



USERS' CONFERENCE

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LUNAR TRANSFERS USING FOUR- BODY DYNAMICS

TECHNIQUES FOR LISSAJOUS, WEAK STABILITY
BOUNDARY AND LOW THRUST ORBITS

Introduction



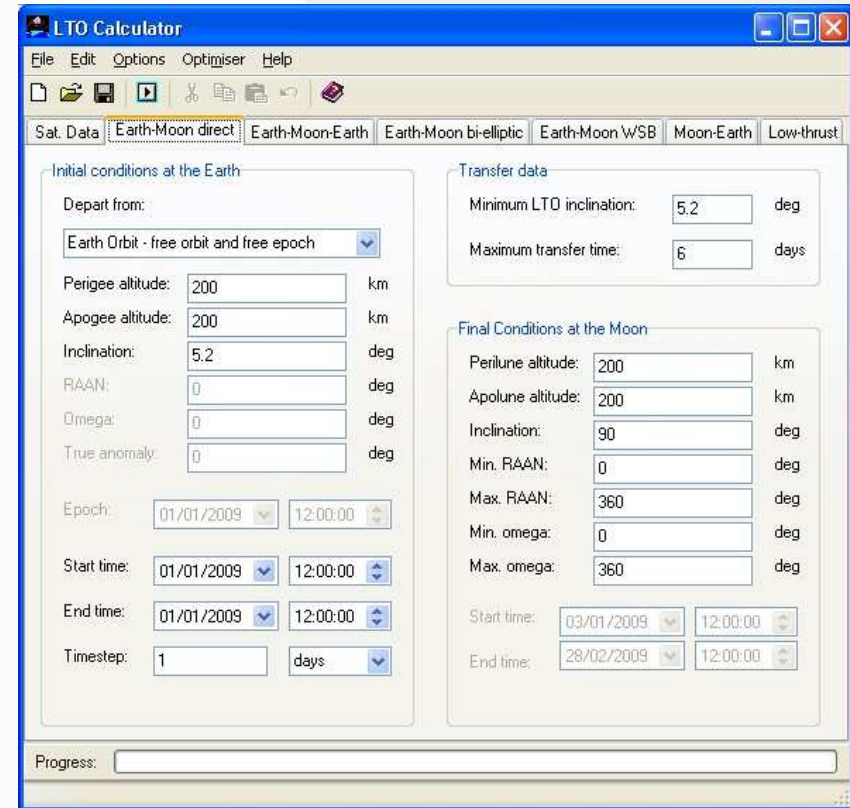
- 2004/2005 : several assessment studies performed at ESA for human missions to the Moon
 - Architecture
 - Transfer vehicles
 - Cargo vehicles
- CDF: Concurrent Design Facility
 - Organization and implementation of the assessment studies.
 - Multidisciplinary design
 - STK used in combination with in-house developed tools (using STK/Connect)
- Project support
 - Educational



STK and the Lunar Transfer Orbit Calculator



- LTOC developed by JAQAR
- Optimizes Lunar trajectories
- Direct / bi-elliptic / WSB / free-return / low-thrust / Moon-to-Earth
- Launcher database
- Handles constraints
- Global optimizer (no initial guess required)
- Local optimizer (improve solution)
- STK/Astrogator scenario created automatically
 - Built using STK/Connect commands



Free-return trajectories



- Method:
 - Propagate to the Moon, Lunar swing-by, propagate to Earth and re-enter
- Applications:
 - Human Lunar missions
 - Maximum transfer time (go & return) is a strong constraint
 - Advantages: spacecraft automatically returns if LOI fails
 - Disadvantages: restricted to low-inclination Lunar orbits (and therefore low-latitude landing sites), typically retrograde, higher ΔV
 - Alternative method for inclination change
 - LEO/GTO high inclination \rightarrow GEO zero inclination
- Problem definition:
 - LTOC Minimizes LTI ΔV based on patched conics
 - Trajectory legs can be propagated forward or using the forward/backward method
 - Two Astrogator differential correctors are created using STK/Connect commands:
 - First Earth to Moon:
 - Initial state: epoch, H_a , H_p , i given. $RAAN_{LTO}$, w_{LTO} and e_{LTO} are target controls
 - Final State: swing-by epoch, $B \cdot T$ and $B \cdot R$ are constraints (calculated by LTOC)
 - Then: Earth-Moon-Earth
 - Initial state: $RAAN_{LTO}$, w_{LTO} and e_{LTO} are target controls
 - Final state: entry epoch, Moon-Earth leg inclination and perigee radius as constraints



