Ephemerides from PRIDE - JUICE
Status Update and Plans

D. Dirkx, PRIDE-JUICE team meeting, JIVE, October 29, 2018

PRIDE

Ephemerides - Science Case

- Jovian system ephemerides are key in
  - Determining dissipation in Io and Jupiter *(Lainey et al., 2009)*
  - Determining the Jupiter mass
  - Possibly sensitivity to other geodetic parameters
  - Robustly planning satellite tour missions

- Dissipation in Jupiter and satellites
  - Effect on moon position is quadratic in time -> long data sets are valuable
  - Estimates of k_2/Q for both Io and Jupiter from astrometry (1873-2008)
  - Constrains the bulk tidal heat dissipation
  - Key in studies of evolution of Galilean moons

- Key question: which parameters could be observe using JUICE-based ephemerides?
  - **Key objective:** dissipation parameters

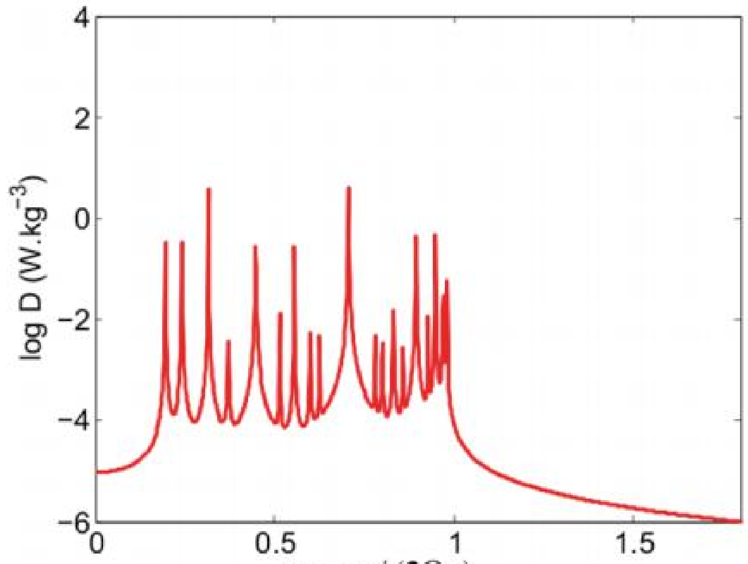
PRIDE

Ephemerides - Science Case

- Dissipation in giant planets
  - Driving force in evolution of satellite system -> key in origin and evolution
  - Highly non-linear function of forcing frequency -> dynamical tide
  - Mismodelled in past evolution studies

- Estimated k_2/Q of Saturn at different forcing frequencies *(Lainey et al., 2017)*
  - Shows possible impact of dynamical tide

- Possible formation of "resonance locks" *(Fuller et al., 2015)*
  - Possible scenario: extremely high dissipation in Jupiter at Callisto's frequency



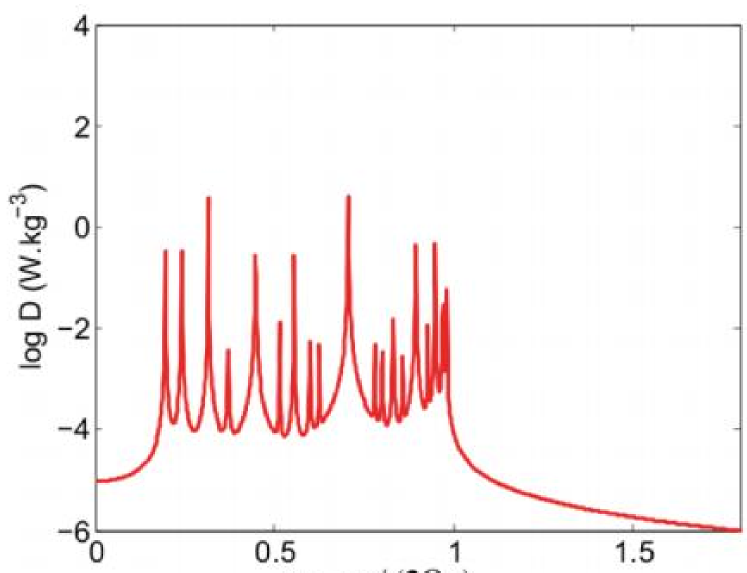
Auclair-Desrotour, et al. (2014)

