Abstract only - not for publication

Innovative Trajectory Designs to meet Exploration Challenges

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Abstract

Missions incorporated into NASA's Vision for Space Exploration include many different destinations and regions; are challenging to plan; and need new and innovative trajectory design methods to enable them. By combining proven methods with chaos dynamics, exploration goals that require maximum payload mass or minimum duration can be achieved. The implementation of these innovative methods, such as weak stability boundaries, has altered NASA's approach to meet exploration challenges and is described to show how exploration goals may be met in the next decade.

With knowledge that various perturbations play a significant role, the mission designer must rely on both traditional design strategies as well as these innovative methods. Over the past decades, improvements have been made that would at first glance seem dramatic. This paper provides a brief narrative on how a fundamental shift has occurred and how chaos dynamics improve the design of exploration missions with complex constraints.

Innovative Trajectory Designs to meet Exploration Challenges

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Presentation to the
New Trends in Astrodynamics

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Agenda

✓ Vision for Space Exploration
- Exploration Overview
- Goals and Missions

✓ Traditional and Innovative Design Methods
- A Historical Perspective of Supported Missions
- Implementation of Chaos

✓ Mission Applications
- Sun-Earth Libration Missions
- Earth-moon Co-linear Libration Missions
- Lunar Mission Design

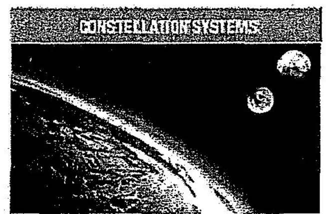
Vision for Space Exploration, A "Current" View

Exploration Systems Mission Directorate (ESMD)

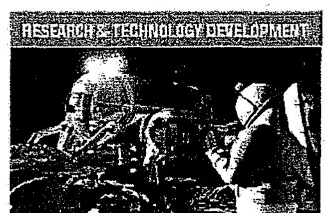
"... develop a constellation of new capabilities, supporting technologies, and foundational research that enables sustained and affordable human and robotic exploration."

Themes:
- Constellation Systems
- Crew Exploration Vehicle (CEV) Development and Launch Vehicles
- Exploration Systems Research and Technology
- Prometheus Nuclear Systems
- Technology and Human Systems

Also part of the ESMD is the Robotic Lunar Exploration Program (RLEP)
- Lunar Reconnaissance Orbiter (LRO)



Developing the vehicles and infrastructure that will allow us to travel to and explore the solar system.

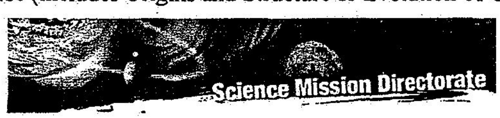


Developing the technologies today for tomorrow's exploration of the solar system.

Vision for Space Exploration, A "Current" View

Science Mission Directorate (SMD)

Combines former enterprises of the Space Sciences and Earth Sciences
- ✓ Solar System Exploration (SSE) *(includes the former Moon and Mars exploration)*
- ✓ Earth-Sun System (Sun-Earth-Connections and Earth Sciences)
- ✓ Universe (includes Origins and Structure & Evolution of Universe)



Examples
- Space interferometry missions,
- James Webb Space Telescope (JWST)
- Micro Arcsecond X-ray Imaging Mission (MAXIM) Concept
- SIRA(?) MMS(?)

Space Operations Mission Directorate (SOMD)
- ✓ Shuttle and ISS activities
- ✓ Space communications systems and the supporting infrastructure.
- ✓ *Ongoing libration orbit missions such as SOHO and WIND missions*

An Innovative Design

Definition: This new theory is defined as the use of chaos to design trajectories and orbits that can be used to meet complex mission goals

Benefits:

- o Minimizes fuel cost (related to Delta-V cost)
- o Optimizes trajectory profiles
- o Provides non-standard and new orbit designs
- o Mitigates operational risks

Other 'synonymous' terms

- o Dynamical Systems
- o Invariant Manifolds
- o Capture Orbits
- o Ballistic Orbits

A Sample of Analysis

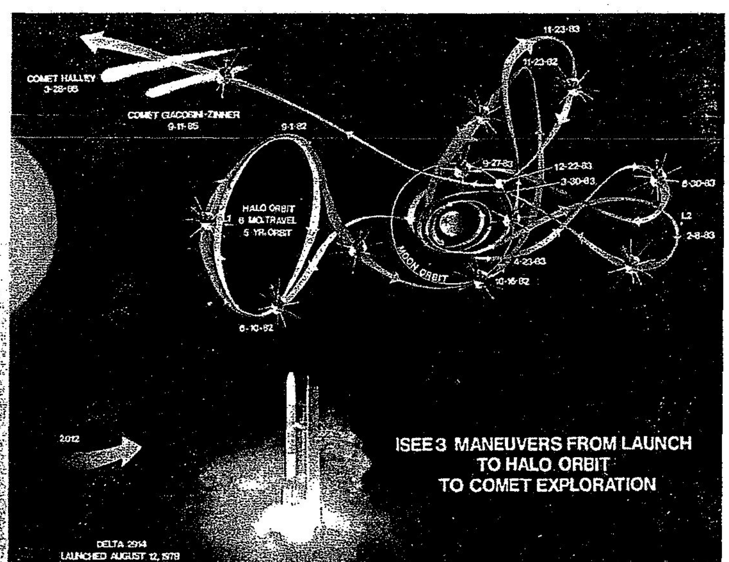
So let us look at a few sample ESMD and SMD missions:

