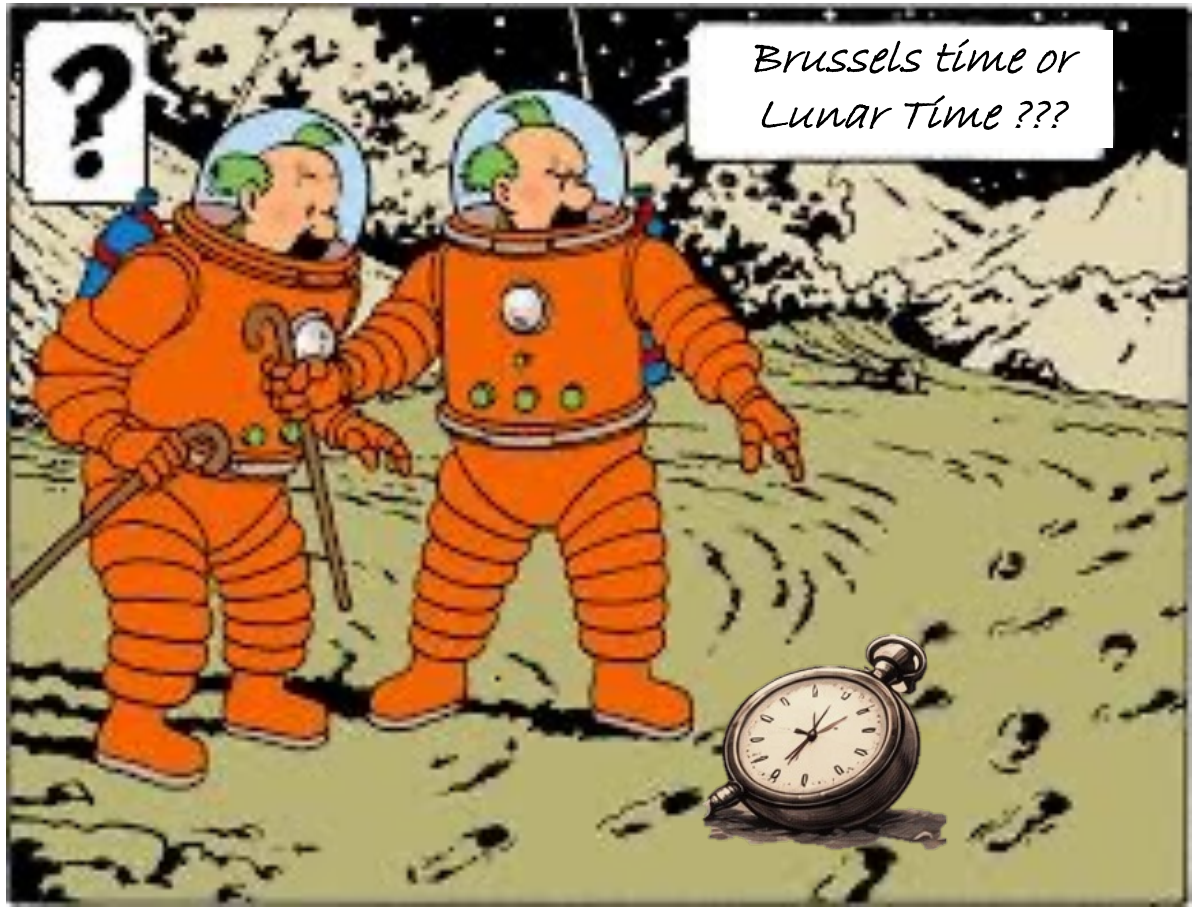


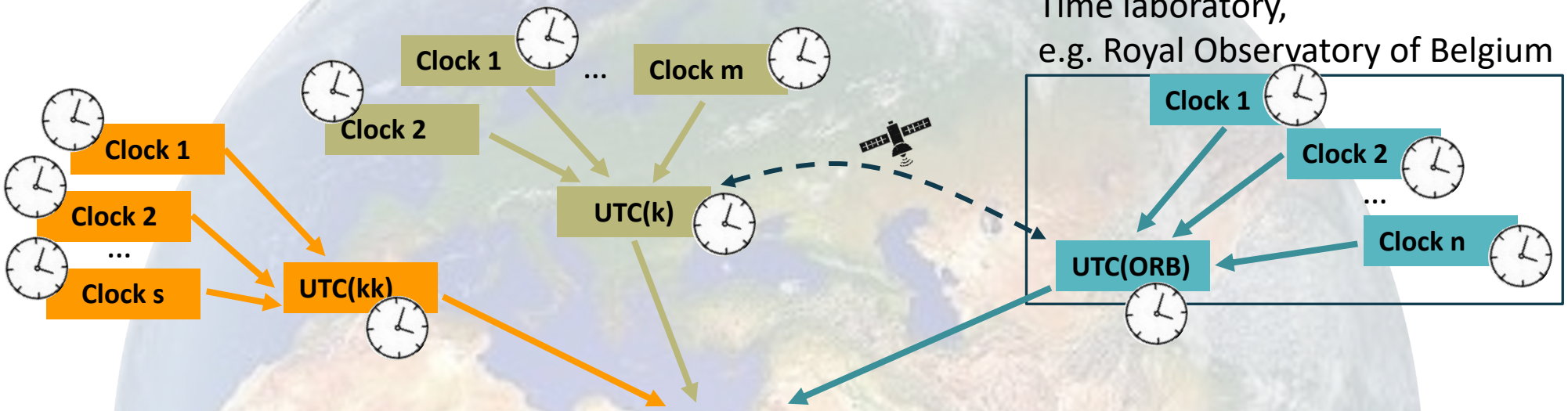
WHAT TIME IS IT ON THE MOON ?

Pascale Defraigne

ROYAL OBSERVATORY
OF BELGIUM

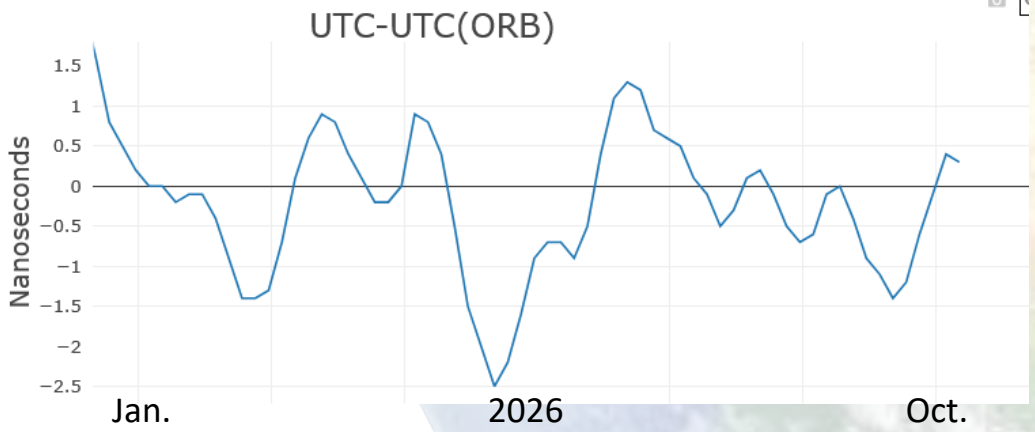
What time is it on the Earth ?