Bi-elliptic transfers



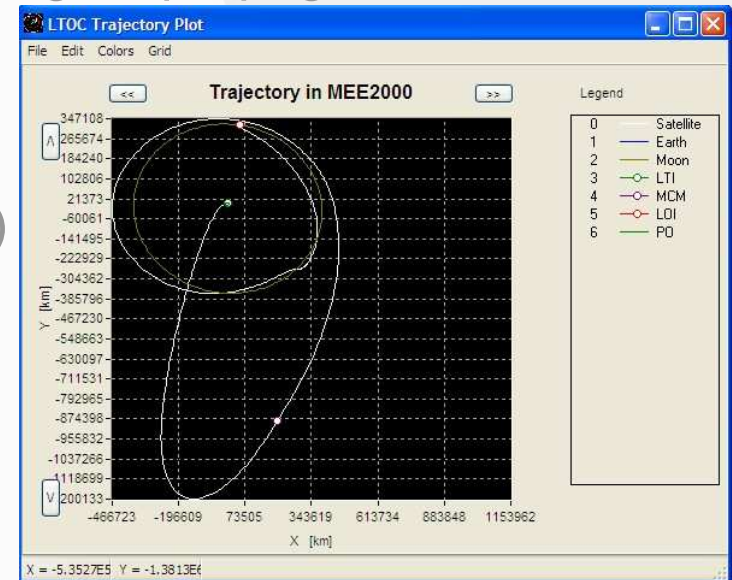
- Method:
 - Propagate to an apogee of ± 1 million km, mid-course maneuver (MCM) to change inclination and raise perigee, propagate to the Moon and Lunar Orbit Insertion (LOI)
- Applications:
 - (near) Equatorial launches
 - Europe: launch from Kourou
 - Moon crosses the equator only twice a month: direct transfers without inclination change only have two opportunities a month
 - Elliptic parking orbits
 - Low-cost missions: hitch-hike with a main passenger to GTO
- Problem definition:
 - LTOC minimizes total ΔV using forward/backward patched conics \rightarrow STK
 - Apogee of LTO given. Target ΔV_{LTI} to reach same apogee date as LTOC
 - Three differential correctors (2x initial guess, then final correction)
 - Controls are always ΔV_x , ΔV_y and ΔV_z , of the mid-course maneuver
 - 1st guess: constraints are Δ right ascension, Δ declination and arrival epoch
 - 2nd guess: constraints are B-plane parameters and arrival epoch
 - Final correction: constraints are perilune altitude, inclination and epoch



WSB transfers



- Method:
 - Propagate to an apogee of 1.4 - 1.5 million km, Sun perturbation used to change inclination and raise perigee, propagate to the Moon and Lunar Orbit Insertion (LOI)
- Applications:
 - Similar to bi-elliptic (but more practical)
 - Low ΔV missions.
 - Low-cost missions, rescue missions
- Problem definition:
 - LTOC minimizes total ΔV using forward/backward numerical propagation \rightarrow Astrogator MCS created using Connect
 - Astrogator scenario like bi-elliptic transfers