- Sun-Earth libration orbits
- Earth-moon libration orbits
- Lunar mission design
- Use of chaos to aid in their design

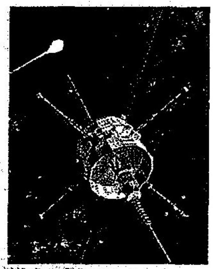
Historical and Future Missions in Libration Orbits

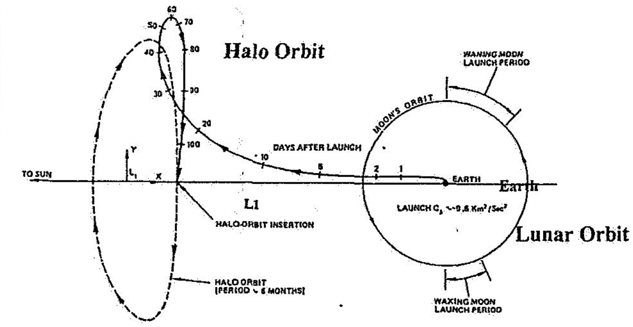
Mission	Location / Type	Amplitudes (Ax, Ay, Az)	Launch Year	Total ΔV Allocation (m/s)	Transfer Type
ISEE-3	L1Halo/L2/Comet 1st mission	175000, 660670, 120000	1978	430	Direct
WIND*	L1 – Lissajous	10000, 350000, 250000	1994	685	Multiple Lunar Gravity Assist
SOHO	L1 – Lissajous	206448, 666672, 120000	1995	275	Direct
ACE	L1 – Lissajous 1st small amplitude	81775, 264071, 157406	1997	590	Direct (Constrained)
MAP	L2-Lissajous 1st L2 Mission	n/a, 264000, 264000	2001	127	Single Lunar Gravity Assist
Genesis	L1-Lissajous	250000, 800000, 250000	2001	540	Direct
Triana	L1-Lissajous Launch Constrained	81000, 264000, 148000	#	620	Direct
JWST	L2-Quasi-Periodic Lissajous	290000, 800000, 131000	#	90	Direct
SPECs	L2-Lissajous Tethered Formation	290000, 800000, 131000	#	Tbd	Direct
MAXIM	L2 – Lissajous Formation	Large Lissajous	#	#	Direct
Constellation-X	L2 – Lissajous Loose Formation	Large Lissjaous		150-250	Single Lunar Gravity Assist
Darwin	L1-Lissajous Large Lissajous	300000, 800000, 350000	2014	#	#
Stellar Imager	L2 – Lissajous ~30 S/C Formation	Large Lissajous	2015	#	Direct
TPF	L2 – Lissajous Formation?	Lissajous	#	#	#

ISEE-3 / ICE



ISEE-3 / ICE



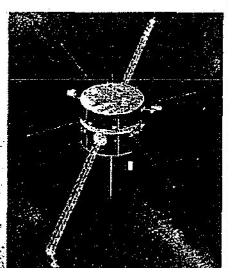


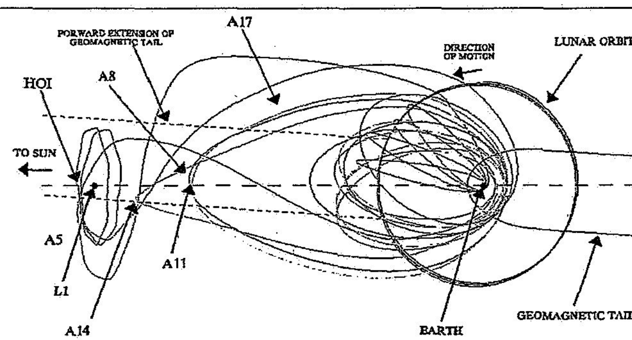
Solar-Rotating Coordinates
Ecliptic Plane Projection

Mission: Investigate Solar-Terrestrial relationships, Solar Wind, Magnetosphere, and Cosmic Rays
Launch: September, 1978, Comet Encounter Sept., 1985
Lissajous Orbit: L1 Libration Halo Orbit, Ax=~175,000km, Ay = 660,000km, Az~ 120,000km, Class I
Spacecraft: Mass=480Kg, Spin stabilized,
Notable: First Ever Libration Orbiter, First Ever Comet Encounter

Farquhar et al [1985] Trajectories and Orbital Maneuvers for the ISEE-3/ICE Comet Mission, JAS 33, No. 3

