

# Models for high precision planetary and lunar ephemerides

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# **Planetary and Lunar Ephemerides**

**Classical**

**Past**

**Present**

**Future**

**Observations**

**Reductions**

**Integrations**

# Classical

## Observations

Optical      0"5  
360 km @ 1 a.u  
1 km @ moon

## Reduction

Catalog errors  
Day/Night  
Phase Effect  
Personal Equation  
Stellar Aberration  
Light-time  
Light-bending

## Integrations (ephemerides: analytical theories)

Newtonian  
Relativity patches  
Great Empirical Term ( lunar  $\dot{n}$  )

# Past

## Observations

<b>Radar</b>	<b>:</b>	<b>1-2 km; 100 m (differential)</b>
<b>Ma9 ('71)</b>	<b>:</b>	<b>40 m</b>
<b>Viking ('76)</b>	<b>:</b>	<b>10 m</b>
<b>LLR ('69)</b>	<b>:</b>	<b>30 cm</b>
	<b>:</b>	<b>15</b>
	<b>:</b>	<b>4</b>
	<b>:</b>	<b>2</b>

## Reductions

**ET-TAI (Moyer '80)**

**Shapiro Effect**

**Timing & Polar Motion**

**Topography**

**Solar corona**

**Antenna modeling**

## Integrations : (numerical; 60-bit mantissa)

**PPN, Isotropic,  $1/c^2$**

**Sun, Planets, Moon, 5 Asteroids**

**Gravity Fields [Earth, Moon, Sun]**

**Earth Tides**

**Librations**

# Present

## Observations

<b>S/C Range</b>	<b>: 1 meter</b>
<b>Doppler</b>	<b>: 0.05 mm/sec</b>
<b>VLBI</b>	<b>: 1 mas</b>
<b>LLR</b>	<b>: 1-2 cm</b>
<b>[ Pulsars ]</b>	<b>: [10-20 meters]</b>

## Reductions

**ET-TAI (FB2C)**

**Enhanced Shapiro Effect (Jup, Sat, curvature)**

**Earth Atmosphere (press., temp., and hum.)**

**Antenna movement**

**Relativistic effects upon each station's clock**

# **Present (cont.)**

## **Integrations (numerical)**

**newtonian : quad precision; the rest : d.p.**

**PPN, Isotropic,  $1/c^2$**

**Earth gravity field (4th degree)**

**Lunar (4th degree)**

**figure-figure terms**

**Solar J2**

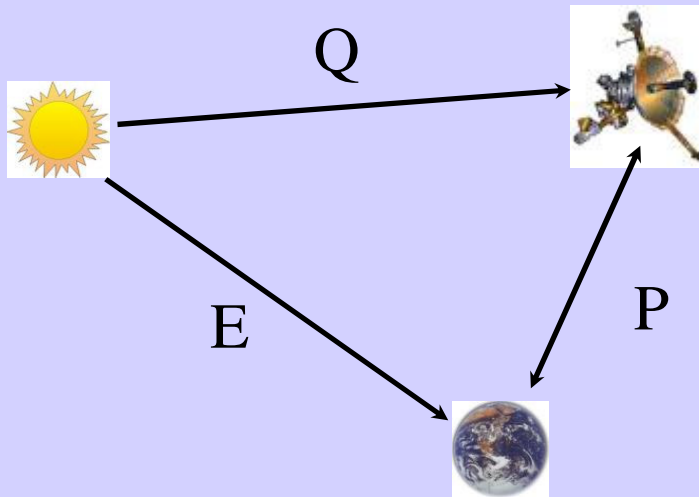
**Earth tides (from Sun, Moon) upon Moon**

**Lunar librations : torques from**

**Sun, Earth, Venus, Mars, Jupiter**

**Rotating lunar mantle and fluid core**

# Gravitational time-delay (Shapiro Effect)



$$\frac{(1+\gamma)GM_S}{c^3} \ln \left[ \frac{Q+E+P}{Q+E-P} \right]$$

$S \rightarrow S, 5, 6$  (add Jupiter, Saturn)

$$\sum_{S,5,6} \frac{(1+\gamma)GM_i}{c^3} \ln \left[ \frac{Q+E+P + \frac{(1-\gamma)GM_i}{c^2}}{Q+E-P + \frac{(1-\gamma)GM_i}{c^2}} \right]$$

