Metrological Aspect of Gaia

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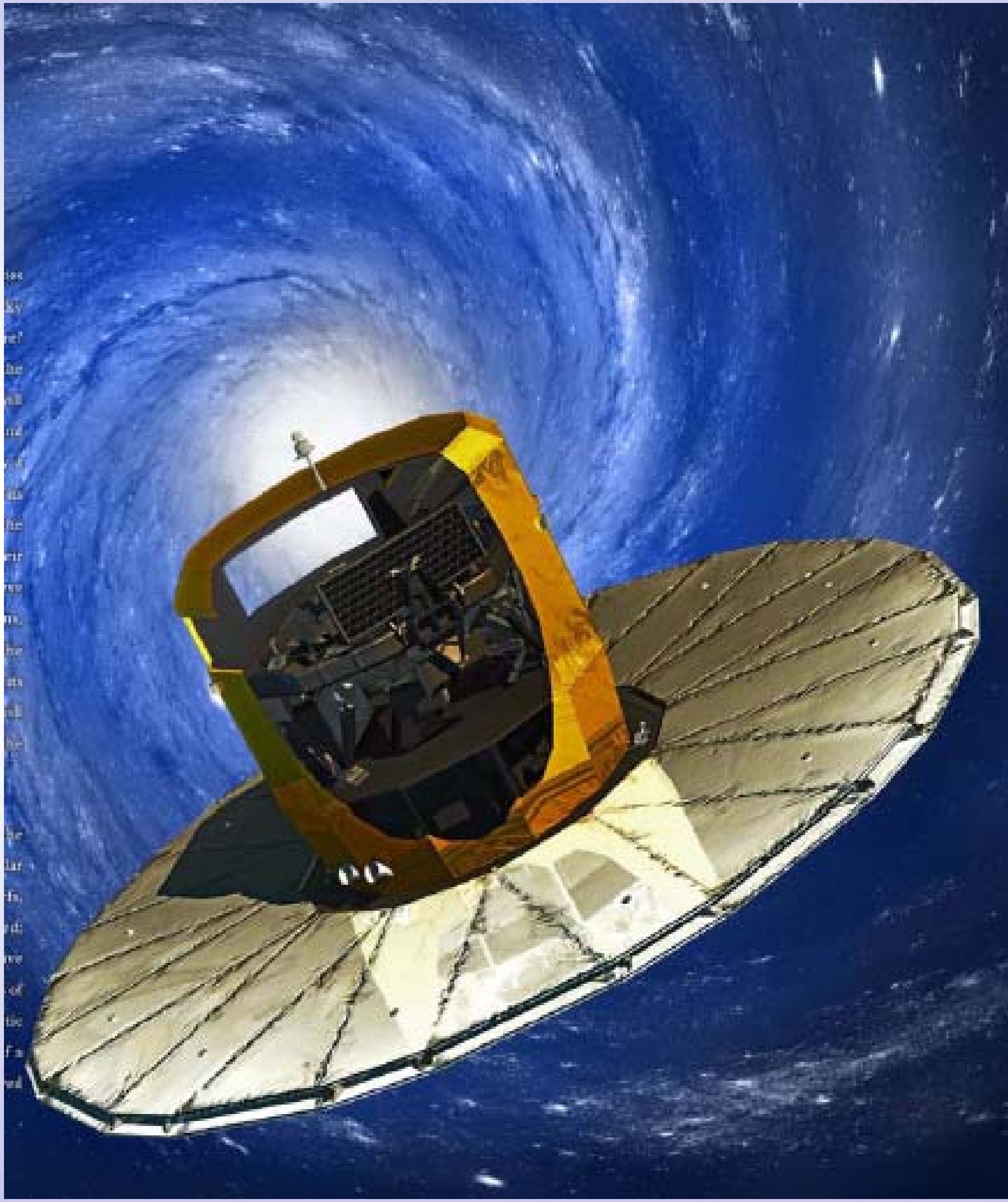
Outline

- Gaia in ultra brief
- On-board space metrology frames
- On-board and ground time metrology



Astrometric accuracy with Gaia

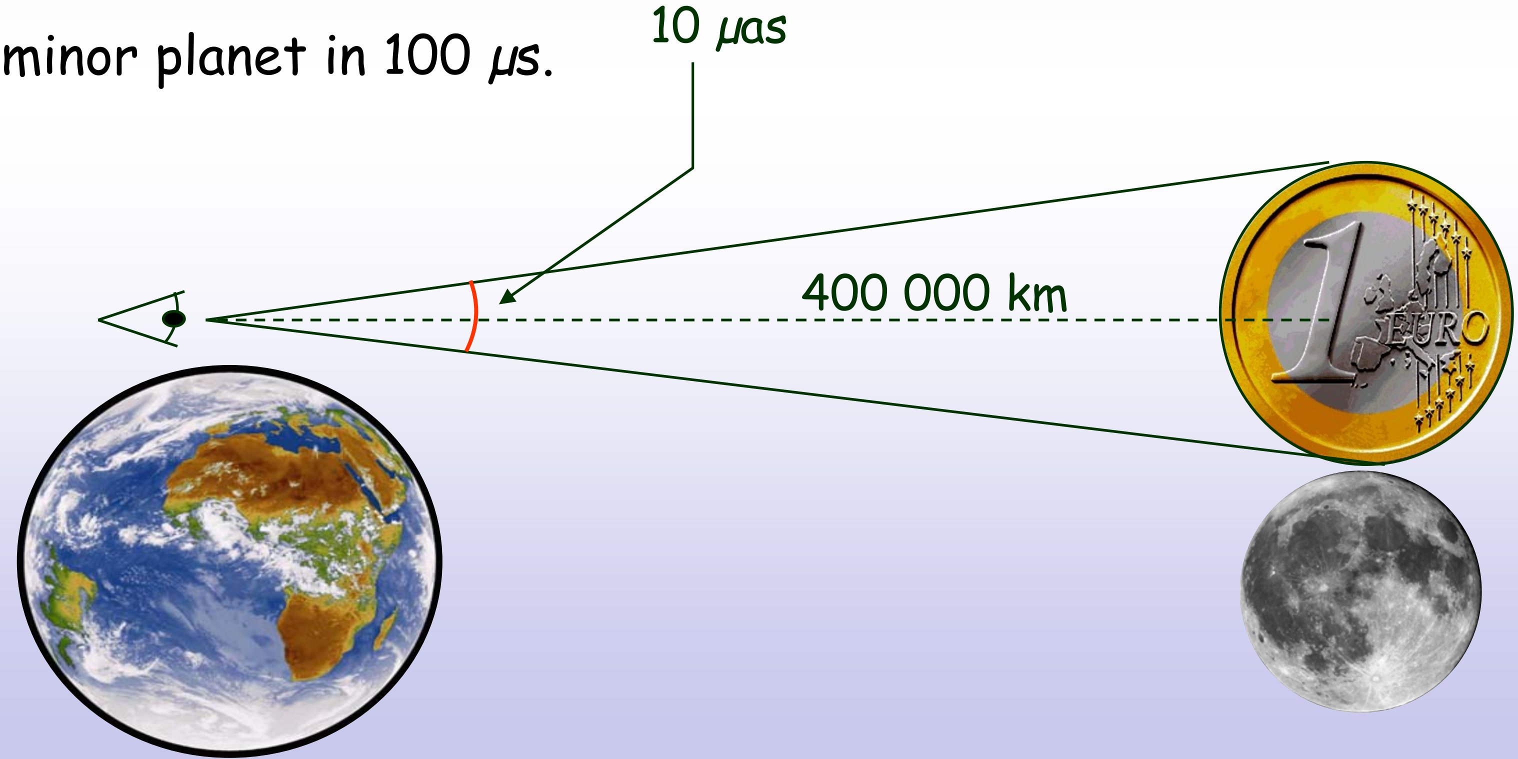
- End of mission
- Sky-averaged standard errors for G0V stars (single stars, no extinction)
- Main point for this talk: parallax accuracy