WIND

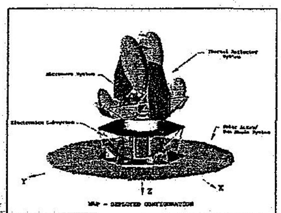


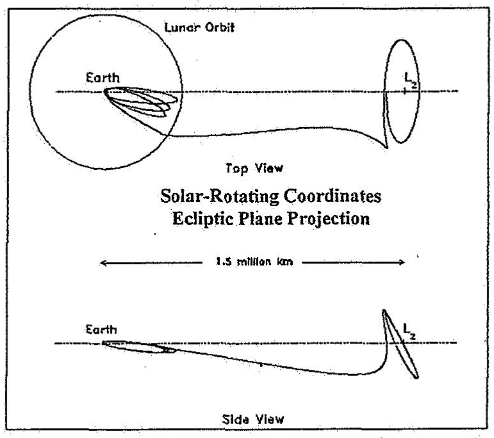


Solar-Rotating Coordinates
Ecliptic Plane Projection

Mission: Investigate Solar-Terrestrial Relationships, Solar Wind, Magnetosphere
Launch: November, 1994, Multiple Lunar Gravity Assist
Lissajous Orbit: Originally an L1 Lissajous Constrained Orbit, Ax~10,000km, Ay ~ 350,000km, Az~ 250,000km, Class I
Spacecraft: Mass=1254kg, Spin Stabilized,
Notable: First Ever Multiple Gravity Assist Towards L1

MAP





Mission: Produce an Accurate Full-sky Map of the Cosmic Microwave Background Temperature Fluctuations (Anisotropy)

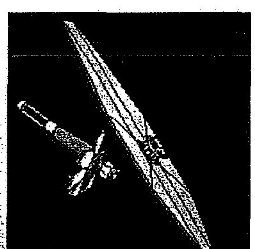
Launch: Summer 2001, Gravity Assist Transfer

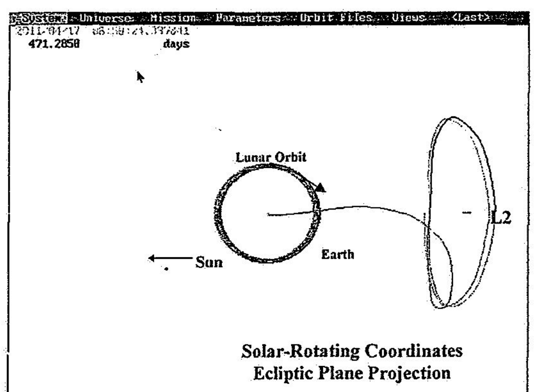
Lissajous Orbit: L2 Lissajous, Constrained Orbit Ay~ 264,000km, Ax~tbd, Ay~ 264,000km, Class II

Spacecraft: Mass=818kg, Three Axis Stabilized,

Notable: First Gravity Assisted Constrained L2 Lissajous Orbit

JWST





Mission: JWST Is Part of Origins Program. Designed to Be the Successor to the Hubble Space Telescope. JWST Observations in the Infrared Part of the Spectrum.

Launch: JWST~2012, Direct Transfer

Lissajous Orbit: L2 large lissajous, Ay~ 294,000km, Ax~800,000km, Az~ 131,000km, Class I or II

Spacecraft: Mass~6000kg, Three Axis Stabilized, 'Star' Pointing

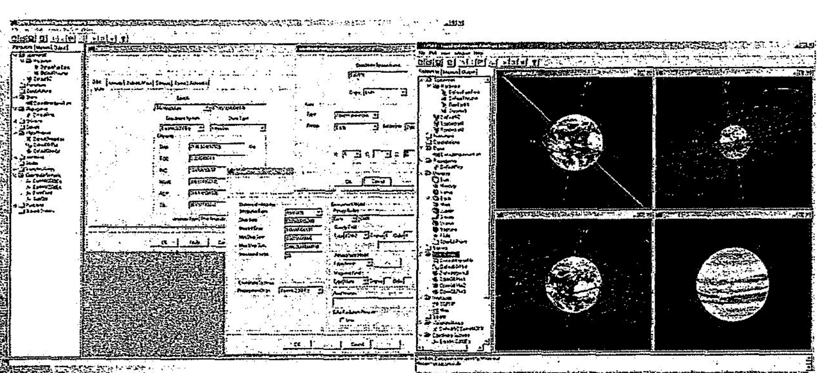
Notable: Observations in the Infrared Part of the Spectrum. Important That the Telescope Be Kept at Low Temperatures, ~3^{0}K. Large Solar Shade/Solar Sail

Using Chaos to Design Orbits

Current Capabilities and Developments

To design vision missions, we need unprecedented capabilities:

- High Fidelity Perturbation Theory Modeling
- Intuitive Numerical Targeting Methods
- Access to Environmental Models and Algorithms
- Commercial and NASA Mission Design Programs
- Inclusion of Dynamical System, Optimization, Control Flow



A General Design Process

In Low Fidelity Software

- Use Chaos mathematical expressions for preliminary orbit design, e.g. Circular Restricted Three-Body (CRTB) problem.
- Generate orbit families via differential correction and continuation.
- Analyze the properties of these orbits and to meet mission requirements.
- Obtain orbit architectures.
- Apply two-step differential correction scheme to selected orbits.
- Add multiple revolutions for baseline mission duration.