PRIDE

Ephemerides - Science Case

- Dissipation in giant planets
  - Driving force in evolution of satellite system -> key in origin and evolution
  - Highly non-linear function of forcing frequency -> dynamical tide
  - Mismodelled in past evolution studies

- Orbital evolution of Titan:
  - Extremely high Saturn Q=100 at Titan's forcing frequency
  - ***Independently*** determined by radio science (Cassini; *Tortora et al.*) and astrometry (Eart-based + Cassini; *Lainet et al.)*

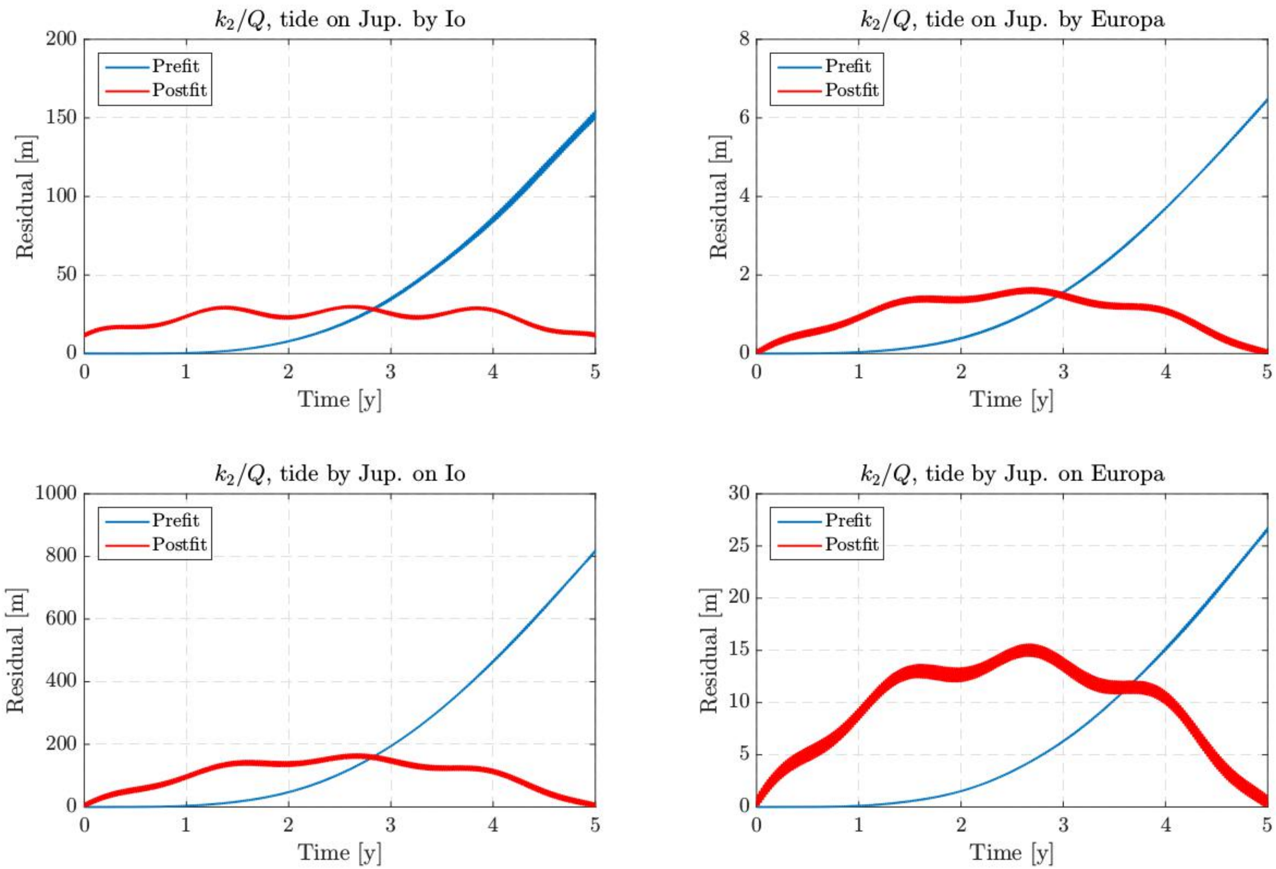


Auclair-Desrotour, et al. (2014)

PRIDE

Ephemerides - Observable Parameters

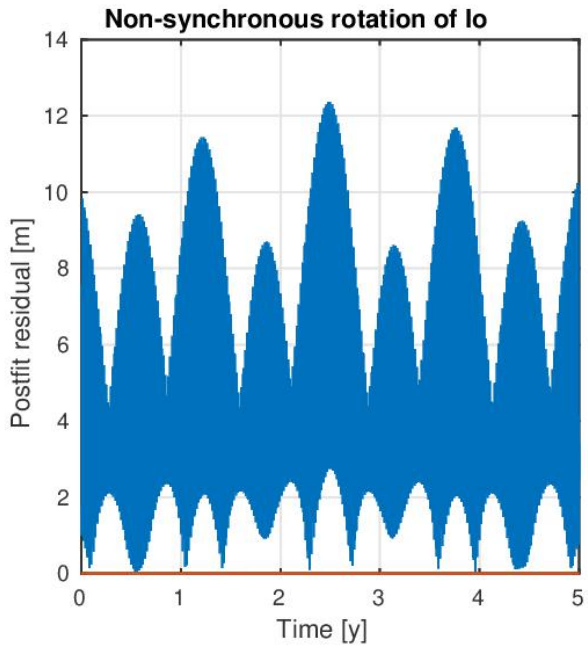
- Analysis of sensitivity of Galilean moon dynamics to Jovian system parameters (*Dirkx et al., 2016*)
    - Some sensitivity to Io/Jupiter dissipation (Io forcing frequency)
    - Sensitivity to tides on/by Europa weak



PRIDE

Ephemerides - Observable Parameters

- Analysis of sensitivity of Galilean moon dynamics to Jovian system parameters (*Dirkx et al., 2016)*
  - Significant sensitivity to Jovian gravity field. But: constraints from Juno (much) stronger
  - Other parameters (almost) fully absorbed into moon initial states
  - Possible exception: Moon k_2 values
  - Possible exception: Moon libration amplitudes



PRIDE

Ephemerides - Data

- PRIDE tracking data provides:
  - VLBI data (right ascension/declination in ICRF)
  - Open-loop Doppler data (range rate w.r.t. ground station)

- Information content of open-loop data largely equivalent to closed-loop
  - PRIDE-Doppler and 3GM-Doppler of comparable quality

- The VLBI observable
  - Provides position perpendicular to ecliptic
  - Provides absolute position -> well suited to long periodic signals: ephemerides

PRIDE

Ephemerides - Data

- Typically ephemerides are generated from
  - Astrometric data (Earth- and spacecraft-based)
  - Range and VLBI data to orbiters
  - Doppler, VLBI and range data during flybys
  - Earth-based radar data

- JUICE generates many different data for ephemerides:
  - Range, Doppler and VLBI during Ganymede, Europa and Callisto flybys
  - Range, VLBI (and Doppler) during Ganymede orbit phase
  - Optical astrometry of Io and Europa (?)