V magnitude	**6 - 13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**mag**
Parallax	8	13	21	34	55	90	155	275	μas
Proper motion	5	7	11	18	30	50	80	145	μas / an
Position @2015	6	10	16	25	40	70	115	205	μas

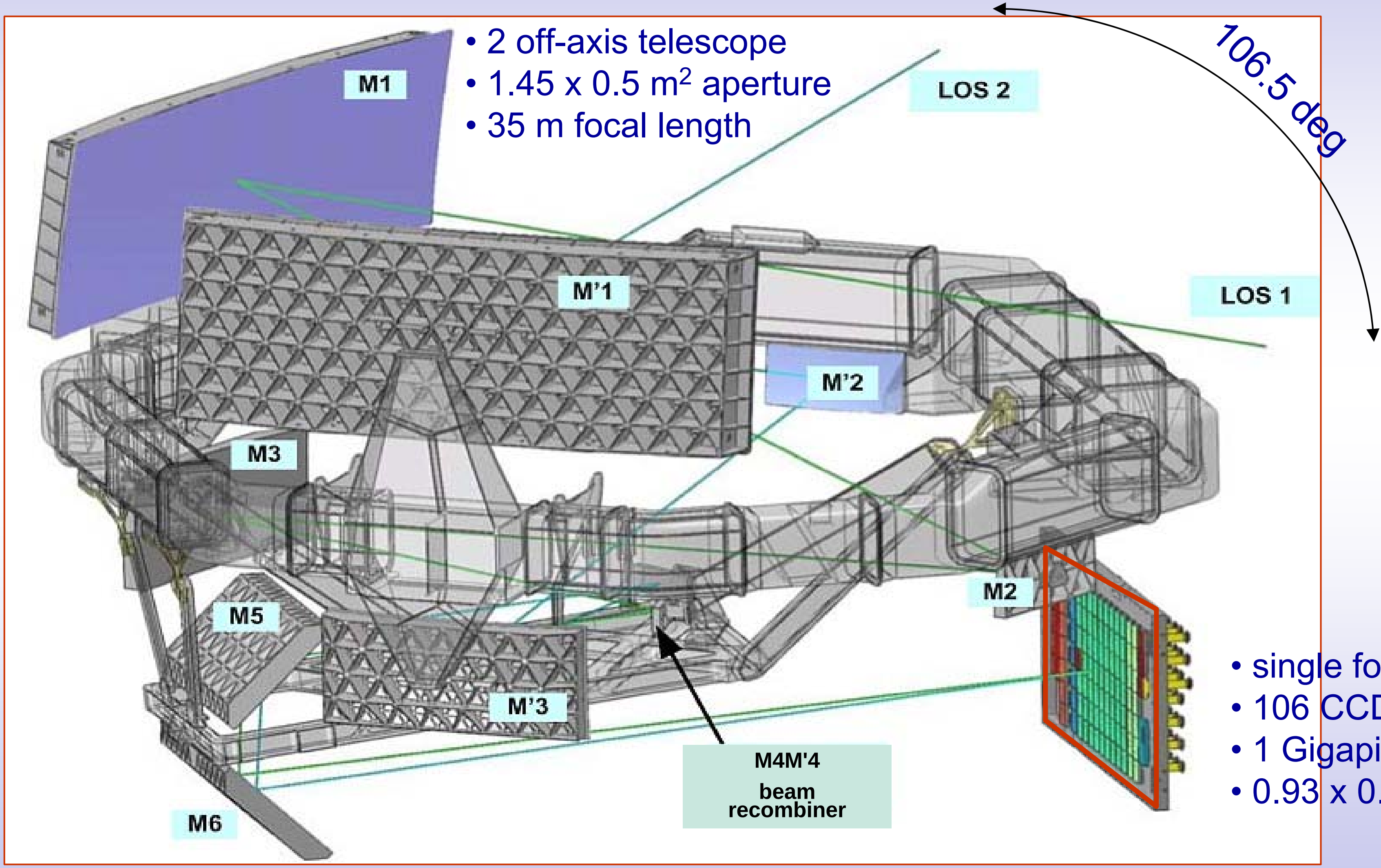
but also: very distant sources should exhibit a zero parallax on the average

10 µas: Incredibly small !

- 0.3 mm displacement on the Earth
- edge-on sheet of paper @ 2000 km
- 1 hair @ 1000 km
- a coin on the Moon
- Displacement of a 100 mas/yr star in one hour
- Motion of a fast minor planet in 100 µs.