In Higher Fidelity Software:

- Differentially correct in full ephemeris model.
- Constrain orbit to desired goals, apply chaos to obtain Δv.
- Acquire Δv and fuel budget for station-keeping by perturbing initial target states in unstable directions and adding Δv errors.
- Analyze mission requirements and constraints (e.g Sun angle limits and Facility access)

Chaos - System Application

Numerical Systems

- Limited Set of Initial Conditions
- Perturbation Theory
- Single Trajectory
- Intuitive DC Process

Chaos Systems

- Qualitative Assessments
- Global Solutions
- Time Saver / Trust Results
- Robust
- Helps in choosing numerical methods

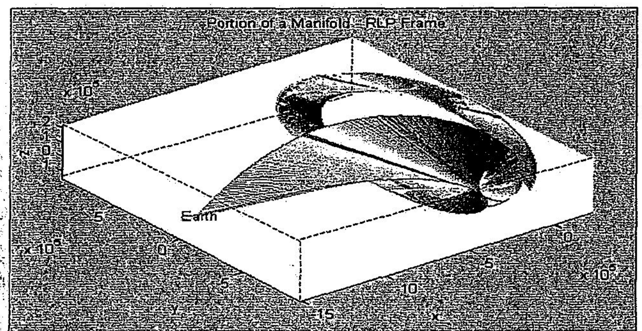
  (e.g., Hamiltonian => Symplectic Integration Schemes?)

Chaos and Invariant Manifolds

✓ Use of invariant manifolds are directly applicable to weak stability boundary and libration trajectory design

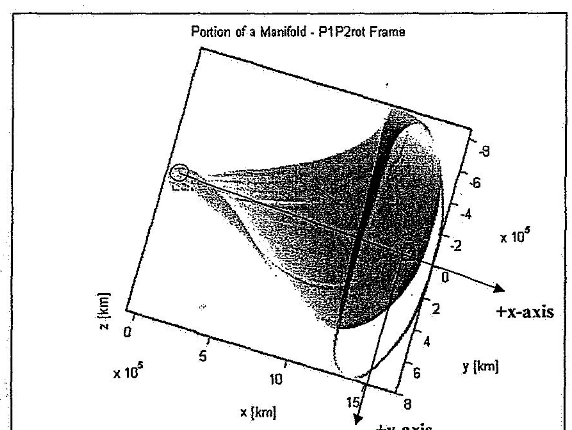
✓ Together with differential corrections, the use of invariant manifolds provides an efficient method to obtain transfers and control

✓ Invariant manifolds results can be used as a initial conditions for NASA mission design software



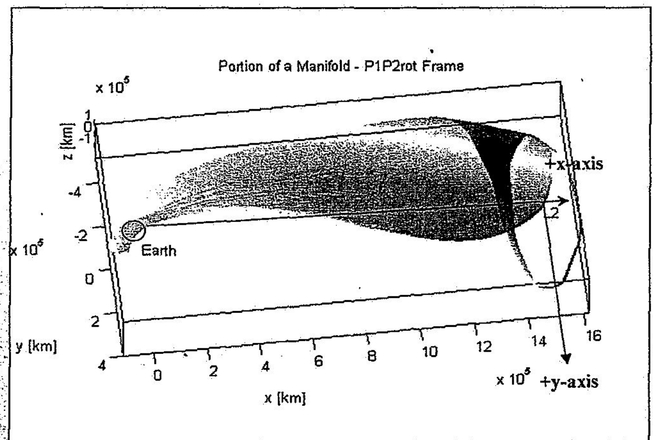
Chaos System Approach Transfer

Design a Large Libration Orbit's Transfer Trajectory - Projections of All Invariant Manifolds for Time Interval

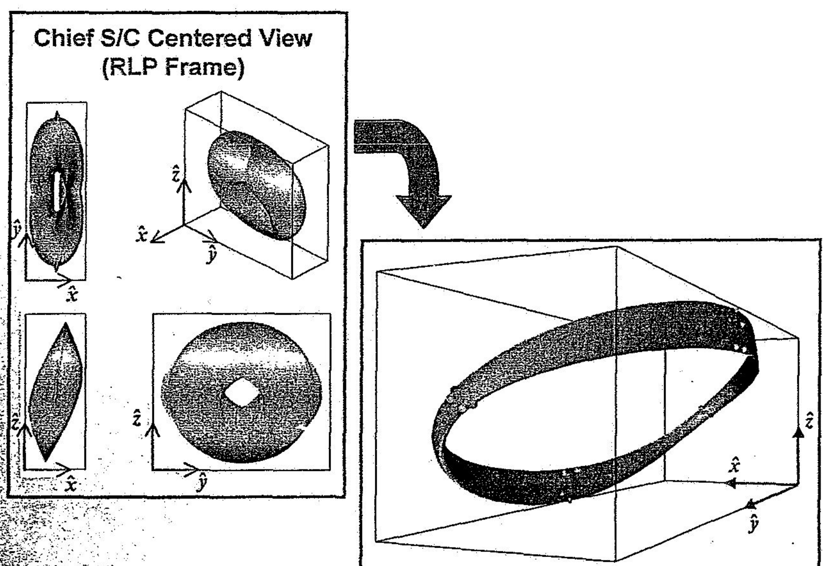


Chaos System Approach Transfer

Design a Small Libration Orbit's Transfer Trajectory
Projections of All Invariant Manifolds for Time Interval



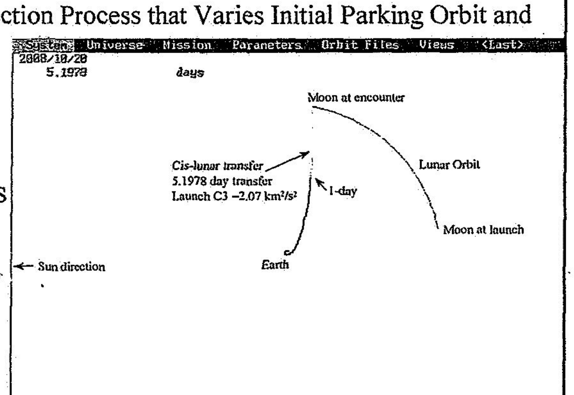
Natural Formations:
Design Quasi-Periodic Orbits → 2-D Torus



