University using Dynamical System Theory. Using these tools, mission are designed and supported using both direct insertion and lunar gravity assists. Missions such as Microwave Anisotropy Probe (MAP), Next Generation Space Telescope (NGST), Triana and Constellation-X have all been designed and/or flown using these tools.

The use of our state-of-the-art interactive tools to support these missions is described. We also provide a brief survey detailing the diverse history of GSFC libration point missions and the methods used to design them.

11:00 **Satellites Formation Transfer to Libration Points.**
Juan C. Bastante, Augusto Caramagno, Luís F. Peñín (Deimos SPACE SL) and José Rodríguez-Canabal (ESA / European Space Operations Centre).

Many of the European space missions whose launch and operational life is envisaged for the next decade base the achievement of their mission objectives on their privileged orbital position around any of the Libration points of the Sun- Earth/Moon system, or even the Earth-Moon system. These environments present very well known advantages in terms of thermal stability, observation and communication geometries stability, and minimum levels of dynamic perturbations, thus requiring low frequencies and budgets for on-orbit maintenance manoeuvres.

On the other side, the concept of satellites formation has definitely emerged as one of the most promising ones that will surely enable the interplanetary exploration, achieving the missions goals by making an effective resources use and hence maximizing the scientific return, while minimizing mission cost. Among the most noticeable advantages, the satellites formation mission concept offers, with respect to the single spacecraft mission concept, an increased instrument resolution, reduced cost, the possibility of on-orbit mission re-configuration and overall system robustness.

The proposed paper treats the transfer of satellites formation to any of the collinear Libration points of the Sun-Earth/Moon system. As a consequence, it is more focused on relative dynamics and GNC issues (satellite with respect to the any of the other satellites in the formation) than on the optimization of an absolute transfer trajectory to the Libration points, which is a problem whose solution is already very advanced in literature. It presents part of the work being developed in the frame of the ESA / ESOC contract awarded to DEIMOS Space SL, for the development of a *Software Tool for Interplanetary Formation Flying*. The major points addressed in the proposed paper are hereafter summarized:

- A characterization of the transfer trajectories to the collinear Libration points is presented, taken as the step stone in the task of delimiting the relative satellites motion issues relevant for the definition of the GNC system.
- A brief presentation of the methodology adopted to face the FF problems in interplanetary scenarios is provided: a first analysis devoted to mission characterization will focus on the major perturbation inducing the relative dynamics that represent the main source for the GNC requirements.
- The dispersion and open loop analyses, regarding the formation evolution as a collection of satellites, are addressed on the basis of the absolute trajectory and dynamic environment previously fixed.
- A qualitative and quantitative characterization of the problem allows then the GNC design. The closed loop analyses provide thus an estimate of the relative formation maintenance cost and needs
- Finally, some important matters related to the relative formation maintenance are treated in more detail. Specifically, the following two points are considered:
  - Propulsion technologies selection for the formation maintenance purposes. It is considered the use of low thrust (and very low thrust) in combination with other propulsion technologies for orbit and FF correction manoeuvres;
  - Derivation of navigation requirements. The case of RF and optical navigation is considered, since these are the systems typically adopted for the formation missions under development.

11:30 **Software Architecture and Use of Satellite Tool Kits Astrogator Module for Libration Point Orbit Missions**
John Carrico and Emmet Fletcher (Analytical Graphics, Inc).

The Satellite Tool Kit (STK) Astrogator software module is the third and most recent version of a program originally developed by NASA Goddard Space Flight Center. This software lineage - Swingby, Navigator, Astrogator V started in 1998 and has since been used to design and operate many missions, including Clementine, Wind, SOHO, ACE, Lunar Prospector, the AsiaSat 3 rescue, and MAP. This paper describes the history of the software program and numerical methods employed. The authors also discuss the software design methodology and goals that led to this mature software product. Limitations encountered during analysis and operations use are described, as well as subsequent architecture changes made to alleviate them, reduce risk, and support automation. Finally, examples of real-world analysis problems are described, with solutions.