Low-thrust transfers



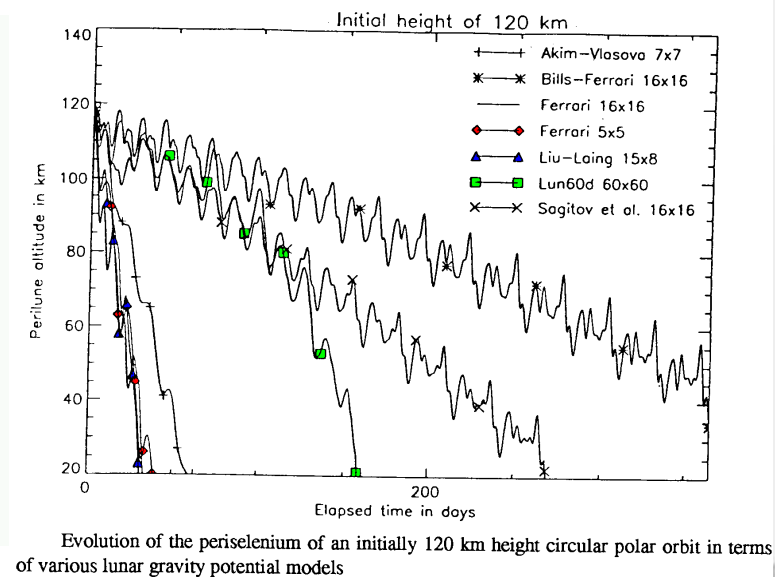
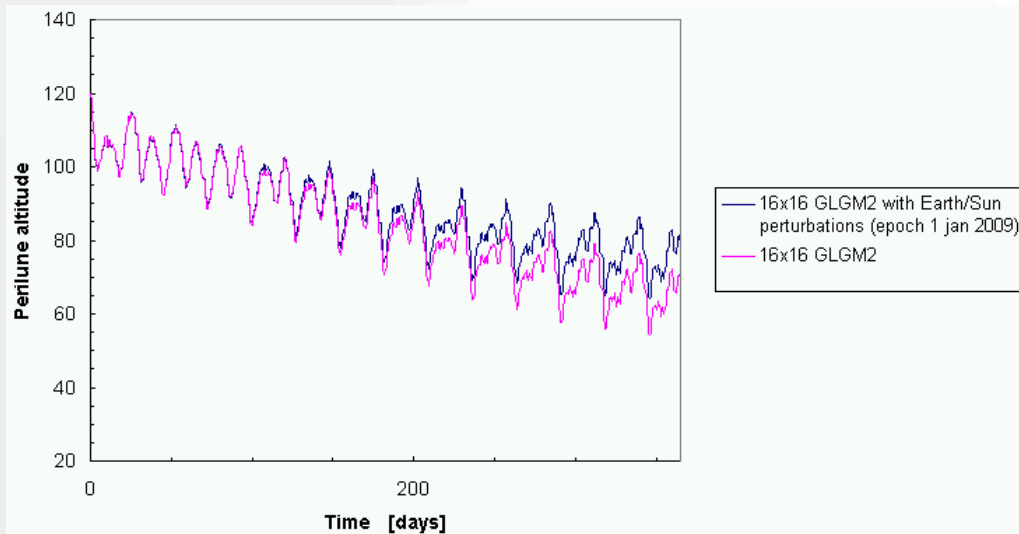
- Method:
 - LTOC: complete backward propagation. Different phases (apogee raising, semi-major axis raising, apolune lowering etc.) with coast arcs
 - STK: Difficult to solve due to forward propagation. Waiting for STK 7!
- Applications:
 - LEO to LLO missions. Small payloads with low fuel consumption.
 - Cargo transport? Often rejected due to high energy consumption
- Problem definition:
 - LTOC minimizes total ΔV using complete backward numerical propagation
 - Coast arc lengths, maximum true anomaly for thrusting are optimization parameters
 - STK imports trajectory. Currently working on Astrogator MCS



Orbit station-keeping



- 1-year propagation of Lunar hub starting at 100 km circular Lunar orbit, using GLGM2 16x16 gravity field with and without Sun/Earth perturbations
 - Comparison to other results



Lissajous orbits



- Lissajous functions inserted as VB scripts:
 - $\Delta X = X1 - \text{Amplitude}_X / C2 * \sin(\omega_{xy} * \text{Epoch})$
 - $\Delta Y = Y1 - \text{Amplitude}_Y * \cos(\omega_{xy} * \text{Epoch})$
 - $\Delta Z = Z1 - \text{Amplitude}_Z * \sin(\omega_z * \text{Epoch})$
 - Using (for Earth-Moon system):
 - $C2 = 2.912604152411$
 - $\omega_{xy} = 0.000004964554944421 \text{ rad/sec}$
 - $\omega_z = 0.00000476073836071 \text{ rad/sec}$
- Use of automatic sequences, triggered every day
 - ΔV targeted such that in one day, all VB scripts (ΔX , ΔY and ΔZ) are zero
- All co-ordinates in either rotating L1 or L2 frame
 - Can be applied to Earth-Sun L1/L2 Lissajous orbits as well
- Method can be improved
 - Least squares (by adding constraints to satisfy at different points in time) but more difficult for targeter to solve



L1 to surface



- Scenario of having a Lunar hub based in the L1 point.
- L1 to surface transfer in maximum 1 day
- All latitudes/longitudes should be reached
- Use of automatic sequences, triggered every 3 days
 - ΔV targeted such that in 3 days day, all co-ordinates within the BBR frame (X, Y and Z) are zero
 - Extreme low ΔV however no perturbations such as noise and solar pressure were applied
- Target DOI burn such that in one day, required latitude/longitude and altitude (=10 km) are reached
- Abort techniques: swing-by at 10 km altitude, back to L1



Conclusions



- Combination of Astrogator, VB scripts and AVO proofs useful for many applications
- Complex transfers require global optimization method
 - LTOC linked to STK using Connect
- Backward propagation would improve convergence of Astrogator targeter
 - STK 7 would allow LTOC to directly optimize Astrogator
- Download LTOC at www.jaqar.com
- More info Lunar & WSB transfers & techniques:
 - <http://esapub.esrin.esa.it/bulletin/bullet103/biesbroek103.pdf>
 - <http://industry.esa.int/ATTACHEMENTS/A7476/ewp2014.pdf>
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