Lunar Orbit Design

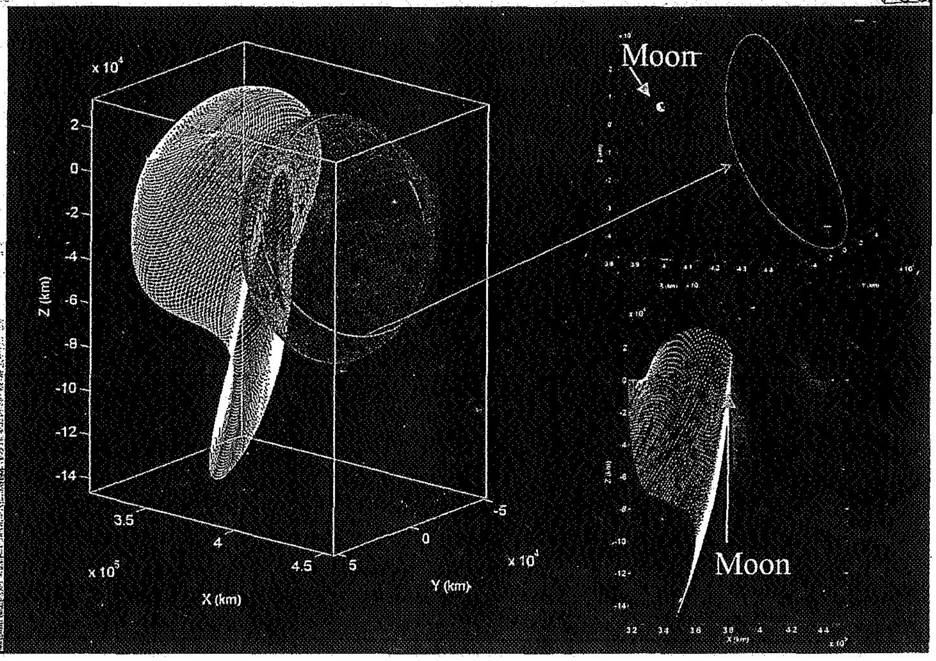
Lunar Orbit Design

- Uses Traditional Approach
  - ✓ Hohmann / Minimum Energy Transfer
  - ✓ Targeting Goals of Lunar Orbit, Moon Position, B-plane, and Orbit Conditions Chosen on Requirements
  - ✓ Numerical Differential Correction Process that Varies Initial Parking Orbit and Injection Velocity
- Successful and Easily Applied to Parametric And Monte Carlo Analysis
- Would Chaos Improve The Design?