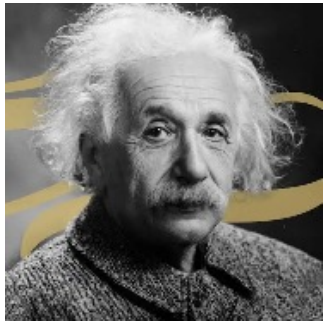


UTC = Average of ~500 atomic clocks in ~60 laboratories
= THE reference
! Computed a posteriori !

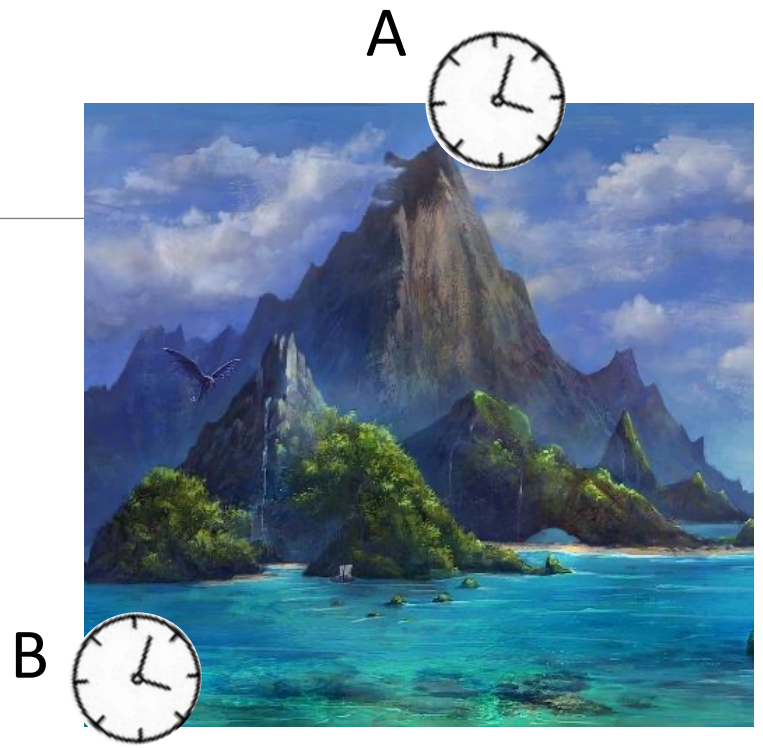
UTC(k) = physical time signal
= clock steered to represent UTC
Distributed to users