12:00 **The LTool Package.**
Martin W. Lo and Roby S. Wilson (NASA-JPL).

LTool is JPL's new mission analysis tool with specialization in libration orbits. It is used by the Genesis Mission for its prelaunch mission design as well as in current post-launch operations. It is also being used by the Terrestrial Planet Mission to study formation flight both in halo orbits and in SIRTF-like heliocentric orbits. It can also be used to design conventional conic-based interplanetary missions. LTool is not a program, but what is known as a Problem Solving Environment which has a Command Line User Interface (CLUI), Graphical User Interface (GUI), and 3D visualization capabilities all integrated into a common software environment. Matlab, Mathematica, and JPL's Quick are other examples of Problem Solving Environments. The user can use LTool interactively, or run LTool in batch mode for larger and longer computations. Various modules enable the users to compute conic orbits, halo orbits, invariant manifolds associated to halo orbits. Using a user-programmable differential corrector (multiple shooting) the various trajectory segments may be "glued together" to produce an end-to-end trajectory. Some of the novel features of LTool are:

- Ability to produce end-to-end trajectories, starting from first guess solutions to fully integrated trajectories with JPL ephemeris models. LTool tracks coordinates and units.
- LTool tracks coordinates and units.
- Trajectories are handled as abstract continuous functions of time. A function algebra permits users to manipulate trajectory functions algebraically.

In addtion to trajectory design, LTool also provides coverage analysis using a technique called multi-resolution visual calculus. Currently, low thrust trajectory integration module is being added.

The LTool environment is created using the object oriented Python CLUI, with Qt GUI, and OpenGL graphics. The integrated environment is called PyShell. Fortran, C, and C++ modules are pulled into the PyShell environment using UDL (Unified Description Language), a tool developed by the LTool Team. Currently LTool runs under LINUX, but within the year, a Windows version is expected.

This modular architecture allows the users to program at a high level, using a high-level language (Python), while providing speed and flexibility with the Fortran, C, and C++ modules. The various LTool modules provide a high level astrodynamic "programming language". This approach greatly increases the user's ability to prototype and to solve problems interactively.

12:30 **COPERNICUS: A Trajectory Design and Optimization System.**
Cesar Ocampo (The University of Texas at Austin).

A high precision system for trajectory design and optimization for single or multiple spacecraft in any gravitational environment within the solar system is discussed. The system consolidates most all trajectory optimization problems by examining the main problem as a series of sub-problems that have a reduced sensitivity. The system also allows the use of several propulsion systems in combination or as the sole propulsion device. The use of multiple reference frames, such as planet-to-moon or planet-to-planet rotating frames, expands the capability to analyze multi-body force field missions such as those associated with libration point trajectories and transfers, cycler trajectories between any given set of celestial bodies, or orbits that exist only in multi-body gravity force fields such as multi-body gravity assists, low energy escape orbits, and distant planet orbits.

The current prototype of the system uses multiple shooting and direct integration for targeting and state propagation. An efficient sequential quadratic programming algorithm is used to optimize a general scalar cost function subject to all specified nonlinear constraints. A complete trajectory is comprised of multiple segments where an individual segment is defined as an arc that connects two endpoints or nodes. The general definition of a segment includes a velocity impulse at each node and a finite burn arc connecting these node points. The node points are tagged with an epoch. Any segment can then be altered to form various segment types, for example, a segment can be defined to be an impulse followed by a coast period, or a finite burn arc without the endpoint velocity impulses, or simply a coast arc.

This generalized approach to the problem facilitates the optimization of trajectories for any type of mission in any force field encountered in most all spacecraft transfer problems. Additionally, inherent to the system is the capability to decouple dynamically any set of segments so that multiple spacecraft missions can be studied. In such cases, the node points are coupled via suitable boundary conditions to examine rendezvous and capture problems or cooperative spacecraft trajectories where any of the spacecraft may be cooperative or passive.