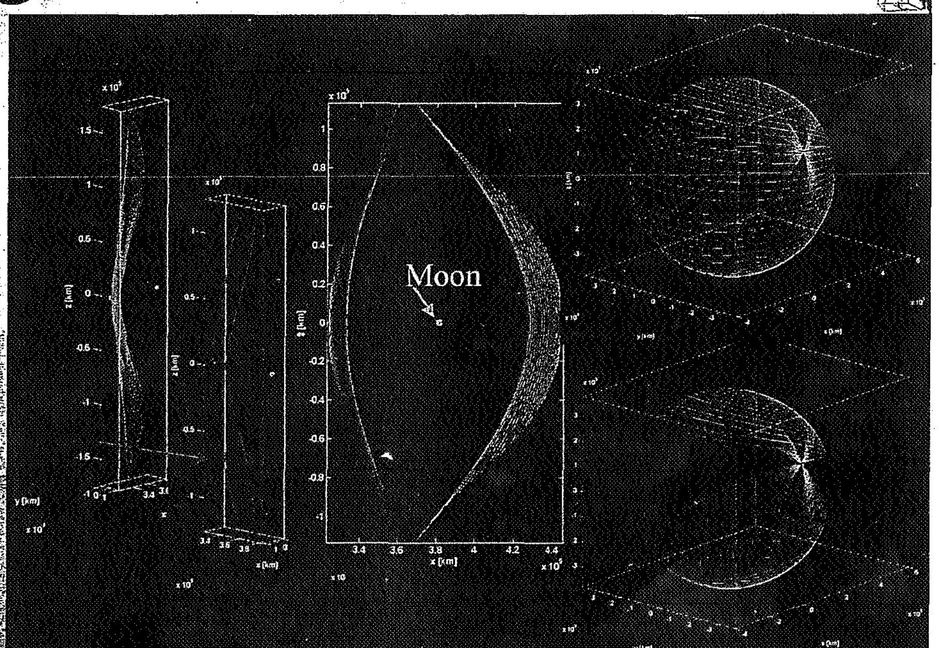


Nominal Cis-lunar Trajectory
Solar Rotating Coordinates

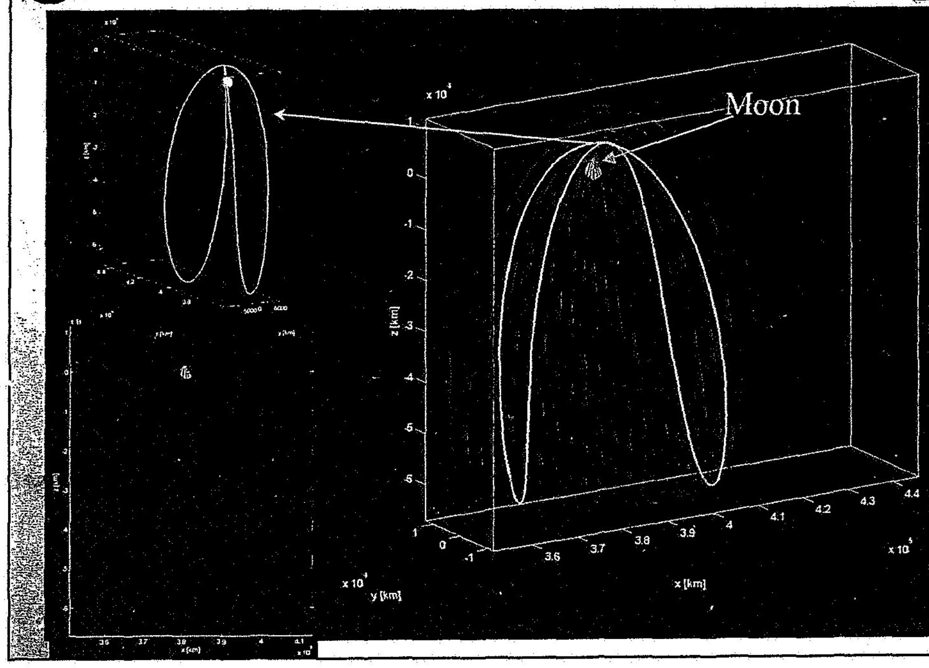
Earth – Moon L_1 & L_2 Halo Orbit Families



L_1 & L_2 Vertical Orbit Families



L_2 Butterfly Orbit Family

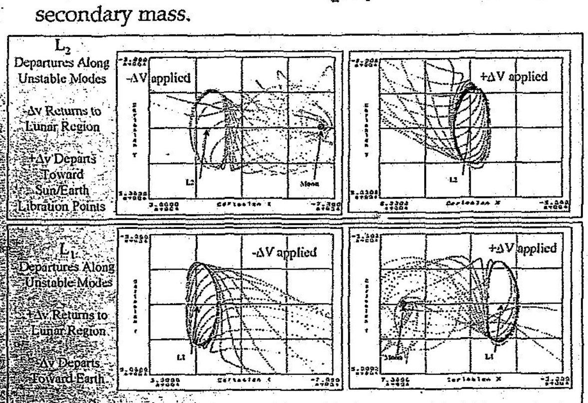


Applications of Chaos in the Earth-Moon Region

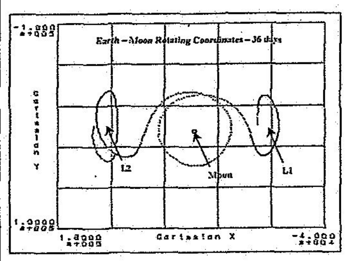
o A natural transfer between co-linear orbits is defined by the Eigenstructure of the co-linear STM and the dynamics in question.

o The co-linear unstable and stable modes are in the familiar directions and indicate that direct transfers between libration points are straightforward

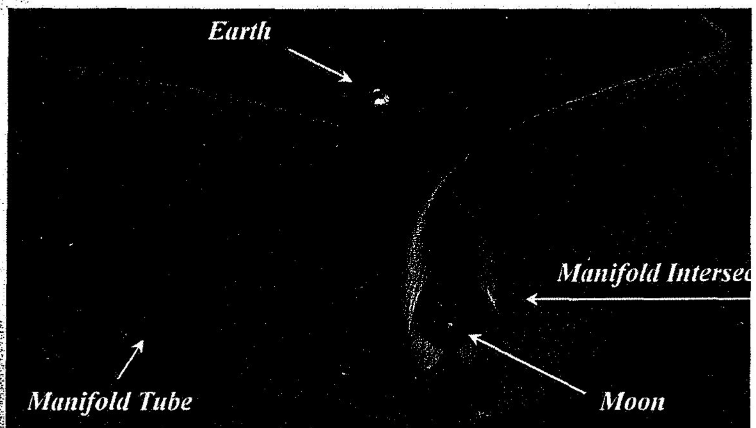
o Use the unstable mode of L_1/L_2 to perform a ΔV (possibly near or at zero magnitude) to transfer to the stable mode of L_2/L_1 once the trajectory has moved to the other side of the secondary mass.