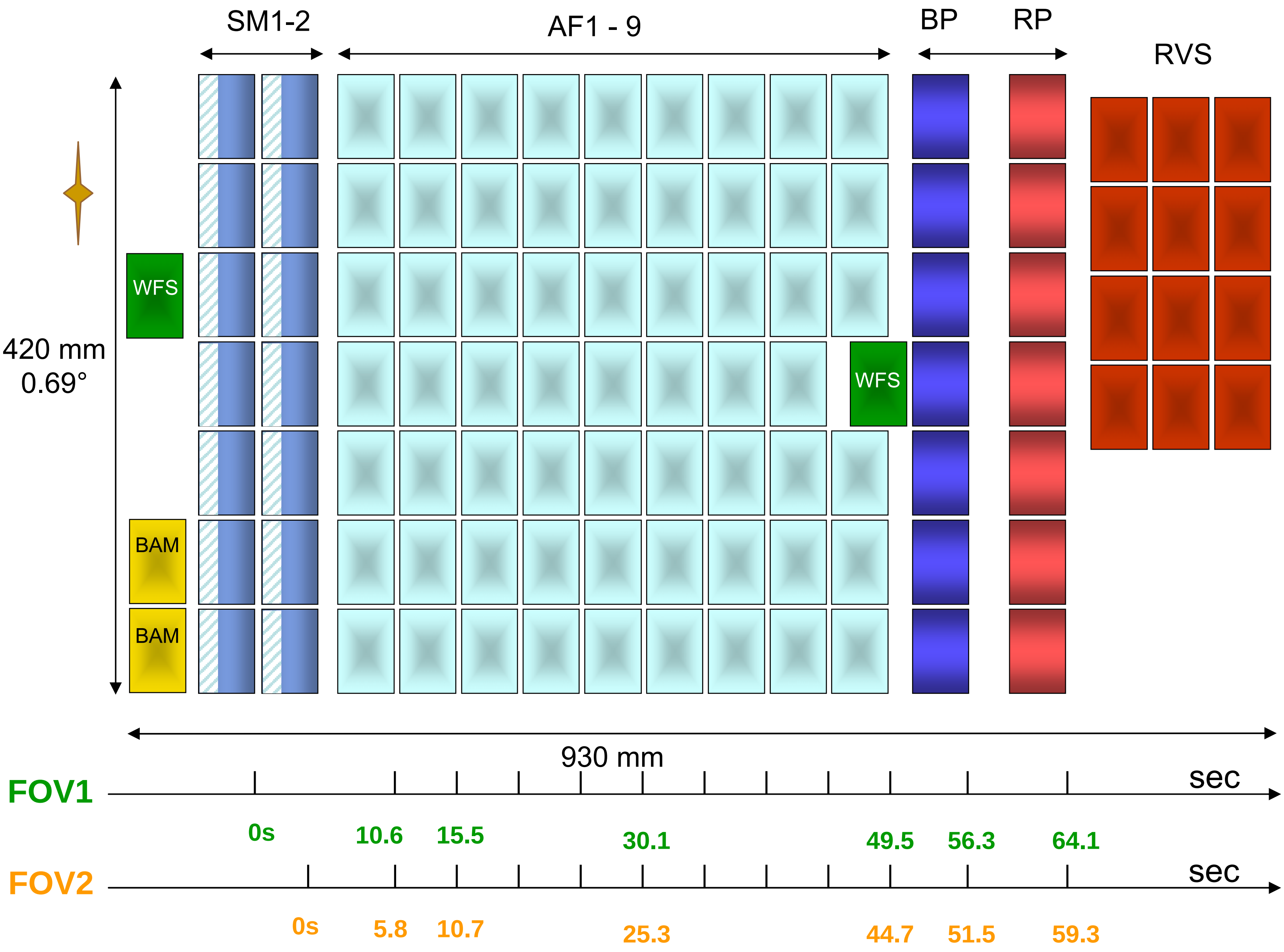
Gaia : telescopes and detector



- 2 off-axis telescope
- 1.45 x 0.5 m^2 aperture
- 35 m focal length

- single focal plane
- 106 CCDs
- 1 Gigapixel
- 0.93 x 0.42 m^2

Focal Plane Assembly


SM1-2

AF1 - 9

BP

RP

RVS

WFS

WFS

BAM

BAM

420 mm
0.69°

930 mm

FOV1

sec

0s

10.6

15.5

30.1

49.5

56.3

64.1

FOV2

sec

0s

5.8

10.7

25.3

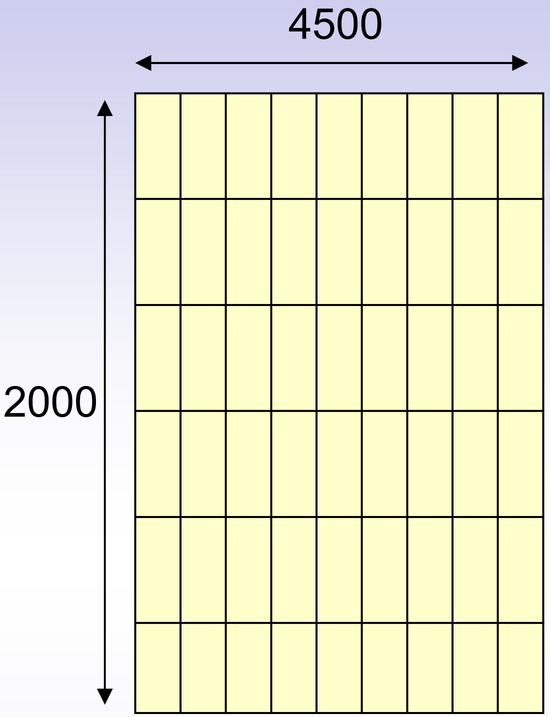
44.7

51.5

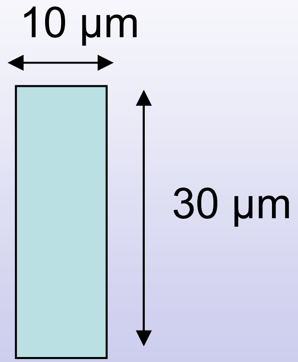
59.3

Gaia : CCD

- Identical structure for every CCD
- Manufactured by the UK company e2v
- Contract granted before formal approval of Gaia
- 106 CCDs in total,   4.5 x 6.0 cm^2 each
- Works in TDI mode