Impulsive maneuvers can be referenced to any fixed-center frame or relative to a vehicle centered frame allowing either for a velocity or radius reference pointing. Finite burn maneuvers can also be steered relative to the trajectory or remain fixed in any fixed-centered frame. In the case of finite burn maneuvers, both constant thrust and specific impulse or constant power (variable thrust and specific impulse) thrust arcs can be modeled. No distinction is made between high thrust or low thrust systems; both are treated equally and the specified propulsion system parameters defines the type of thrust arc.

Additionally, several types of problems are solved indirectly as a well defined multi-point boundary value problem that results from Primer Vector theory for the optimization of single or multiple segments using either impulsive or finite burn maneuvers.

As a demonstration of the capabilities of the system several practical trajectory design and transfer problems are modeled, solved, and, optimized using various types of propulsion systems. These classes of problems include:

- Planet centered transfer orbits
- Planet to Planet/Moon or Planet to Sun/Planet Libration Point transfer trajectories
- Libration point orbit trajectory design and targeting
- Heliocentric Planet to Planet transfers

Specific examples transfer missions can also be solved with the current system, these include:

- Earth Orbit to Moon Orbit transfers
- Earth-Moon and free return trajectories
- Libration point orbit trajectory design in the Sun/(Earth+Moon) system
- Libration point trajectories in the Rotating/Pulsating Earth Moon system
- Heliocentric Mars Sample Return missions
- Heliocentric Earth-Mars Cycler trajectories
- Distant Retrograde Orbit Transfers
- Low Energy Earth Escape Transfer Orbits

13:00 **AUTO2000 and the Computation of Periodic Solutions of the 3-Body Problem.**
Donald J. Dichmann (Astrodynamics Consultant), Eusebius Doedel (Concordia University) and Randy Paffenroth (California Institute of Technology

AUTO2000 is a software tool for continuation and bifurcation problems in ordinary differential equations. This paper discusses the parameter continuation algorithms that underlie the AUTO2000 software, and describes a method for computing families of periodic solutions of conservative systems. This method is then used to compute families of periodic solutions about the libration points in the Circular Restricted 3-Body Problem. It is shown that there are intricate connections between the families of orbits about the various libration points. Possible applications of some of the libration point orbits for space missions are also discussed.

Thursday, June 13, 2002
09:00 AM – 13:00 PM and 15:15 PM – 19:30 PM

Session Room: Bahía
Session Title: Dynamics Around the Libration Points
Session Chair: Kathleen C. Howell

09:00 **Technical Constraints Impact on Mission Design to the Collinear Sun-Earth Libration Points.**
Natan Eismont and Alexander Sukhanov (Space Research Institute).

For the practical realization of the mission to the collinear Sun-Earth libration points technical constraints play a significant role. In the paper the influence of the constraints generated by the use of piggy-back mode of the delivering spacecraft to the vicinity of libration points is studied. High elliptical parking orbit of MOLNIYA is taken as initial orbit for start to the L_1, L_2 libration points. The parameters of this orbit is supposed to be fixed and determined by the main payload demands.The duration of the passenger payload keeping on the mentioned 12 hours period orbit is limited for the case when launcher upper stage is used for the velocity impulse applying to put spacecraft onto transfer orbit to the libration point. The possibilities to use one axis attitude control of the spacecraft for the executing correction maneuvers are investigated, supposing that spacecraft is spin stabilized with the spin axis directed to the Sun and maneuver impulse goes along this axis. The cost of constraints is presented in terms of characteristic velocity and time of transfer to the libration point vicinity. The goal of the paper is to understand the possibility of using regular launches of MOLNIYA communication satellites by Soyz -Fregat launch vehicle for sending low cost scientific spacecraft to Sun- Earth libration points.

09:45 **Orbit Determination and Control of a Spacecraft in a Libration Point Orbit.**
Daniel J. Scheeres (The University of Michigan).