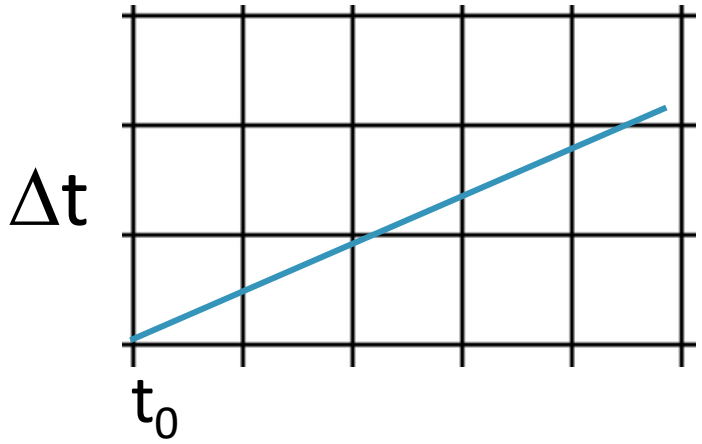


Relativity of time



Time contraction with gravity
Time dilation with velocity

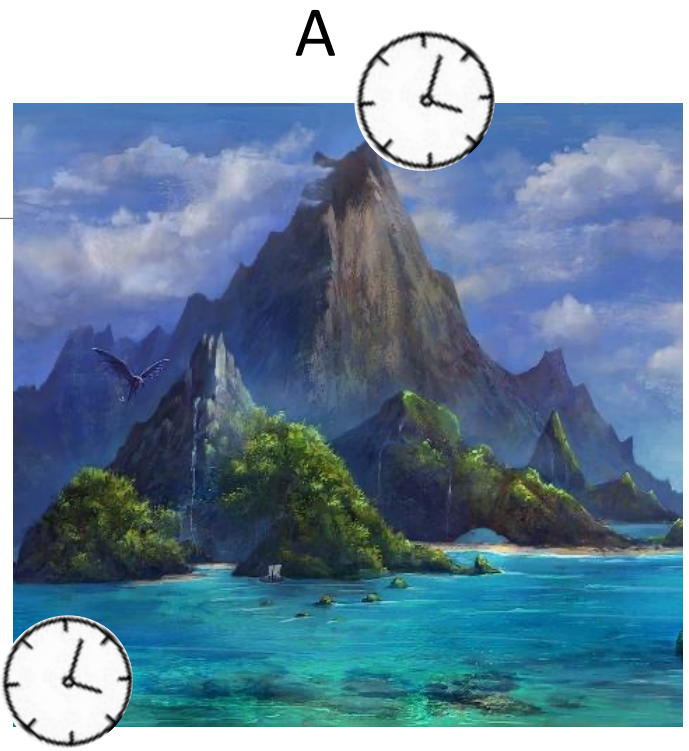




~ few ns /day

Starting the clocks at same time t_0
clock A will show an increasing advance with respect to B

Definition of UTC



- **ORIGIN**:
  t_0 fixed on « mean solar time Greenwhich 1958.0 »
- **SCALE**:
  1 second of UTC = 1 second of time at the sea level.

  → Time (UTC) in A
  = Time (clock_A) – relativistic correction

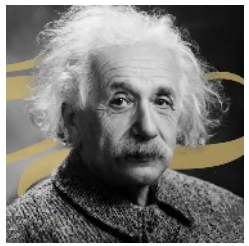
  (most of the time, the clock error is larger than the relativistic effect)

The most accurate atomic clocks today: optical clocks

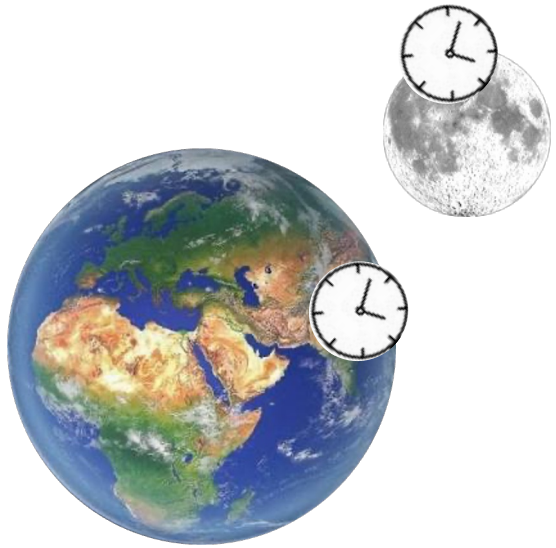
→Accuracy in frequency ~10^{-18}

→Able to measure gravity potential difference at the level of 1 cm in altitude.