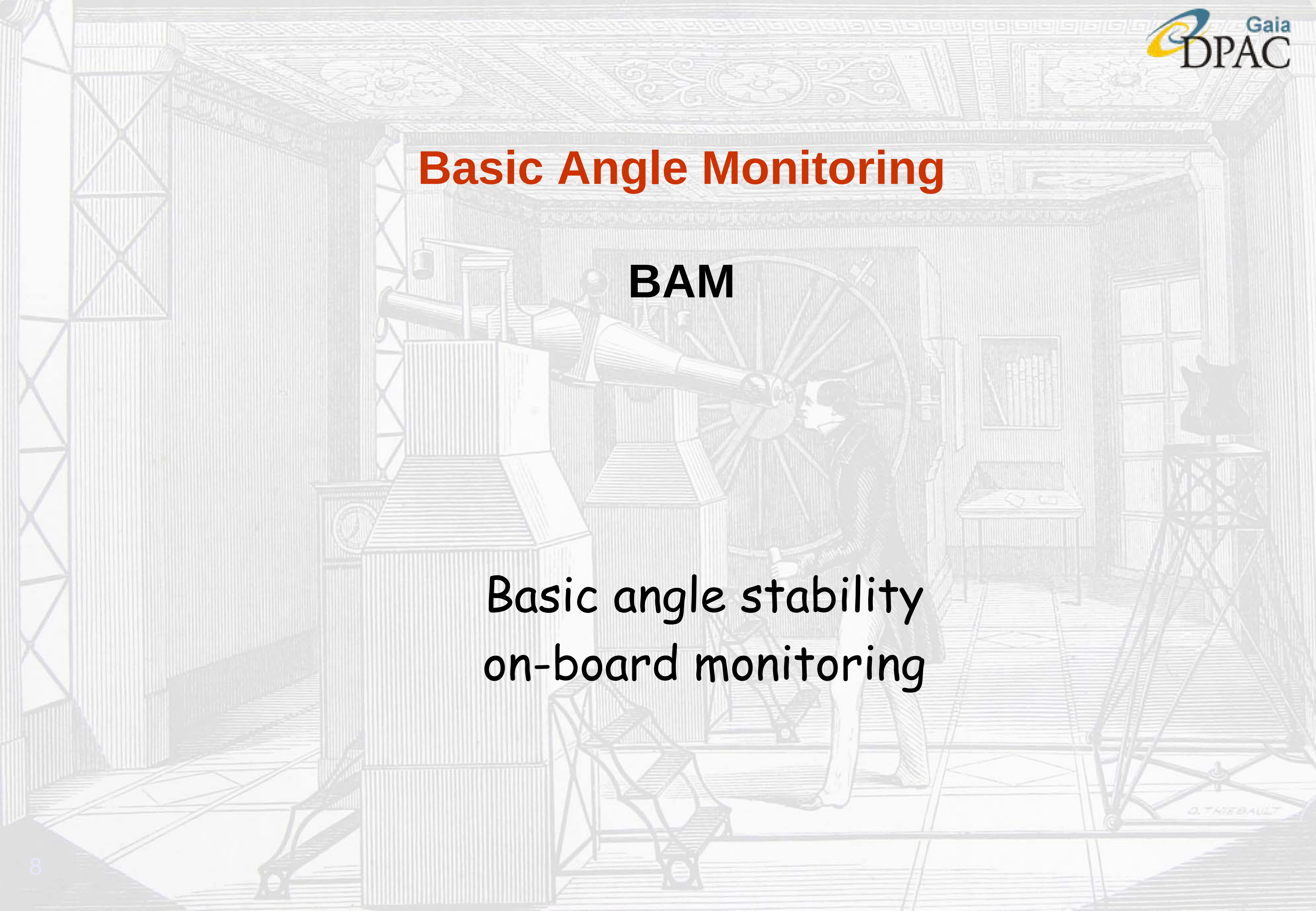


Pixel:



Basic Angle Monitoring

BAM



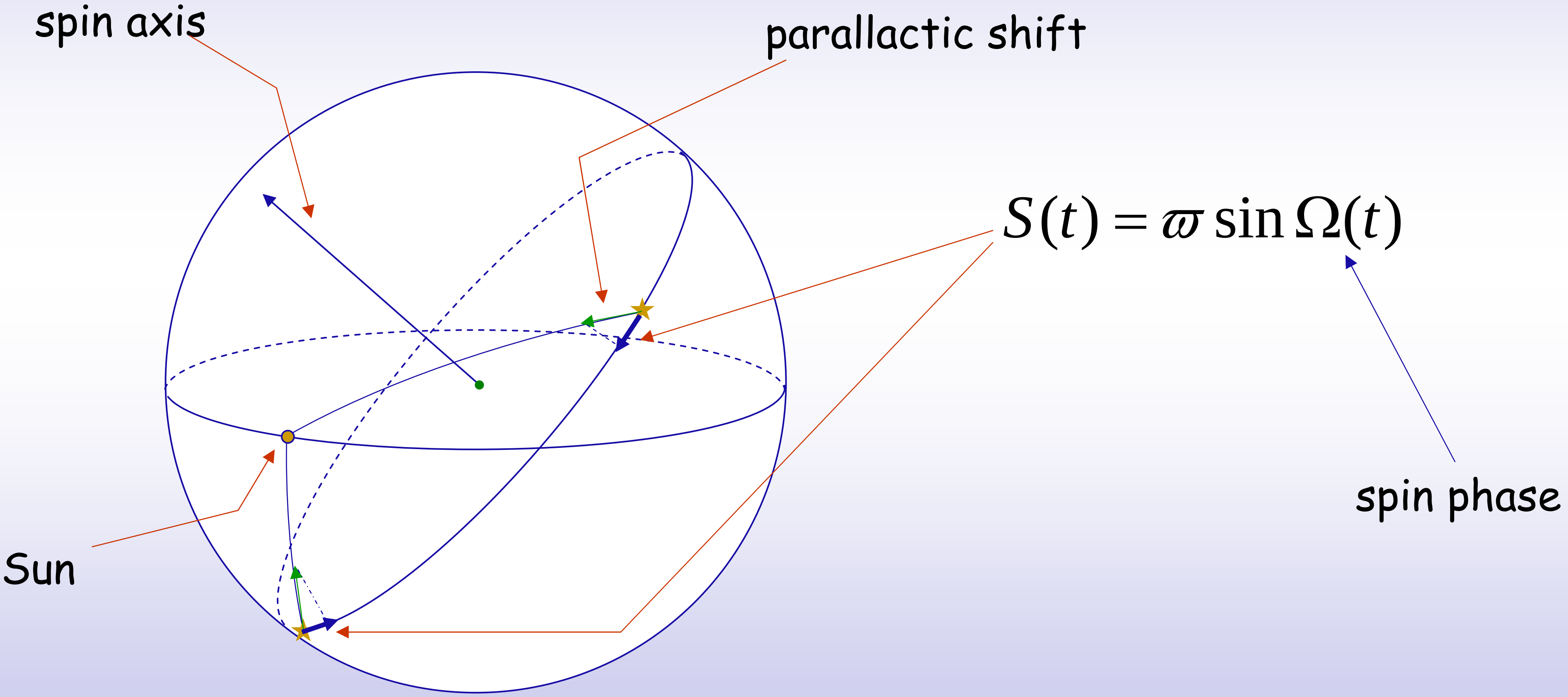
Basic angle stability
on-board monitoring

