On the Importance of International Collaboration for Deep Space Navigation

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Overview

- Interplanetary navigation at ESA/ESOC involved at all times international collaboration
- Our most important partner to date is the Navigation Section at NASA/JPL
- The benefits from the collaboration with JPL/NAV are gratefully acknowledged
- This talk will outline the evolution of interplanetary navigation at ESOC highlighting the role of international collaboration
- The scope for international collaboration will increase as we need to meet future challenges

What is Flight Dynamics?

"Flight Dynamics deals with the estimation
and control
of orbit and attitude
(mainly) of artificial satellites"

Flight Dynamics at ESOC

- Functions:
  - Orbit Determination
  - Maneuver Optimization
  - Attitude Monitoring
  - Command Generation
  - **Test and Validation**
- Flight Dynamics experts perform mission studies, design, develop and test operational Software and support operations.

ESA's Interplanetary Missions

- Giotto (10. 7. 1985)
- Ulysses (6. 10. 1990 – 31. 12. 2009)
  - **DSA 1 at New Norcia, Australia (March 2003)**
- Mars Express (2. 6. 2003)
- Smart-1 (27. 9. 2003)
- **Mars Express MOI (25. 12. 2003)**
- Rosetta (2. 3. 2004)
  - **DSA 2 at Cebreros, Spain (September 2005)**
- Venus Express (9. 11. 2005)
- **Venus Express VOI (11. 4. 2006)**
- Herschel-Planck (14. 5. 2009)
- GAIA (mid 2012)
- Lisa Pathfinder (mid 2012)
  - **DSA 3 at Malargüe, Argentina (mid 2012)**
- **Rosetta at Churyumov-Gerasimenko (22. 05. 2014)**
- BepiColombo (2014)
- ExoMars Orbiter (2016)
- SOLO (2017)
- ExoMars Rovers (2018)

Past: Giotto and Ulysses

- Ulysses (originally planned to be launched prior to Giotto):
  - Out-of-ecliptic mission
  - Joint ESA / NASA mission
  - Navigated by JPL / NAV
  - S/C operated by an ESA team located at JPL
- Giotto:
  - Encounter with Halley's comet (March 1986)
  - First interplanetary mission fully supported by ESA/ESOC with own navigation S/W
  - Navigation capability at ESOC developed in collaboration with JPL / NAV

Current Interplanetary Missions of ESA

- Preparations for Rosetta, Mars Express, Smart 1 started in late 90ties
- S/W for interplanetary navigation was developed based on legacy from Giotto with significant enhancements:
  - lander targeting,
  - planetary orbit insertion,
  - OD in planetary orbit
- Our S/W development was based largely on algorithms described in:
  - “Mathematical Formulation of the Double-Precision Orbit Determination Program (DPODP)”, 1971
  - “Formulation for Observed and Computed Values of Deep Space Navigation Data Types for Navigation”, 2000

  both by Ted Moyer / JPL

Collaboration in Support of ESA Missions

- Intensive collaboration with JPL included:
  - Consultancy
  - Independent cross-verification between our new system and S/W of JPL/NAV
  - Operational validation and navigation assurance
- Regular Technical Interchange Meetings (TIMs) were held between ESOC/FD and JPL/NAV from Sep 2000 onwards

Independent cross-verification

- Verification took the form of both Agencies making computer runs, using identical input data, comparing the results and critically assessing differences.
- Since JPL's OD S/W was mature and had been used successfully for interplanetary missions, JPL results have been treated as reference against which ESOC's results have been compared
- The tests were performed in a phased approach, i.e. each module of the orbit determination S/W has been tested sequentially and with increasing complexity:
  - Trajectory propagation with scenarios that were representative for Mars Express and Rosetta
  - Modeling 2-way Doppler, range and DDOR observable
  - Computation of partial derivatives
  - Covariance mapping and B-plane targeting
- Finally dedicated tracking campaigns with Ulysses were performed to compare full orbit determination results.

Operational validation and navigation assurance

- Final software cross-verification and validation of operational interfaces between ESOC Flight Dynamics and JPL/NAV were performed by comparing orbit determination solutions during:
  - a Mars Express tracking campaign 2 months after launch lasting 2 weeks
  - a joint simulation by using simulated tracking data generated by the ESOC / FD Test & Validation group. The data were based on the expected MEX approach scenario.
- During Mars Express approach to Mars navigation assurance was provided by JPL / NAV. This was achieved by performing the following on a daily basis:
  - Both Agencies were retrieving and processing the same tracking and auxiliary data.
  - Both agencies were running their orbit determination software in a pre-agreed and validated configuration.
  - Orbit determination solutions and B-plane targeting parameters for both, Mars Express and Beagle-2 were exchanged and carefully compared.