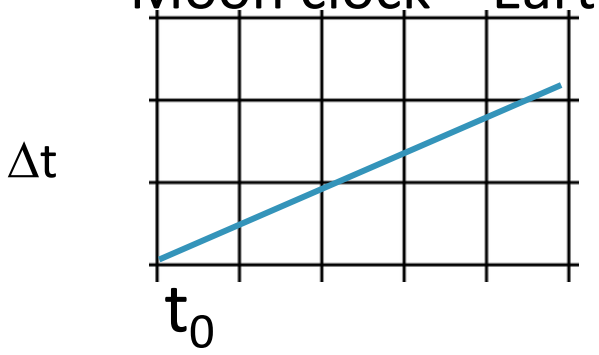
What time on the Moon?



Time contraction with gravity
Time dilation with velocity

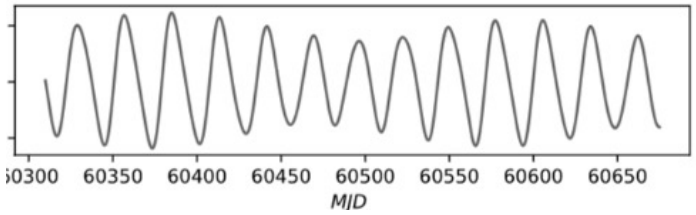


Moon clock – Earth clock



~ 56 µs/day
(1 s in 50 yr)

After drift removed



Monthly Periodicities, ~µs
position-dependent

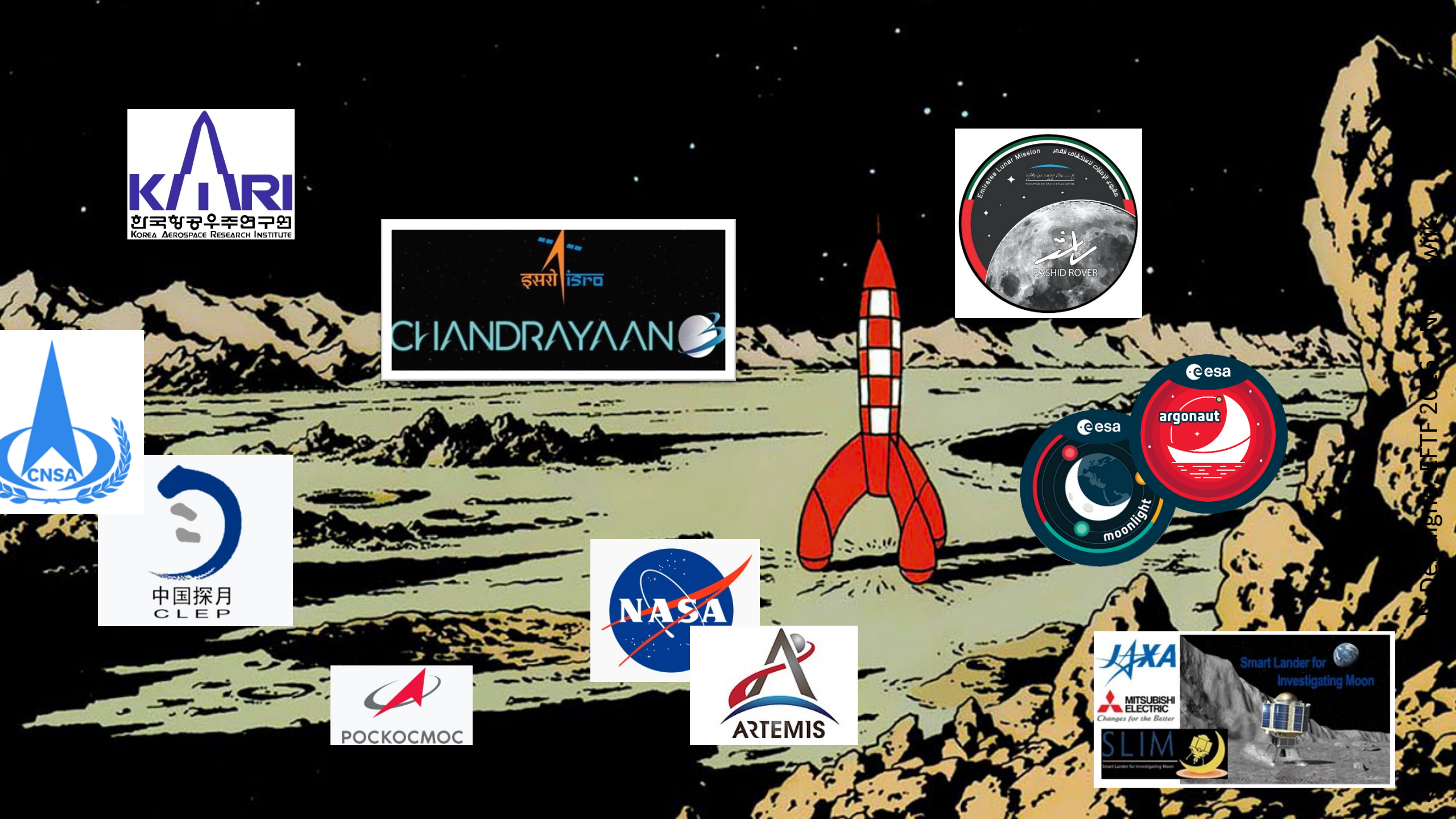
Time on the Moon?