Science and parallax offset

- Systematic effect in zero- parallax has a serious scientific impact
- A globular cluster distance is determined by averaging the parallaxes over individual stars
    - d ~ 5 – 10 kpc , ϖ ~ 100 μas
    - n ~ 10^4 stars V ~ 18 σ_ϖ ~ 100 μas per star
    - Average distance to $\sigma_\varpi / n^{1/2}$ ~ 1 μas
        - if no systematic larger than 0.5 μas
- LMC/SMC d ~ 50 kpc, ϖ ~ 20 μas
    - n ~ 10^6 stars V ~ 19-20 σ_ϖ ~ 200 μas per star
    - Average distance to $\sigma_\varpi / n^{1/2}$ ~ 0.2 μas, 0.1% accuracy
        - if no systematic larger than 0.1 μas
- Relativistic PPN parameter γ
    - Correlated (r ~ 0.9) with the zero-parallax
    - PPN γ to 2×10^{-6} if zero parallax < 0.01 μas

Parallax offset conundrum

- Parallactic signal: projection of the parallax effect on the scan circle



spin axis

parallactic shift

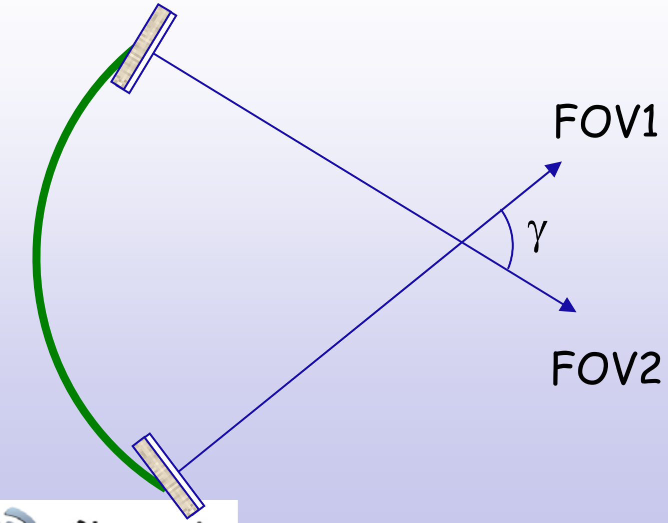
$$S(t) = \varpi \sin \Omega(t)$$

spin phase

Sun

Consequences

- Random changes in the basic angle propagate to astrometric measurements
  - typically $\sigma_{\pi\_ran} \sim 0.15\ \sigma_{\gamma\_ran}$
- Systematic error in the basic angle propagate also to parallax
  - systematic means here correlated with the geometry of observation
    - orientation with respect to the Sun
    - correlated with the thermal behaviour of the instrument
  - A 6-hour periodic change in the BA yields a systematic zero parallax effect
    - typically $\sigma_{\pi\_sys} \sim 0.8\ \sigma_{\gamma\_sys}$



Basic Angle Monitoring

- BA: Basic angle = angle between the two fields of view
  - γ = 106.5 °
- This is the angular yardstick of Gaia
  - together with the full 360° revolution
- γ must be known very accurately
- Over periods > 6h, is determined by the astrometric solution
  - this is one of the fundamental calibration parameter
  - Much more difficult for higher frequencies
  - Impossible for 1/S ➔ mimics perfectly constant parallax shift