*(Account for path's curvature)*

# Gravitational time-delay on Earth-Mars ranging

	[meters]	
sungraze	40,000	
light-bending	-3	
Mars opposition	1,000	
field of Jupiter	1.5	( $\propto \rho$ )
field of Saturn	0.2	( $\propto \rho$ )
into Earth's surface	0.1	
into Mars' surface	0.01	

# Future : Planets

## Observations

<b>S/C ranging</b>	<b>: 10-20 cm</b>
<b>VLBI/VLBA</b>	<b>: 0.1 mas</b>
<b>SIM</b>	<b>: 0.010 mas (7 m @ 1 a.u.)</b>

## Reductions

**Enhanced media calibrations**

**real time**

**higher frequency**

**multiple frequencies**

**Refined telescope movement**

**use determinations from VLBI**

**Better transponder calibrations**

**temperature, pressure, humidity**

# Future: Planets (cont.)

## Integrations

Planet barycenters  $\longrightarrow$  Planets & Satellites

Enhanced asteroid perturbations

External bodies

pluto mass @ 100 a.u.	: 2 cm in $\lambda_4$
solar-mass at 1 p.c.	: 1/4 mm
galactic center	: 0.02 mm

Decrease of the solar mass

Relativity  $\sim 1/c^3$  ?

# Future: Moon

## Observations : APOLLO Project

### Apache Point Observatory, NM



**3.5 m telescope**  
**enhanced power and sensitivity**  
**good seeing**

**→ multiple photons / pulse**

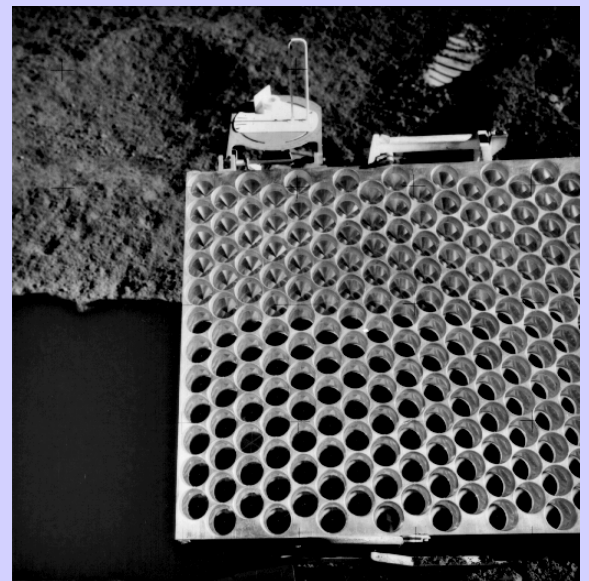
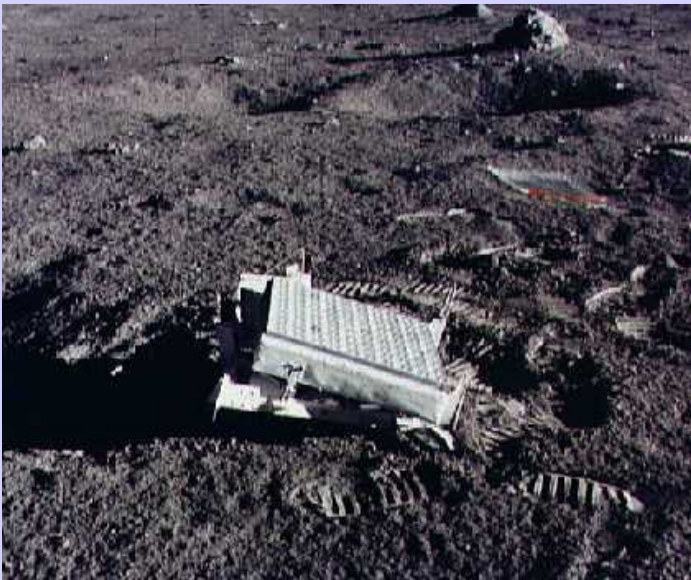
**First success:**