Apollo missions :
no need for high accuracy timing

Some missions required precise timing,
but working on their own
→ no need for coordination

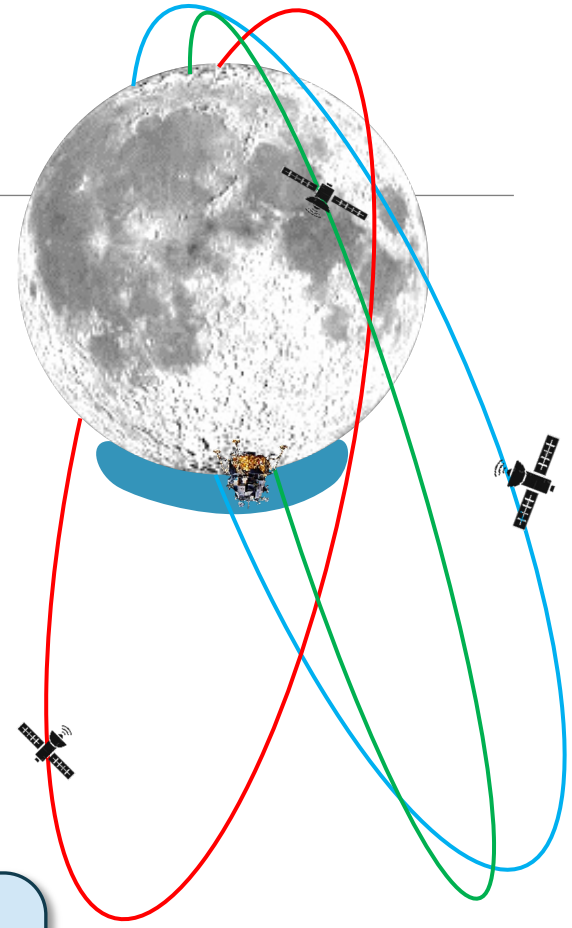



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इसरो isro
CHANDRAYAAN
Emirates Lunar Mission
RASHID ROVER
CNSA
esa
argonaut
esa
moonlight
中国探月
CLEP
NASA
ARTEMIS
POCKOCMOC
JAXA
MITSUBISHI ELECTRIC
Changes for the Better
SLIM
Smart Lander for Investigating Moon

Increasing need for safe navigation

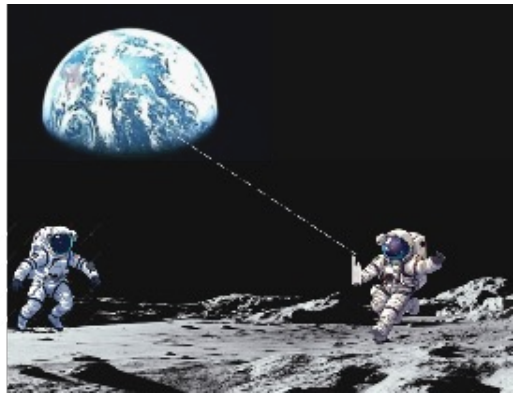
→To land accurately
→To find your way

Navigation Satellite System (GPS-like)
around the Moon



Several systems from different space agencies → need for coordination:
define a common reference system
define a common reference time