- To be combined with
  - Earth-based astrometry (back to 1873), reanalyzed with Gaia catalogue

PRIDE

Ephemerides - PRIDE contribution

- Analysis of contribution of VLBI data (*Dirkx et al., 2017)*
  - Simulate JUICE tracking data with/without VLBI data
- Vary observation parameters:
  - Spacecraft position uncertainty
  - VLBI data quality

	Relative initial position formal errors [%]							
	Ganymede		Io		Europa		Callisto	
Measurement case	IP	OP	IP	OP	IP	OP	IP	OP
JUICE Position Error Case 1, σ_h=0.1 nrad	-10.1	-80	–	–	-51.3	-66.8	-63.2	-95.9
σ_h=0.5 nrad	–	-39.7	–	–	–	-18.2	-60	-85.2
σ_h=1.0 nrad	–	-18.3	–	–	–	-9.24	-57.9	-73.9
JUICE Position Error Case 4, σ_h=0.1 nrad	-9.04	-81.2	-7.72	–	-54.6	-79.1	-66.6	-97.3
σ_h=0.5 nrad	–	-43.1	–	–	-14.1	-32.1	-60.7	-91.6
σ_h=1.0 nrad	–	-21.3	–	–	–	-15.4	-59.7	-84.7
JUICE Position Error Case 5, σ_h=0.1 nrad	-18	-95.1	–	–	-61.1	-85.9	-70.9	-98.2
σ_h=0.5 nrad	–	-83.4	–	–	-16.8	-50.3	-63	-95.9
σ_h=1.0 nrad	–	-69.2	–	–	-5.95	-26	-61.2	-93.2

PRIDE

Ephemerides - PRIDE contribution

- Primary contribution:
  - Ganymede/Callisto out-of-plance components

- Jupiter ephemeris out-of-plane also strongly constrained

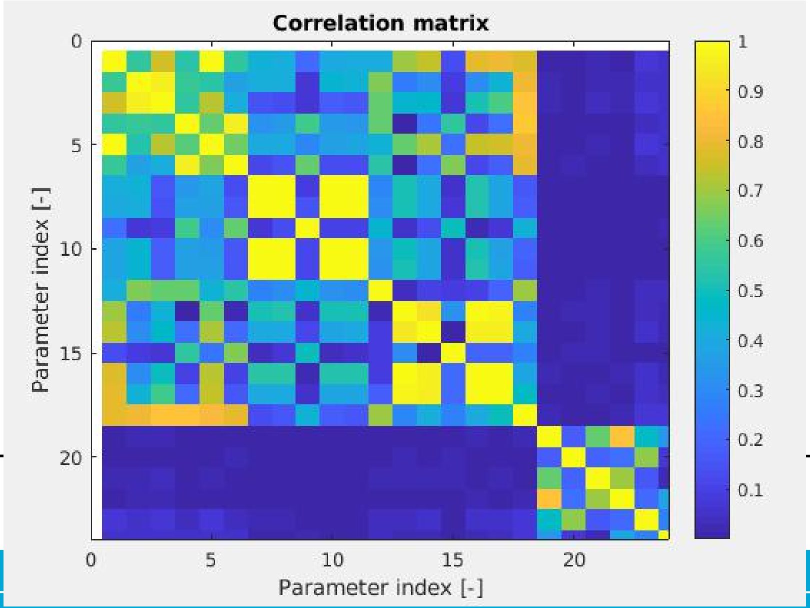
	Relative initial position formal errors [%]							
	Ganymede		Io		Europa		Callisto	
Measurement case	IP	OP	IP	OP	IP	OP	IP	OP
JUICE Position Error Case 1, σ_h=0.1 nrad	-10.1	-80	–	–	-51.3	-66.8	-63.2	-95.9
σ_h=0.5 nrad	–	-39.7	–	–	–	-18.2	-60	-85.2
σ_h=1.0 nrad	–	-18.3	–	–	–	-9.24	-57.9	-73.9
JUICE Position Error Case 4 σ_h=0.1 nrad	-9.04	-81.2	-7.72	–	-54.6	-79.1	-66.6	-97.3
σ_h=0.5 nrad	–	-43.1	–	–	-14.1	-32.1	-60.7	-91.6
σ_h=1.0 nrad	–	-21.3	–	–	–	-15.4	-59.7	-84.7
JUICE Position Error Case 5, σ_h=0.1 nrad	-18	-95.1	–	–	-61.1	-85.9	-70.9	-98.2
σ_h=0.5 nrad	–	-83.4	–	–	-16.8	-50.3	-63	-95.9
σ_h=1.0 nrad	–	-69.2	–	–	-5.95	-26	-61.2	-93.2