**October 19, 2005 : 2400 photon returns**

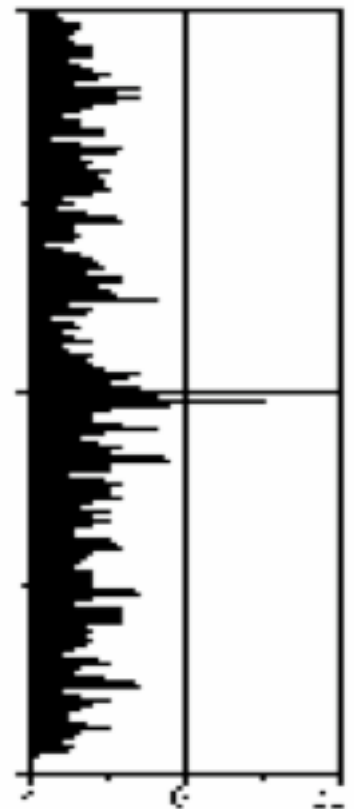
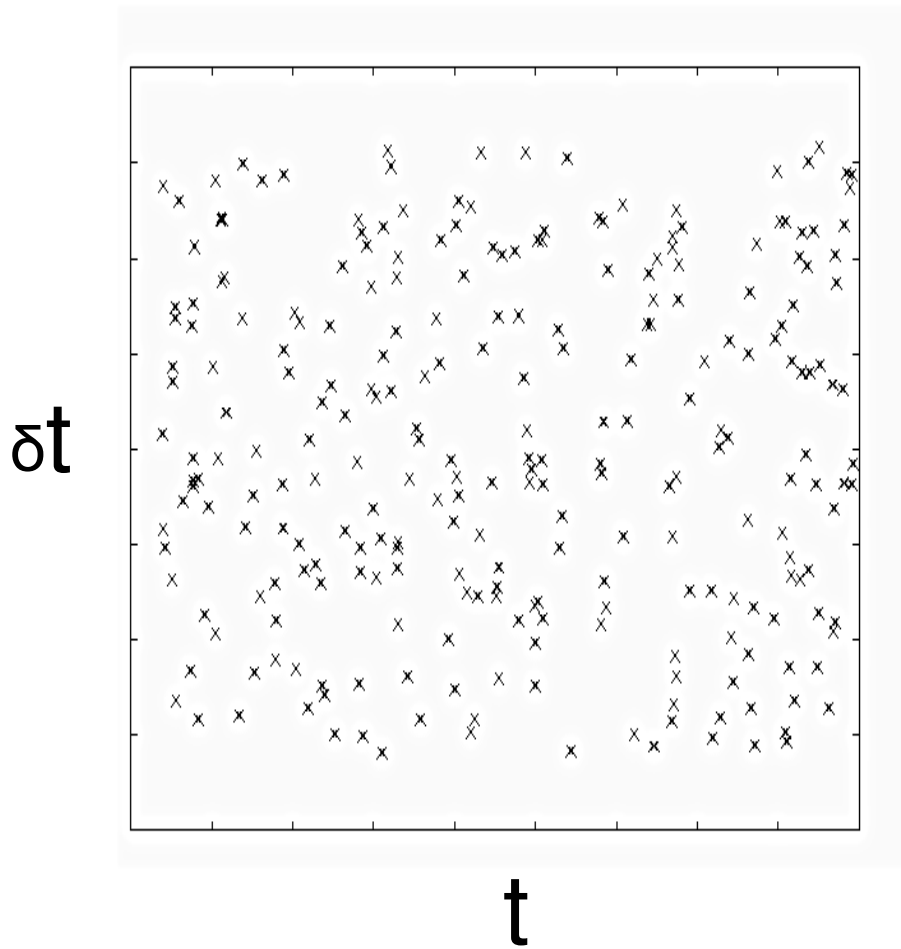
**[ ~ 3 yrs at McDonald]**