UTC cannot be the reference on the Moon

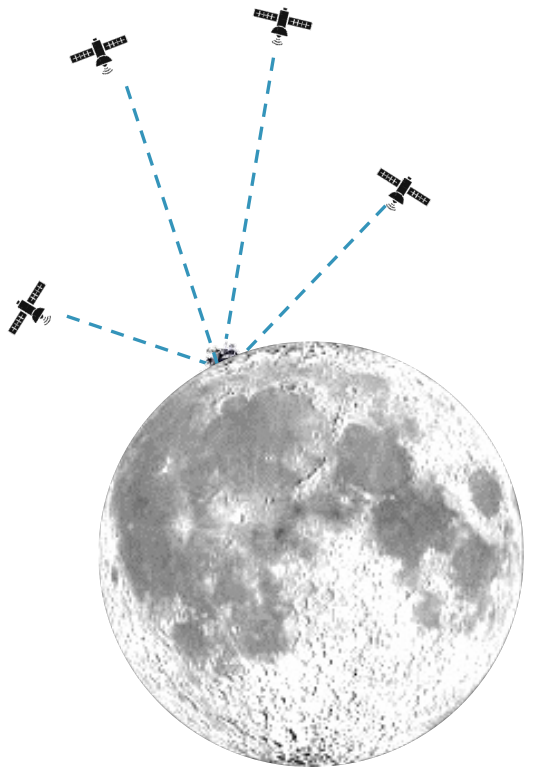


Use UTC ??

OK → ~milliseconds

Navigation signals : 300.000 km/s

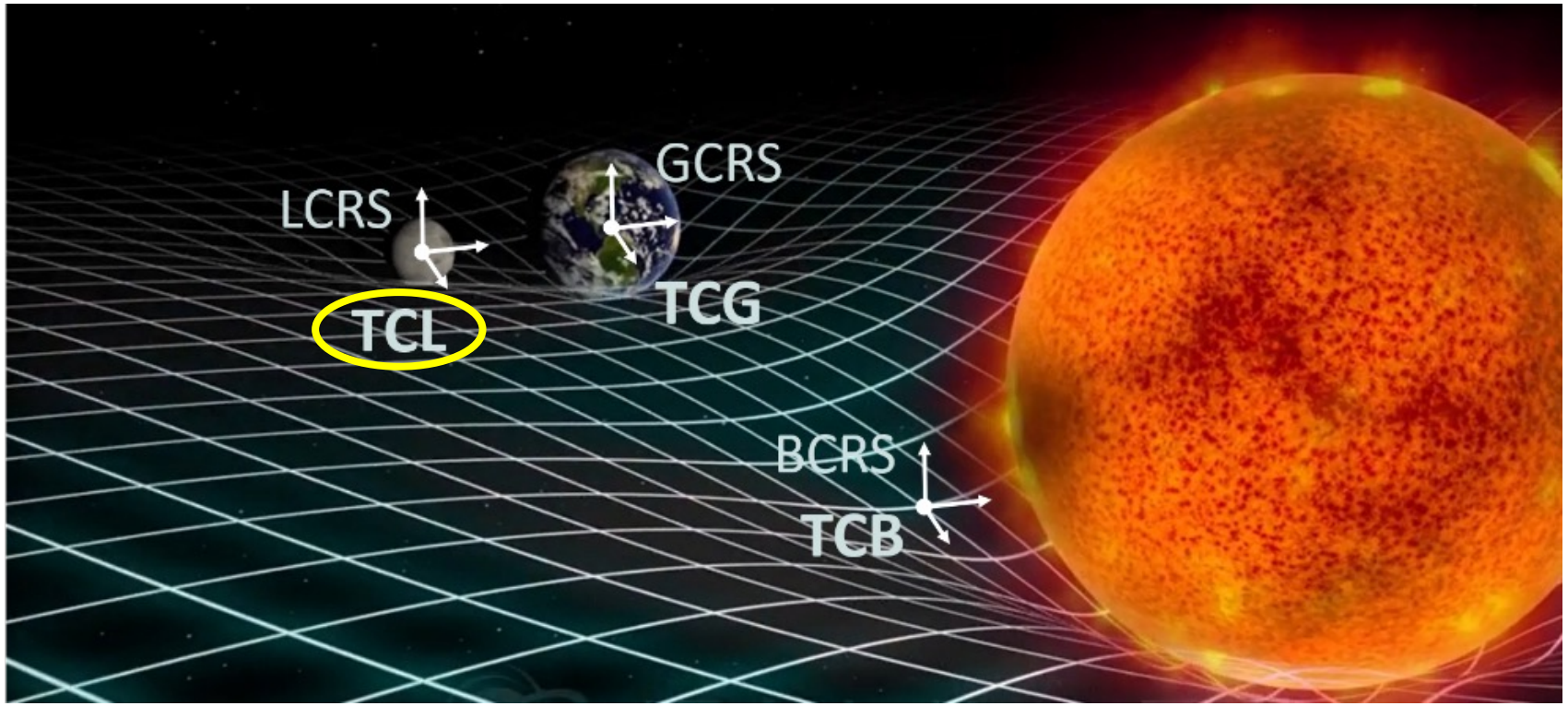
Synchronization needed between satellites
A few ns errors ~ a few meters in position
→ UTC cannot be directly used