Earth-Moon Co-linear Departures from L_1 and L_2



Applications of Chaos in the Earth-Moon Region

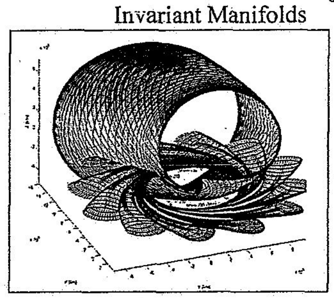


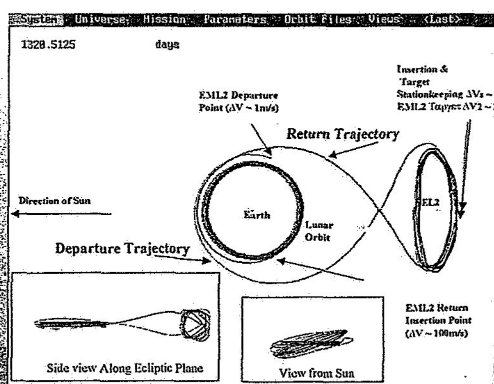
Placing a facility at the South Pole of the Moon poses questions concerning the orbital architecture of the communicating satellites. Constant communication can easily be achieved with Earth-Moon libration point orbits. We analyze different architectures for nearly rectilinear halo orbits, vertical orbits, and other three-body variations for lunar coverage of the South Pole. Using invariant manifold theory, we also analyze the transfer and station-keeping costs for these orbits. Libration point orbits may be a cheaper alternative to pole-sitters or even two-body, highly eccentric orbits.

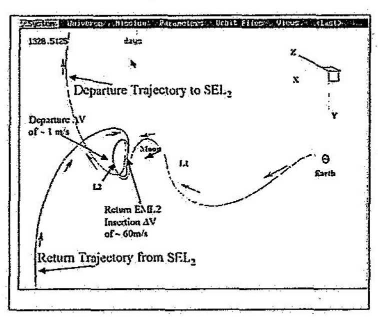
Applications of Chaos in the Earth-Moon Region

- Dynamical system provides the structure
- Numerical DC used for targeting process
- Need to improve methods
- Example: Finding intersections of Sun-Earth and Earth-Moon Manifolds for Transfer Trajectories

Invariant Manifolds



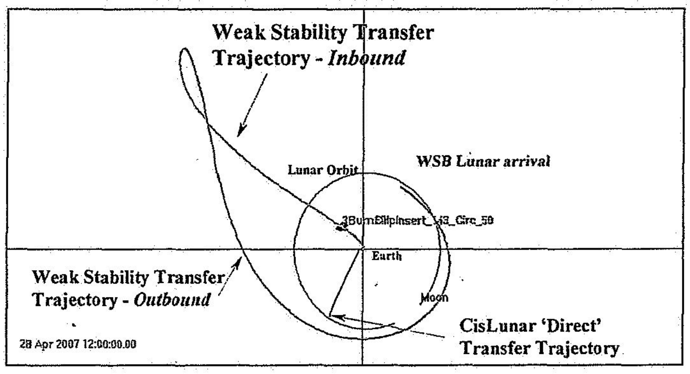




Comparison of Direct and Weak Stability Boundary Transfer to a 100km Circular Lunar Orbit

	Direct Transfer	Weak Stability Transfer
Launch Vehicle Injection (km/s)	3.13	3.17
Launch C3 (km^2/s^2)	-2.11	-0.59
Equivalent launch mass for C3	1595	1545
Total Delta-V to attain mission orbit (m/s)	821	664
Trip Time (days)	4.5	98.0
Max distance from Earth (million km)	0.367	1.5

- ΔV Improvement of 19.12%

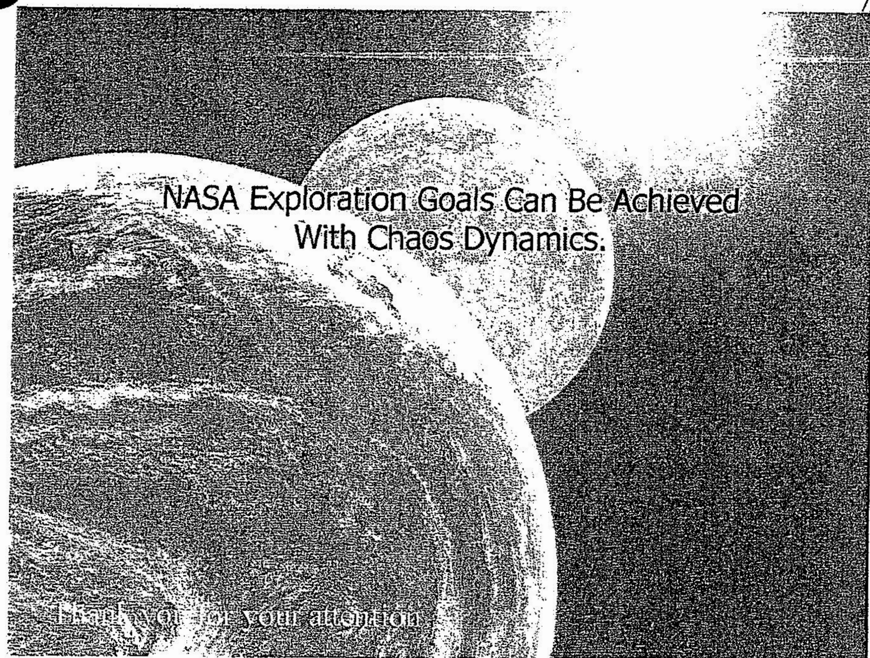


Assumptions:
- Polar lunar mission orbit at 100km altitude
- Launch Vehicle of Delta-II
- Final mass computed via rocket equation with starting launch mass, Isp=220, thrust = 22N, ΔV as above

New Orbits and Future Challenges

Upcoming missions also bring new challenges that individually may easily be met, but in combination they become problematic. These may include:

- Lunar Orbits for Relay Spacecraft
- Biased Orbits when using large sun shades
- Frequent Spacecraft Perturbations (momentum unloads)
- Constrained communications
- Shadow restrictions
- Very small libration orbit amplitudes (<10000km)
- Limited thruster directions
- Transfers Between Libration Orbits and the Moon
- Earth-Moon libration orbits
- Continuous control to reference trajectories
- Quasi-stationary orbits
- Human exploration
- Servicing of resources in libration orbits


NASA Exploration Goals Can Be Achieved
With Chaos Dynamics.
Thank you for your attention

Backup

History, Definitions, & Modeling

Mathematical History

Euler
- Defined three body problem in work on lunar motion.
- Proved existence of co-linear points

Lagrange
- Development of equilibrium points

Poincare
- Stability of motion and use of potential functions
- First to recognize the need for a qualitative approach to three body problem which is unsolvable in closed form

Jacobi
- One exact integral of three body system

Definitions & Modeling
- Easiest to model the system as the Circular Restricted Three Body Problem (CRTBP) where $m_1>>m_2>>m_3$
  - m_1 - primary, m_2 - secondary, m_3 - body of interest
  - motion of Earth about Sun is circular
  - motion of m_3 is in plane of m_1 & m_2
- CRTBP can be solved exactly
- Unfortunately, unmodeled forces (solar radiation pressure, other gravitational bodies - Jupiter, etc.) and physical reality (non-circular motion or EM system about sun) cause perturbations

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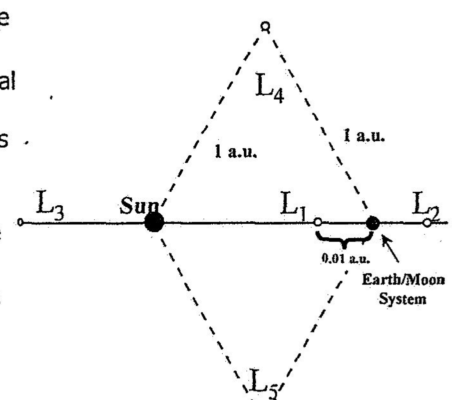
Libration Points

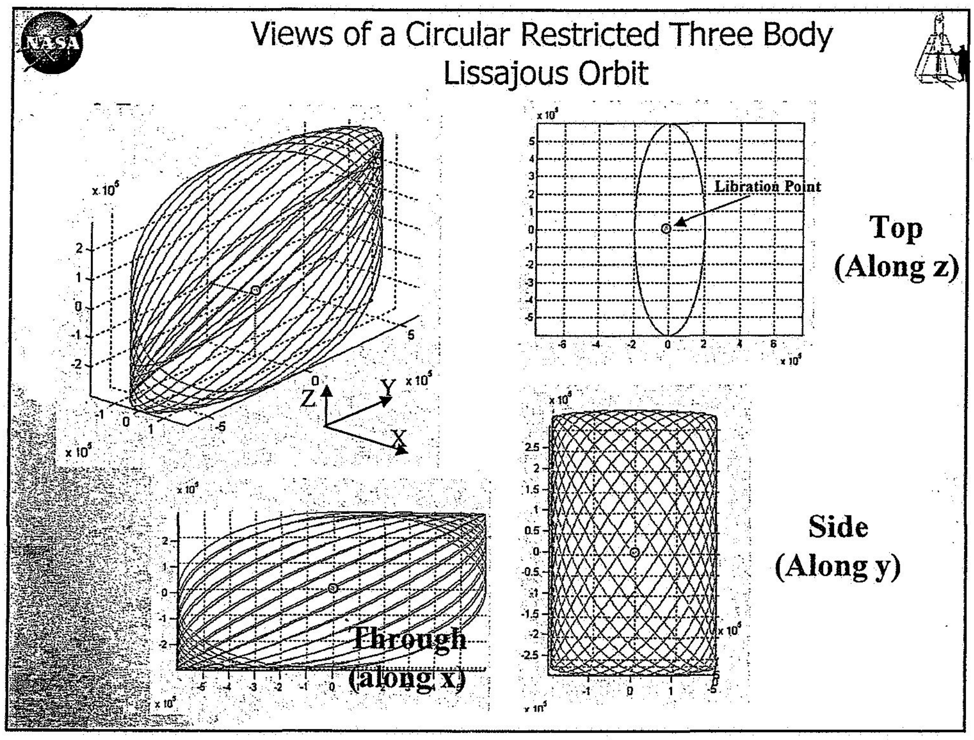
What Are They??
- Equilibrium or libration points represent singularities in the equations of motion where velocity and acceleration components are zero and the forces are balanced
- Viewed in the rotating frame: centrifugal (Coriolis-Type) force balances with gravitational forces of the two primaries
- Libration points are in plane with no Z component. Orbits are mapped to a rotating frame where there are no time dependent forces
- Our system of interest involves the Sun (m_1), the Earth-Moon system (m_2) and the spacecraft m_3
- L_1 and L_2 distance of 1.5 million km
- L_4 and L_5 distance of 150. million km

Where Are They?
- Collinear Points: L_1, L_2, L_3 (unstable)
- Triangular Points: L_4, L_5 (stable)



Solar Rotating Coordinates
Ecliptic Plane Projection

34


Views of a Circular Restricted Three Body Lissajous Orbit
Libration Point
Top
(Along z)
Side
(Along y)
Through
(along x)
Z
Y
X