The novelty of libration point orbits is their hyperbolic instability. It is this basic property that allows them to serve as connections between disparate regions of space, and gives them their many practical uses. This same property also makes the navigation of spacecraft in libration point orbits a fascinating subject, one of which exposes new questions in orbit determination and control that have not been considered previously. The problem of spacecraft navigation and control is essentially concerned with the statistical distribution of orbits in phase space, and how best these statistical distributions can be sensed and controlled. When placed into an unstable orbital environment, the dynamics of these distributions become quite interesting, with volume preserving stretching and contraction of the phase flow occurring over times on the order of the Lyapunov Characteristic Time of the nominal orbit. The interplay between dynamics and spacecraft navigation in such an environment creates new opportunities for research and understanding. In this talk the basic theory of orbit determination and control will be presented in the context of libration point orbits. A review of past techniques applied to Sun-Earth libration point orbiters will be given, as well as a discussion of the challenges that exist for Earth–Moon libration point orbiters. Recent developments in this field will be presented and discussed.

11:00 **Orbit Determination Issues for Libration Point Orbits.**
Mark Beckman (NASA Goddard Space Flight Center).

Libration point orbits present a unique challenge to orbit determination analysts. The regime is clearly not the low Earth orbit or the interplanetary trajectories supported regularly by Goddard Space Flight Center (GSFC) and the Jet Propulsion Laboratory respectively. All past missions have been limited to ground based tracking through the Deep Space Network (DSN) using standard range and Doppler measurement types. Advanced technology is enabling other orbit determination (OD) options.

A survey of OD results from past LPO missions including ISEE-3, SOHO, ACE and MAP will be presented. Issues of prime importance to LPO missions will be addressed including the future DSN tracking loads, the use of X-band frequencies, the importance of solar radiation pressure modeling, the effects of spacecraft perturbations on OD and the limitations of Earth-based tracking to form an adequate baseline.

Advanced technology is enabling alternatives to the standard OD scenario for LPO missions. The implementation of Delta Differenced One-Way Range (DDOR) capability at the DSN 70-m sites will possibly enable greater accuracy and/or reduced DSN loads. OD can now be performed on-board and can incorporate additional measurement data from on-board sensors. GSFC's CelNav software has been ground tested and is the current baseline for the future Constellation-X mission.

The OD accuracy for LPO missions is important to mission designers in order to design station-keeping and correction strategies.

11:30 **Trajectory Correction Maneuvers in the Transfer to Libration Point Orbits.**
Gerard Gómez, Manuel Marcote (Universitat de Barcelona) and Josep J. Masdemont (Universitat Politècnica de Catalunya).

In this communication we revisit the paper by Serban et al. ("Halo orbit mission correction maneuvers using optimal control", Automatica 38, (2002) 571–583) about the study of the first required trajectory correction maneuver for a halo orbit space mission, which compensates the departure velocity errors introduced by the inaccuracies of the injection maneuver into the transfer orbit. The mentioned work uses a combination of dynamical systems concepts merged with an optimal control algorithm. In this new work we only use dynamical systems ideas. The study considers halo and Lissajous orbits around the libration points and an accurate computation of its stable manifold is used. The effect of using rough approximations for these invariant manifolds is also analyzed.

12:00 **Space Trajectories Between the Lagrangian Points and the Primaries in the Sun-Earth System.**
Antonio F. Bertachini (Instituto Nacional de Pesquisas Espaciais-DMC).

This paper is concerned with trajectories to transfer a spacecraft between the Lagrange points of the Sun-Earth system and the primaries (Sun and Earth). The well-known Lagrange points that appear in the planar restricted three-body problem are very important for astronautical applications. They are five points of equilibrium in the equations of motion, what means that a particle located at one of those points with zero velocity will remain there indefinitely. The collinear points (L_1, L_2 and L_3) are always unstable and the triangular points (L_4 and L_5) are stable in the present case studied (Sun-Earth system). They are all very good points to locate a space-station, since they require a small amount of ΔV (and fuel) for station-keeping. The triangular points are specially good for this purpose, since they are stable equilibrium points. The planar circular restricted three-body problem in two dimensions is used as the model for the Sun-Earth system, and Lemaitre regularization is used to avoid singularities during the numerical integration required to solve the associated Two-Point Boundary Problem. This combination is applied to the search of families of transfer orbits between the Lagrange points and the primaries (Sun and Earth), in the Sun-Earth system, with the minimum possible energy. The results show families of transfer orbits, parameterized by the transfer time. To solve the TPBVP in the regularized variables the following steps are used:

(a) Guess a initial velocity, so together with the initial prescribed position the complete initial state is known;

(b) Guess a final regularized time and integrate the regularized equations of motion from 0 until this final time;

(c) Check the final position obtained from the numerical integration with the prescribed final position and the final real time with the specified time of flight. If there is an agreement (difference less than a specified error allowed) the solution is found and the process can stop here. If there is no agreement, an increment in the initial guessed velocity and in the guessed final regularized time is made and the process goes back to step i). The method used to find the increment in the guessed variables is the standard gradient method.

12:30 **Astrodynamical Applications of Invariant Manifolds Associated with Collinear Lissajous.**
Jordi Cobos and Josep J. Masdemont

One method of transfer between two Lissajous around the same collinear equilibrium point is developed making use of the geometry of the phase space around these points. In a first step, a clean and clarifying approach from the linearized problem is presented, which also provide good guesses for orbits of small amplitude. After a complete understanding of the geometry of this problem in terms of dynamical structures, a solution for the nonlinear problem is presented as a natural generalization of the former. This solution is actually expected to be the optimum strategy for the problem.

An optimum strategy for eclipse avoidance in the L_2 case is also developed in this context, that gives for the Herschel/Planck Mission 6 years free of eclipse expending 15 m/s typically. for these invariant manifolds is also analysed.

Session Room: Bahía
Session Title: Dynamics Around the Libration Points
Session Chair: Carles Simó

15:15 **The InterPlanetary Superhighway and the Development of Space.**
Martin W. Lo (NASA-JPL).

Our Solar System is interconnected by a vast system of tunnels and passageways called "The InterPlanetary Superhighway (IPS)". Loosely speaking, IPS is the family of invariant manifolds generated by the Lagrange points of all the planets and moons in the Solar System. IPS contributes to our understanding of various transport phenomena within the Solar System. Comet Shoemaker-Levy-9 and the killer asteroid which caused the extinction of dinosaurs are conjectured to have traveled the IPS to their demise. On the other hand, the materials of life may also have been brought to Earth via the IPS. Today, NASA is using the IPS to plan ultra-low-energy missions. For example, we used it to compute the orbit for the Genesis spacecraft, which launched in August 2001 and will bring solar wind samples back to Earth in 2004. IPS is enabling many new mission concepts beyond Genesis, some examples are: formation flight for terrestrial exo-planet detection, human servicing of space missions from a lunar L_1 Gateway station, sample return missions from the Moon and Mars.

16:00 **Phase-Space Transition States.**
Turgay Uzer (Georgia Institute of Technology).

We use dynamical systems theory to construct a general phase space version of Transition State Theory. Special multidimensional separatrices are found which act as impenetrable barriers in phase space between reacting and non-reacting trajectories. The elusive momentum-dependent transition state between reactants and products is thereby characterized. A practical algorithm is presented and applied to a strongly coupled Hamiltonian.

17:00 **A Statistical Semi-Analytical Theory of Transport Rates.**
Shane Ross (California Institute of Technology).

The dynamics of comets and other solar system objects which have a three-body energy close to that of the collinear Lagrange points are known to exhibit a complicated array of behaviors such as rapid transition between the interior and exterior Hill's regions, temporary capture, and collision. The invariant manifold structures of the collinear Lagrange points for the restricted three-body problem, which exist for a range of energies, provide the framework for understanding these complex dynamical phenomena from a geometric point of view. In particular, the stable and unstable invariant manifold "tubes" associated to Lagrange point orbits are the phase space structures that provide a conduit for orbits traveling to and from the smaller primary body (e.g., Jupiter), and between primary bodies for separate three-body systems (e.g., Mars and Earth). Using the structures around Lagrange points, a statistical semi-analytical theory for the rate of escape of asteroids temporarily captured by Mars can be developed. Theory and numerical simulation are found to agree to better than a percent. These calculations suggest that further development of these statistical methods, as an alternative to large-scale numerical simulations, will be a fruitful approach to mass transport calculations.