→ Need to fix Reference Time for the Moon

Choosing a reference time

4D Reference systems
defined by the International Astronomical Union (IAU)



Natural systems

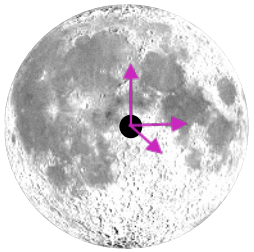
Governed by known relativistic transformations

TCL = **L**unar **C**oordinate **T**ime of 4D relativistic system (x,y,z,t)

Reference Lunar Time: Should be either **TCL** or a linear function of TCL

2 options for lunar reference time

1

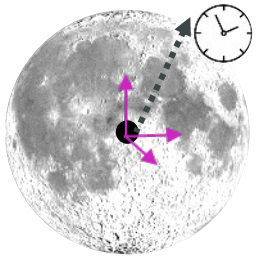


Use TCL

= the coordinate time scale of the LCRS (Lunar Celestial Reference System)

1 second of TCL = 1 second of a clock that would be at the center of the Moon (without the Moon around)

2



Use TL = scaled version of TCL

1 second of TL = 1 second of a clock on the surface of the Moon

$TL = TCL - L_L \times (t-t_0)$ $\quad L_L \sim 3.14 \times 10^{-11}$

But … What is « the surface » ?



[-10,+10] km

P. Defraigne, November 18, 2026

Impact of scaling

Scaling the time TL = TCL – L_L. (t-t_0)

→ scaling distances : x' = (1-α). x and scaling mass parameters (GM)'= $(1-L_L)$. GM

Additional complexity:

coefficients in all transformation equations between Barycentric, Moon, Earth, Mars, … coordinate systems

TCL-compatible TCB-compatible

$$\overrightarrow{x}_m^{\dagger} = (1-L_L)\,\overrightarrow{x}_m = (1-L_L)\left(\vec{x}_m - \vec{x}_M + \mathcal{O}(c^{-2})\right) = \left(\frac{1-L_L}{1-L_B}\right)\left(\vec{x}_m^{**} - \vec{x}_M^{**} + \mathcal{O}(c^{-2})\right)$$

TL-compatible 4D transfo TCL-TCB TDB-compatible

→ Risk of confusion, risk of error

→ Preferable to avoid scaling

What time is it now in Lunar Time ?

Using t_0 =1977.0 as defined by the IAU
where all coordinate times are equal (at 1977.0: TCL = TCG = TCB)

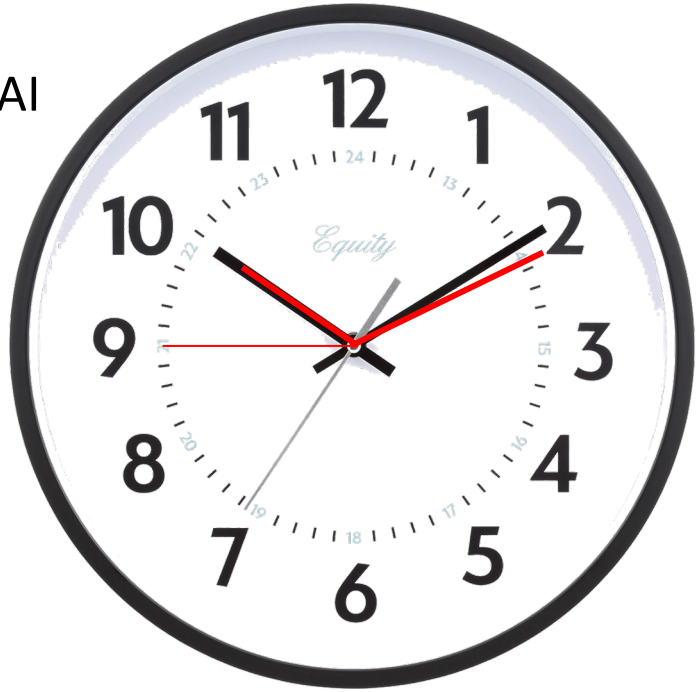
with ~1 s divergence in 50 yr between the TCL and Earth time

BUT
To agree with ephemeris time in 1977: delay of 32.184 s in TAI
+ 37 leap seconds in UTC.