Basic Angle Monitoring

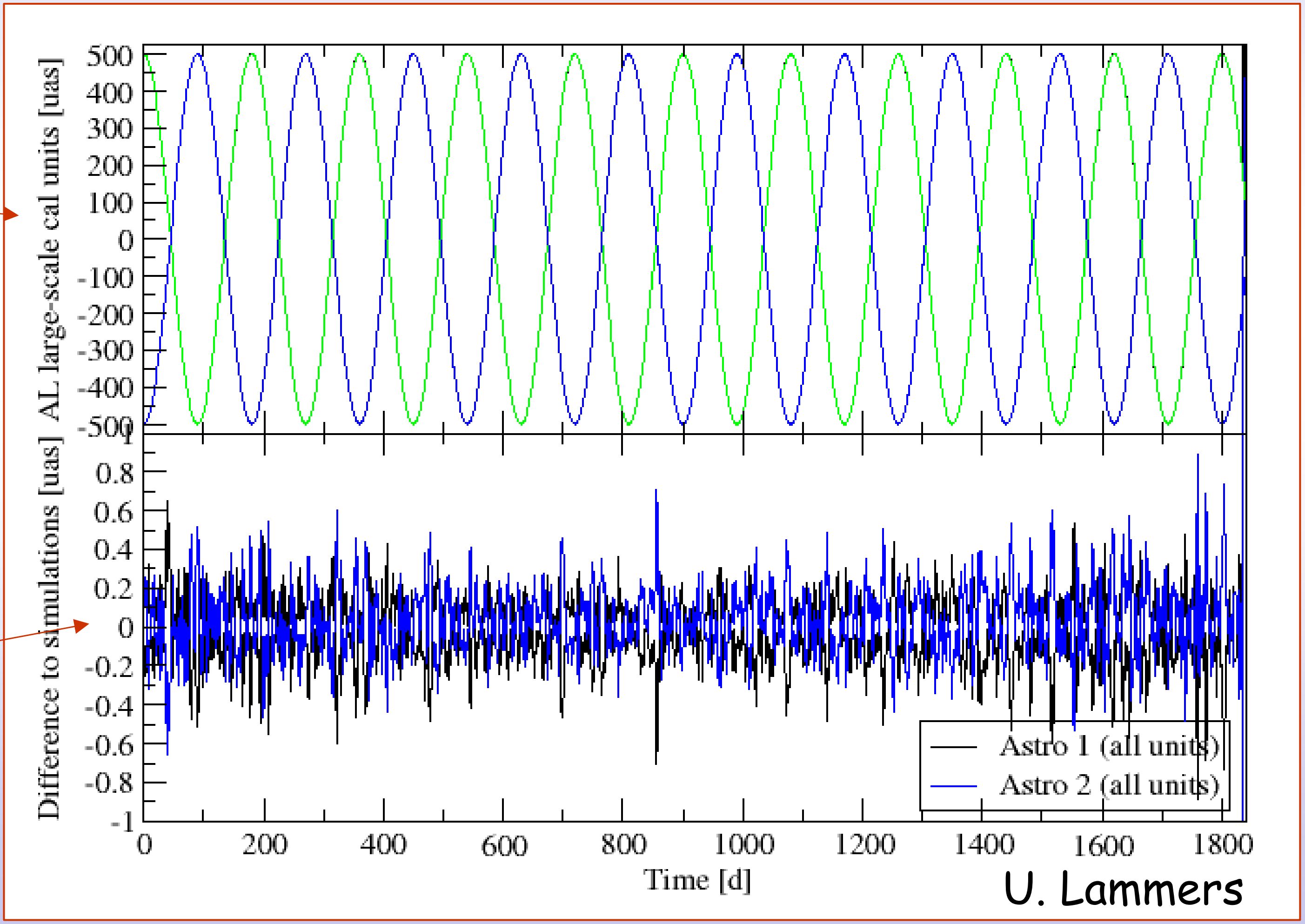
- Must be stable over shorter timescale
  - requirements:
    - stability better than 7 μas RMS for random part ➔ 1 μas on parallax
    - stability better than 4 μas for systematic part (~ spin period)
  - should be monitored to check that stability level
- This is achieved normally with thermal stability
  - should be few 10 μK with passive insulation
- However this not enough to keep the parallax offset < 0. 1 μas
  - a passive accurate monitoring is required
  - this must be processed with the science data

Long term BA fluctuation

- Simulated BA variation
  - 1 mas amplitude, 180 days period
- Recovered in global astrometry solution to sub-μas accuracy

Simulation
μas

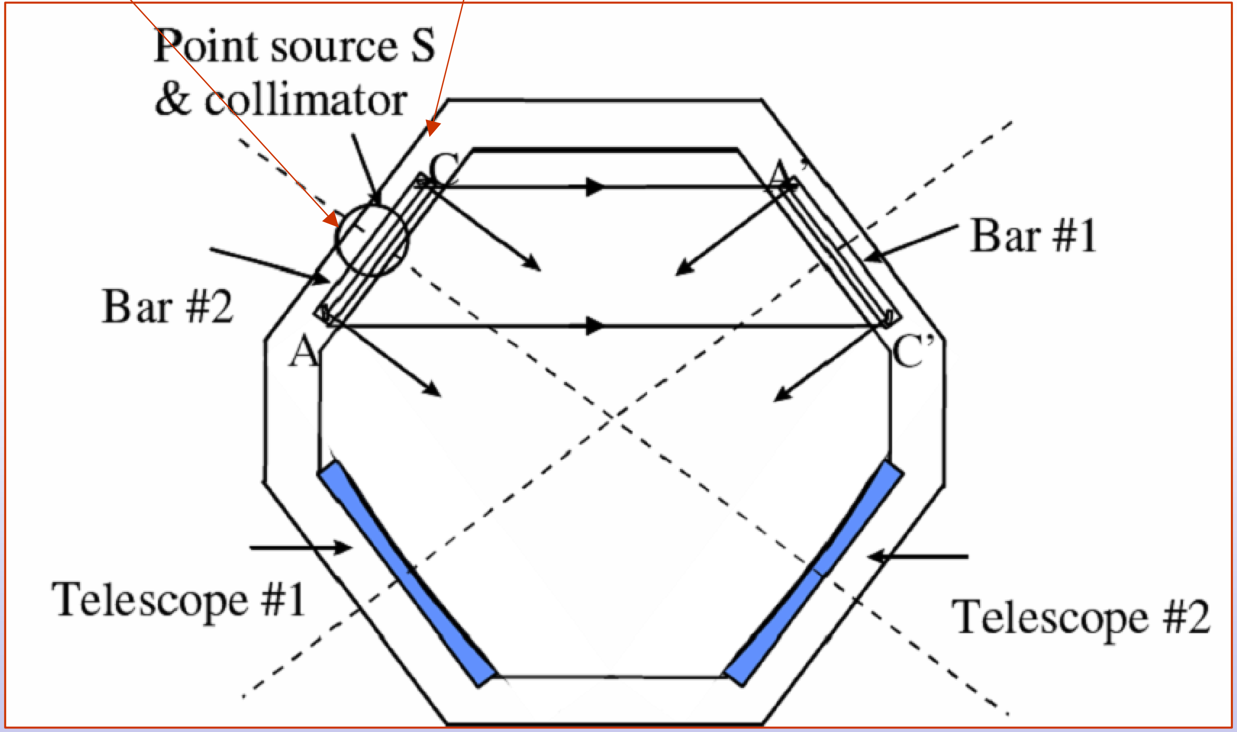
Residuals
μas



U. Lammers

Basic Angle Monitoring (BAM)