17:30 **Statistical Theory of Asteroid Escape Rates.**
Charles Jaffé (West Virginia University).

Transition states are found in phase space and shown to regulate the rate of escape of asteroids temporarily capture in circumplanetary orbits. The transition states, similar to those occurring in chemical reaction dynamics, are then used to develop a statistical semi-analytical theory for the rate of escape of asteroids temporarily captured by Mars. Theory and numerical simulations are found to agree to better than a percent. These calculations suggest that further development of transition state theory in celestial mechanics, as an alternative to large-scale simulations, will be a fruitful approach to mass transport calculations.

18:00 **Smaller Alignment Index (SALI): Determining the Ordered or Chaotic Nature of Orbits in Conservative Dynamical Systems.**
Charalampos Skokos (University of Patras and Research Center for Astronomy Academy of Athens).

We apply the method of the Smaller Alignment Index (SALI) for determining the ordered or chaotic nature of orbits, both in Hamiltonian systems and symplectic maps. The computation of the SALI for a sample of initial conditions allows us to distinguish easily between regions in the phase space where ordered or chaotic motion occurs. The computation of SALI is performed rather easily: for a given orbit we follow the evolution in time of two different initial deviation vectors computing the norms of the difference (parallel alignment index) and the addition (anti-parallel alignment index) of the two normalized vectors. The time evolution of the smaller alignment index reflects clearly the chaotic or ordered nature of the orbit. In general the SALI tends to zero for chaotic orbits, while it fluctuates around non-zero values for ordered orbits.

18:30 **ROUND TABLE**

Friday, June 14, 2002
09:00 AM – 13:00 PM

Session Room: Bahía
Session Title: Solar System Dynamics and New mission conceps.
Session Chair: Gerard Gómez

09:00 **The Trojan Web.**
Jacques Henrard (Universite de Namur).

We describe and comment the results of a numerical exploration of the numerous natural families of periodic orbits associated with the equilateral equilibria of the restricted problem. Many (if not all) of these families are organized in a very structured network or cobweb. This structure evolves, again in a very organized way, when the mass-ratio varies. Such an organization is not due to chance and indeed most of its features can be explained either with full mathematical rigor or at least as likely possibilities. They are mainly due to the local behavior of parametrized two degrees of freedom Hamiltonian systems in the vicinity of an equilibrium. But some of the features are of a more global character. Some can be explained by continuity from the local behavior; others by another factor of organization for small values of the mass ratio: the approximation by the integrable two-body problem in rotating coordinates.

09:45 **Dynamics Near the Lagrangian Points of the Real Earth-Moon System.**
Enric Castellà and Àngel Jorba (Universitat de Barcelona).

In this work we consider the motion of an infinitesimal particle near the equilateral points of the real Earth-Moon system. We use, as real system, the one provided by the JPL ephemeris: the ephemeris give the positions of the main bodies of the solar system (Earth, Moon, Sun and planets) so it is not difficult to write the vector-field for the motion of a small particle under the attraction of those bodies. Numerical integrations of this vector-field show that trajectories with initial conditions in a vicinity of the equilateral points escape after a short time.

On the other hand, it is known that the Restricted Three Body Problem is not a good model for this problem, since it predicts a quite large region of practical stability. For this reason, we will discuss some intermediate models that try to account for the effect of the Sun and the eccentricity of the Moon. As we will see, they are more similar to the real system in the sense that the vicinity of the equilateral points is also unstable. However, these models have some families of lower dimensional tori (2-D and 3-D), some of them elliptic and some of them hyperbolic. The elliptic ones give rise to a region of effective stability at some distance of the triangular points in the above mentioned models. It is remarkable that these regions seem to persist in the real system, at least for time spans of 1000 years.