→ At 2027.0 : Lunar Time – UTC ~ 70.2 s

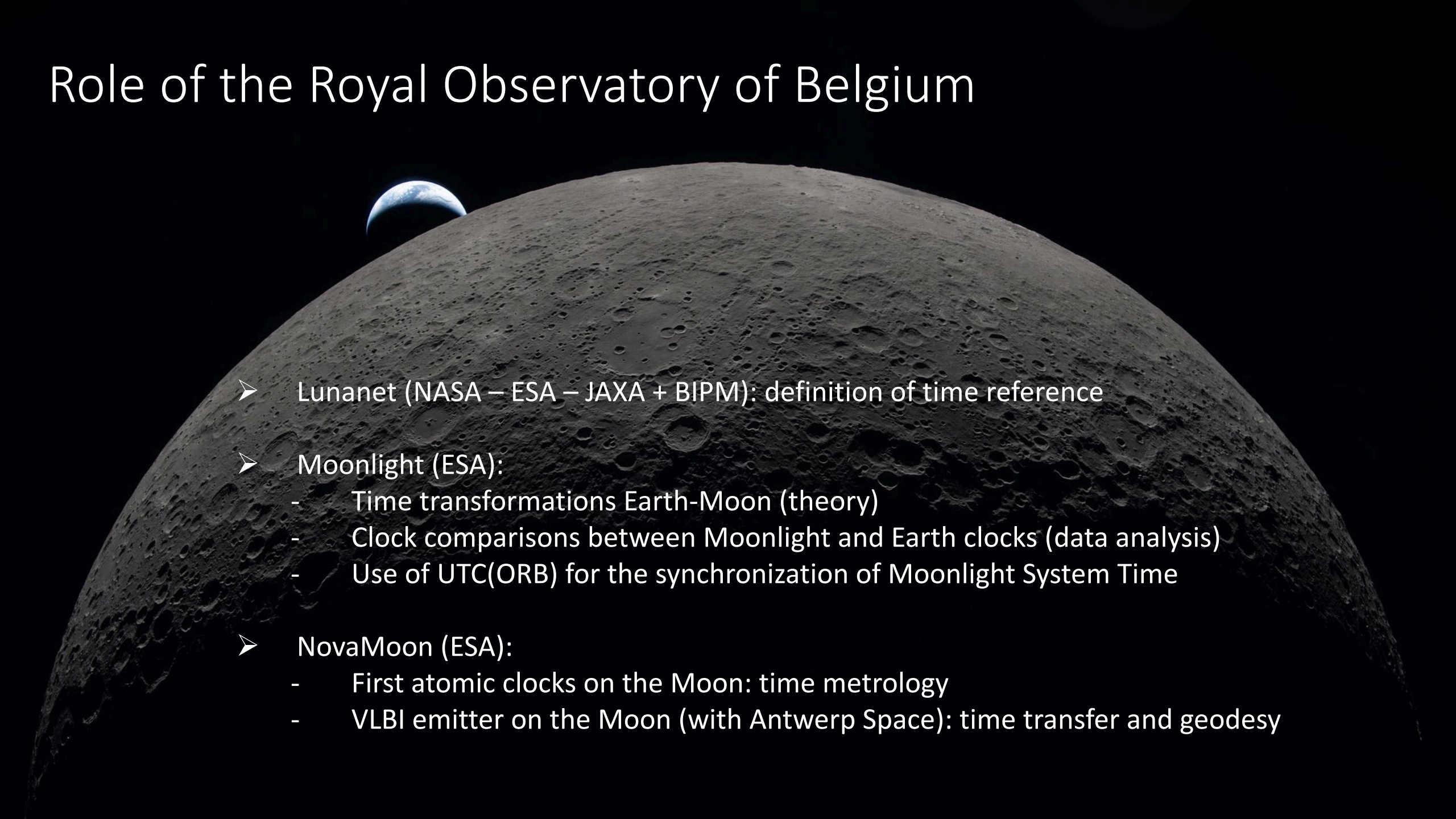
↓

Time in Greenwich
in Winter



NOT YET ADOPTED

Role of the Royal Observatory of Belgium



- Lunanet (NASA – ESA – JAXA + BIPM): definition of time reference

- Moonlight (ESA):
  - Time transformations Earth-Moon (theory)
  - Clock comparisons between Moonlight and Earth clocks (data analysis)
  - Use of UTC(ORB) for the synchronization of Moonlight System Time

- NovaMoon (ESA):
  - First atomic clocks on the Moon: time metrology
  - VLBI emitter on the Moon (with Antwerp Space): time transfer and geodesy