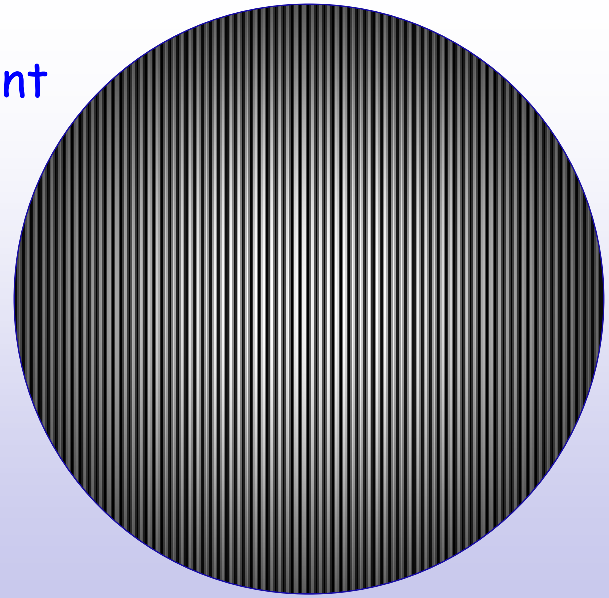
- Interferometer producing two sets of fringes
- Point source (laser diode) mounted on a rigid bar
  - flashes of 150 μs ; 5x10^9 photons
- Two beams to telescope #1 and two beams to telescope #2
  - each path produces its own fringe patterns o a CCD



BAM: How it works

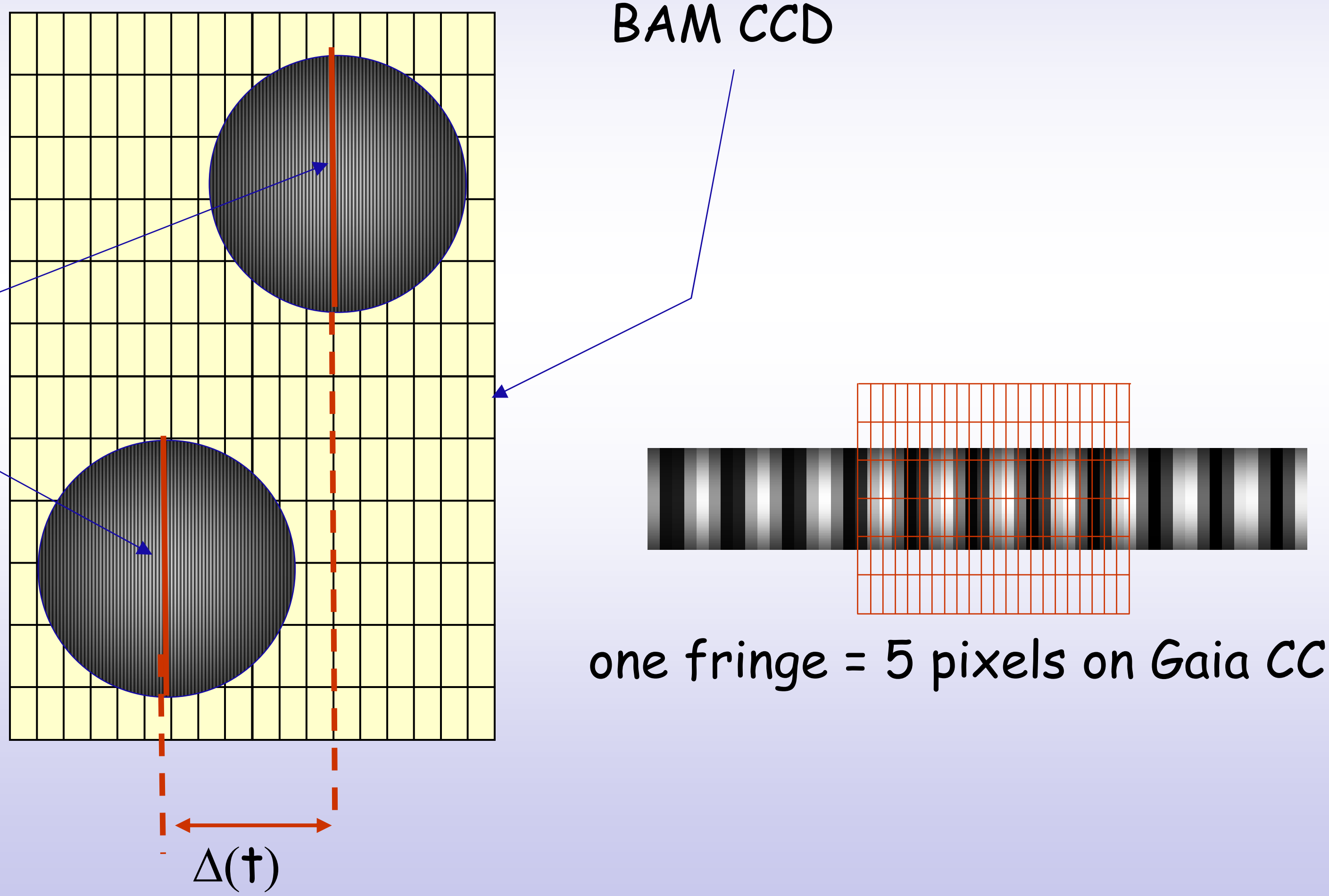
- System invariant to rigid rotation, uniform thermal variations
- Point source (laser diode) mounted on a rigid bar
  - flashes of 150 μs ; 5x10^9 photons
- Two beams to telescope #1 and two beams to telescope #2
  - each path produces its own fringe patterns
- Fringes spots located with centroiding algorithm
  - 25 measures with 4.5s interval to produce one data point

OPD	Fringe	Angular	FPA	FPA
μm		mas	μm	px
0. 8	1	300	50	5



Measurement principle

- The system sees the relative variation of the two LOS
- It says nothing about the value of the basic angle



one fringe = 5 pixels on Gaia CCDs

Performances

- Central fringe location
- Estimate using all the fringes information

$$\sigma(\xi) \sim \frac{1}{2\pi}\,\frac{\lambda}{BN^{1/2}} \qquad \left.\begin{aligned} B &= 60\,\mathrm{cm}\\ \lambda &= 850\,\mathrm{nm}\\ N &= 5\mathrm{x}10^{9}\end{aligned}\right\} \Rightarrow \sigma(\xi) \sim 0.5\mu as$$