**December 2005 : 2150 returns in 12.5 mins**

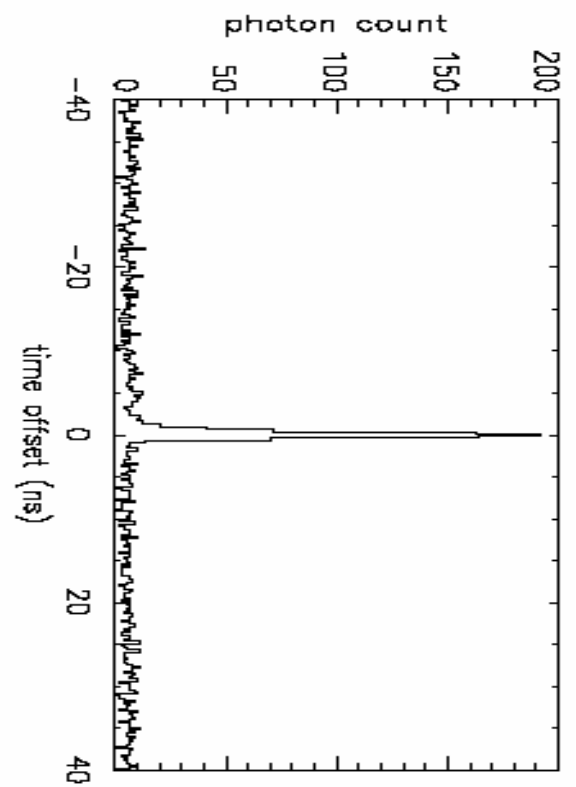
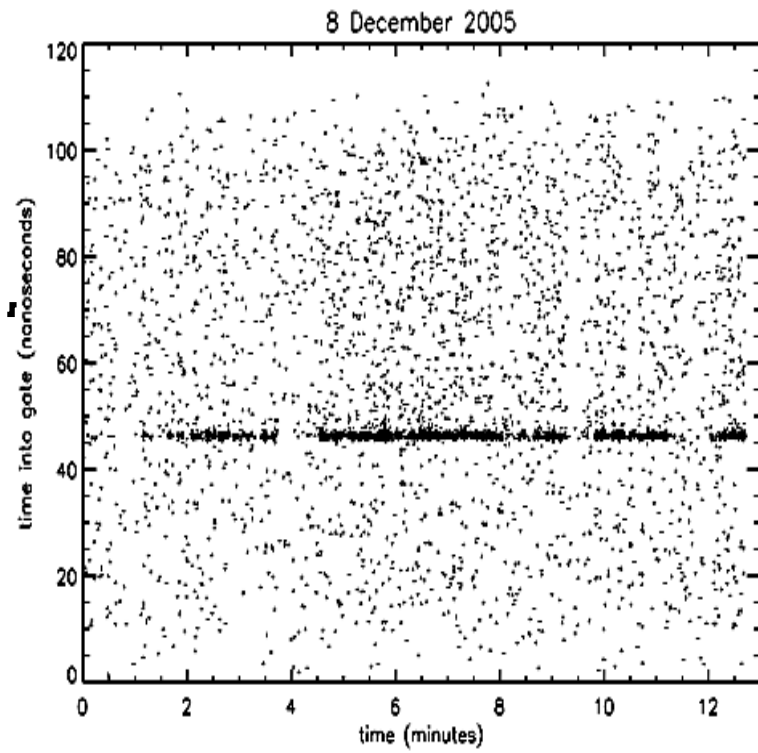
**( ~ full moon)**



# McDonald



# Apache Point



$\sigma = 1 \text{ mm} !$

# **Future : Moon (cont.)**

## **Reductions**

**Retroreflector Array Statistics**

**Thermal expansion of the retroreflectors**

**Movement of the retroreflectors**

**Refined movements of the telescopes**

**Enhanced media calibrations**

## **Integrations**

**Lunar inner core ?**

**Higher degree gravity fields**

**Time-dependent gravity fields**

**Decrease of the solar mass**

# Personnel

**near future**

**e m standish → w m folkner**

**further future**

**j g williams → ???**