PRIDE

Ephemerides - PRIDE contribution

- Ephemeris generation will be particularly complex for JUICE
  - Combination of flyby, orbiter and astrometric data: how best to merge?
  - Europa observations only in a very short period -> weak constraints
  - Large concentration of data at Ganymede

- Laplace resonance
  - Io, Europa, Ganymede ephemerides strongly linked
  - Ephemeris quality for Ganymede degrades due to scarcity of Io/Europa data



PRIDE

Ephemerides - PRIDE contribution

- Next steps for simulation study
    - Combine JUICE data (simulated) with existing data (astrometric)
    - Merge data sets at normal equation level
    - Incorporate 'synthetic' Earth-based astrometry 2018-2030

- Investigate:
    - Synergy between data sets
    - Evolution of satellite state uncertainty
    - Possible determination of Jupiter's dissipation at multiple frequencies

- Separate analyses close to done
    - Merge of data sets to be done in early 2019

PRIDE

Ephemerides - PRIDE contribution

- Upcoming step for simulation study:
  - Combined determination of JUICE orbit and moon ephemeris
  - Allows information content of data to be robustly analyzed
- Possible issues:
  - Significant correlations (flybys): coupled variational equations needed!
  - Computational resources

PRIDE

Ephemerides - Challenges for JUICE

- Ephemeris quality for Ganymede degrades due to scarcity of Io/Europa data
- Poor conditioning of normal equations
    - Strong *a posteriori* correlations
    - Increase in (formal) estimation errors
- Mitigation options
    - Optical astrometry (JANUS) of Io (and Europa) crucial
    - Synergy with Europa Clipper likely to be substantial

PRIDE

Data Analysis - Plans

- Efficient data analysis pipelines will be needed for PRIDE
    - Data volume (much) higher than for past PRIDE experiments
    - Orbit determination and ephemeris creation should be "automated"
    - Integration with 3GM radio-science data

- Orbit determination tool: Tudat
    - Fully open-source
    - Developed at TU Delft
    - Use for wide range of interplanetary tracking simulation studies
    - Used LRO orbit determination from one-way laser ranging data

PRIDE
Data Analysis - Plans

- Orbit determination tool: Tudat

- Steps required for PRIDE operations
  - Implement detailed models for real radio data analysis (data corrections, high-accuracy reference frames, data corrections, *etc.*)
  - Use existing data archives as test cases
  - Cross-validate with other software (GINS, MONTE, GEODYN, ...)
  - **Requires dedicated personnel** (Ph.D./postdoc)

PRIDE

Data Analysis - Plans

- Tudat software
  - Currently used for simulations of PRIDE-JUICE for ephemerides
  - Next step: combined solution for JUICE orbit and moon ephemerides

- Goal: automated setup to rerun analysis when new Crema is released

- Goal: provide a flexible interface (JSON file) through which mission/data settings can be varied, and simulations rerun
  - Data cadence/quality
  - Mission properties
  - System parameters
  - Estimated parameters
  - ....

PRIDE

Data Analysis - Plans

- ExoMars-LaRa as test case for JUICE
  - Mission scenario very different
  - Data analysis pipelines very similar

- LaRa data
  - To be used to constrain Mars fluid core size through measurements of rotational variations
  - Very low data cadence (1 hour per week) means PRIDE Doppler data may be very valuable
  - VLBI data will not impact experiment, but will be valuable input to Mars ephemeris

- Less