11:00 **Restricted Four and Five Body Problems in the Solar System.**
Frederic Gabern and Àngel Jorba (Universitat de Barcelona).

We focus on the dynamics of a small particle near the Lagrangian points of the Sun-Jupiter system. To try to account for the effect of other planets, such as Saturn or Uranus, we develop specific models based on the numerical computation of periodic and quasi-periodic (with two frequencies) solutions of the N-planetary problem and write them as perturbations of the Sun-Jupiter restricted Three Body Problem. The Jacobi formulation for the reduced N-planetary problem is described and a method for numerically computing 2-D invariant tori is reviewed.

11:30 **CLOSING.**

POSTER ABSTRACTS

– **Solving the TPBVP to Calculate Rendezvous Manoeuvre for Space Vehicles in the Halo Orbits.**
Annelisie A. Correa, Antonio F. Bertachini (Instituto Nacional de Pesquisas Espaciais-DMC) and Terezinha J. Stuchi (Universidade Federal do Rio de Janeiro).

The aim of this work is to study the periodic solutions in the restricted three-body problem, such as the tridimensional periodic orbits around the interior Lagrangian point L_1 in the Earth-Moon system. This family was computed by the numerical continuation method of solutions and is known as Halo orbit family. Our main purpose is to find transfer orbits to put a space vehicle in one of the Halo orbit in order to realize a rendezvous manoeuvre. To attain this task we have applied the Lambert's method in the three-body dynamics which is able to solve the two-point boundary value problem considering a time constraint, i. e., the particle leaves from a fixed point in the parking orbit around the Earth in direction to a fixed point on the Halo orbit in a selected time interval, which is the time of flight. Due to the symmetry of the restricted three-body problem, the return trajectory is equivalent to the direct one. The space vehicle could leave from the Halo orbit in direction to the parking orbit around the Earth. We have considered two kinds of the parking orbit: the circular and the elliptic one. The required ΔV to put this point of mass in an elliptical orbit around the largest primary is calculated assuming a fixed energy for the parking orbit. The rendezvous manoeuvre is applied in the following order: the target vehicle is orbiting the Halo orbit while the chaser leaves the parking orbit. The final position and the final time interval must be the same for the both vehicles. Following this context we have investigated which manoeuvre gives the minimum fuel consumption.

– **Evolution of Periodic Orbits Around Stationary Positions.**
Justyna Kaczmarek, I. Wytrzyszczak (A. Mickiewicz University) and Iwona Gacka (Wrocław University).

By the method of numerical continuation we generate families of periodic orbits in a vicinity of stable and unstable geostationary points under perturbing action of zonal and tesseral harmonics up to the order and degree 6. Next, we investigate the evolution of the families taking into account a certain spectrum of $J_{\ell,m}$ coefficients values, where $\ell = 2, 3$, $m = 0, ..., \ell$.

– **Locating Periodic Orbits by Topological Degree Theory.**
Charalampos Skokos (University of Patras and Research Center for Astronomy Academy of Athens).

We consider methods based on the topological degree theory to compute periodic orbits of area preserving maps. Numerical approximations to the Kronecker integral give the number of fixed points of the map provided that the integration step is small "enough". Since in any neighborhood of a fixed point the map gets four different combination of its algebraic signs we use points on a lattice to detect the candidate fixed points by selecting boxes whose corners show all combinations of sign. This method and the Kronecker integral can be applied to bounded continuous maps such as the beam-beam map. On the other hand they cannot be applied to maps defined on the torus, such as the standard map which has discontinuity lines propagating by iteration, or unbounded maps such as the Henon map. However, the systematic use of the bisection method initialized on the lattice, even though unable to detect all fixed points of a given order, allows us to find a sufficient number of them to provide a clear picture of the dynamics, even for maps of the torus because the discontinuity lines have measure zero.

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