Collaboration in Support of:

- NASA missions:
  - DAWN: Tracking support during LEOP (2007)
  - Phoenix: 1st acquisition support after launch (2007), DDOR support during Mars approach phase and support of relay during EDL (2008)
- China
  - Chang'E1 (lunar orbiter / 2007): Consultancy and tracking support
  - Chang'E2 (lunar orbiter and lander / 2010): Tracking support is foreseen
- India
  - Chandrayaan-1 (2008): Consultancy for orbit determination software development (operational support was provided by NASA / JPL)
- Russia
  - Phobos-Grunt (end 2011): Tracking support during all phases of the mission including provision of DDOR are foreseen

Technical Challenges of Next Decade 1. Operations of Rosetta at comet Churyumov-Gerasimenko (2014):

- Irregular target body, a-priori unknown shape and kinematics
- Gas and dust environment, increasing activity
- Perturbation due to gas eventually exceeding gravitational attraction
- Simultaneous determination of S/C trajectory, comet gravity potential, shape, kinematics, characteristic of the gas and dust coma
- Delivery of a lander at a comet – sun distance of 3 AU when the comet may be partly active
- Need to characterize the comet properties and landing sites sufficiently accurate for landing within limited time

Technical Challenges of Next Decade
2. Operations of ExoMars, incl. aerobraking and technology demo of EDL

- The ExoMars program comprises two missions:
  - An ESA-led orbiter with US payloads also carrying an Experimental Descent Module (EDM), launched 2016 by an US launcher
  - A NASA-led mission, carrying an European and an US rover, both deployed by an US EDL system, launched 2018 by an US launcher
- ExoMars orbiter mission:
  - Release of EDM from hyperbolic orbit several days before arrival
  - Retargetting of the orbiter for capture
  - Provision of data relay from four-sol orbit for EDM (8 days)
  - Transfer to 1-sol orbit at 74º inclination
  - Aerobraking for 9 month to science and communications orbit 2 hours period, 400 km altitude
  - After 2018: data relay for rovers and future ESA/NASA missions

Facilitators: Standardisation

- Standardization facilitates collaboration by simplifying the design and implementation of interfaces for data exchange.
- **The Consultative Committee for Space Data Systems (CCSDS) is a major multi-national, inter-agency forum for the standardization of space related communication and data exchanges.**
- The CCSDS organization is structured in areas and working groups.
- **Navigation / Flight Dynamics aspects are covered by the Navigation Working Group within the Mission Operations and Information Management Services Area (MOIMS-NAV)**
- In parallel to the collaboration with JPL on interplanetary navigation, the working group has developed several standards of relevance to this collaboration, covering the exchanges of e.g.:
  - orbital data
  - attitude data
  - tracking data
- Development of standards by CCSDS working group and collaboration between JPL / NAV and ESOC / FD have been of mutual benefit.
- Standards have also proven useful to collaboration with other partners

Facilitators: ISSFD conferences

- The International Symposium on Space Flight Dynamics (ISSFD) is the major international forum for the exchange of information on operational Navigation / Flight Dynamics. The ISSFD is sponsored by various space agencies, including CNES, DLR, ESA, INPE, JAXA, KIAM and NASA.
- Areas covered by the ISSFD are:
  - Trajectory design and optimization
  - Orbital dynamics, perturbations, orbit determination and tracking
  - Attitude dynamics, determination and control
  - Space environment, orbital debris and collision risk mitigation
  - In orbit servicing, rendezvous, formation flying
  - Autonomous on-board guidance, navigation and control
- Next ISSFD conferences:
  - 22nd ISSFD: March 1st – 5th, 2011, São José dos Campos, Brazil (org. by INPE)
  - 23rd ISSFD: 2012, Pasadena, CA, USA (org. by NASA/JPL)

Summary

- Interplanetary navigation at ESA/ESOC has made a big step forward in the past decade.
- Collaboration with our colleagues at JPL/NAV has helped a lot in making this step.
- International collaboration has played a major role in the history of interplanetary navigation and will play an increasingly important role in it's future.
- An organizational challenge for the future is to extend collaboration to emerging important new players in the area of interplanetary flight.