OPD	Fringe	Angular	FPA	FPA
µm		mas	µm	px
0. 8	1	300	50	5
pm		µas	pm	px
1.3	$2\mathrm{x}10^{-6}$	0.5	80	10^{-5}

- Proven feasible on optical bench
- With repeated measures every 4.5 s, should meet the requirements

Time Metrology

Gaia Rb clock

Timing on board

Relation to astronomical timescales

Accurate time metrology for Gaia

- Time stamping accuracy is high for Gaia
  - The requirements in the timing of on-board event to 1 μs
  - Clock stability over ~ 1 day of 10^{-12}
    - daily link with ground stations over ~8 h
  - One Rb clock on-board
- Objective: link between on-board time and astronomical time to 0.1 μs
  - Clock model and clock monitoring
    - relationship between OBT (clock delivered time) and TG (Gaia proper time)
  - Relativistic modeling of the time metrology chain
    - events timed in UTC, TT, TCG, TCB, TG
  - Details depends on Gaia position and velocity
- Synchronisation sessions every day during visibility period
  - Synchronisation event triggered on-board every ~ s
  - real time downlink in current TM frame

Accurate time on board ; why and how

- Operations on board are primarily charge shifts on TDI periods
  - done every 0.9828 ms over 5 years
- Observations must be time tagged on board
  - each CCD transits is a time of crossing of a fiducial line
- Time is generated by a 20 MHz master clock
  - highest resolution of τ= 50 ns
  - all other intervals are integral multiples of τ
- Two different requirements: Stability and accuracy

First requirement: stability

- Every timing (frequency or time stamp) are derived from on master clock
- The on-board time generation must be stable ➔ constant frequency
  - basic tick intervals (eg for TDI operation) must be of constant duration during CCD transit
    - not immediately related to the SI second at this stage
  - TDI operation depends on the spin rate derived from on-board attitude some time earlier
  - complex interplay between the two effects
- The on-board clock is free (no contact with the ground) 16h/day
  - this interval could grow larger in case of problem with transmission
  - The whole on-board system relies on the clock stability between two synchronisations

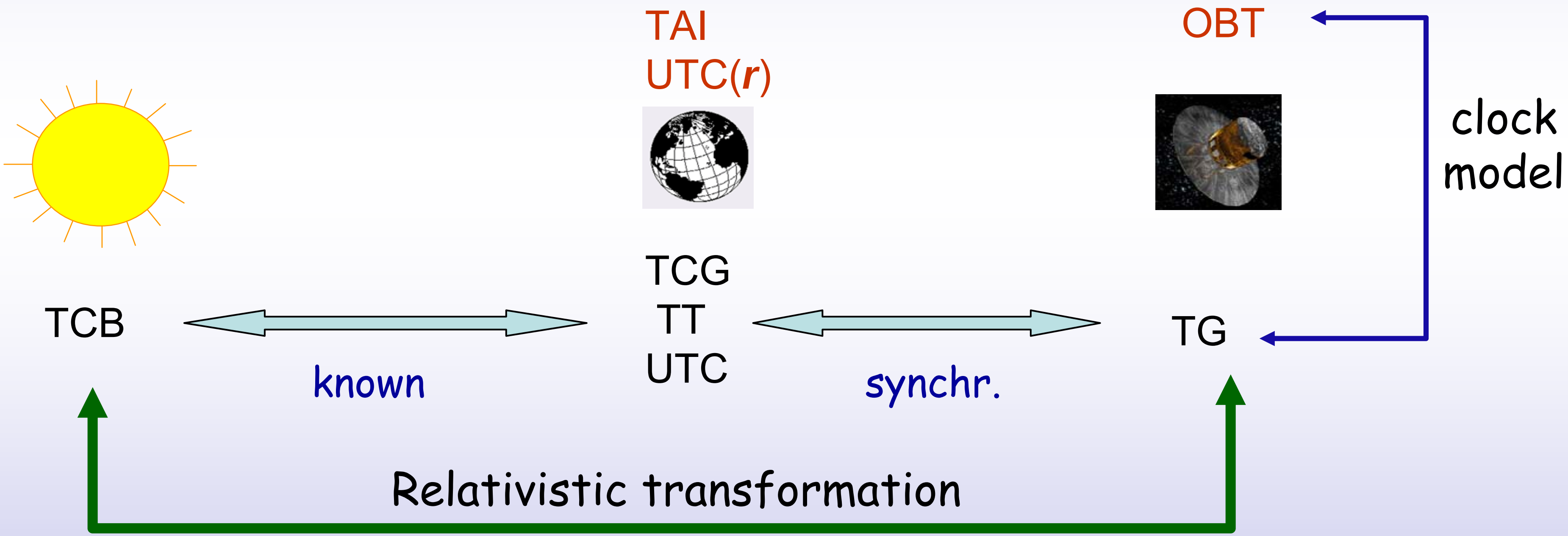
$$\boxed{\sigma(\tau) < 5 \text{x} 10^{-10} / \tau^{1/2}}$$

Second requirement: accuracy

- accuracy refers to the ability of the clock to beat the second
- One must be able to convert clock reading into SI second on ground
  - on-board operations require only a stable clock.
- The accuracy constraint is more on the link than on the clock itself
  - would be on the clock if left free for a long period of time
- Normally synchronisation data with the ground every day
  - but one must rely on the clock behaviour outside these periods
    - typically 16h per day.
    - this is again a stability requirements once it has been syntonised
- Requirements: Derived from the needs of final science product
  - most demanding: astrometry of fast moving solar system objects
- One needs to establish transformation from on-board time to astronomical time to 0.1 μs (with factor 10 margin)

Relevant timescales for Gaia

- Modelling and DP in TCB
- on-board clock delivering a realisation of TG (➔ OBT)
- tracking and ground-based timing in UTC



TAI
UTC(***r***)

OBT

clock
model

TCB

TCG
TT
UTC

TG

known

synchr.

Relativistic transformation

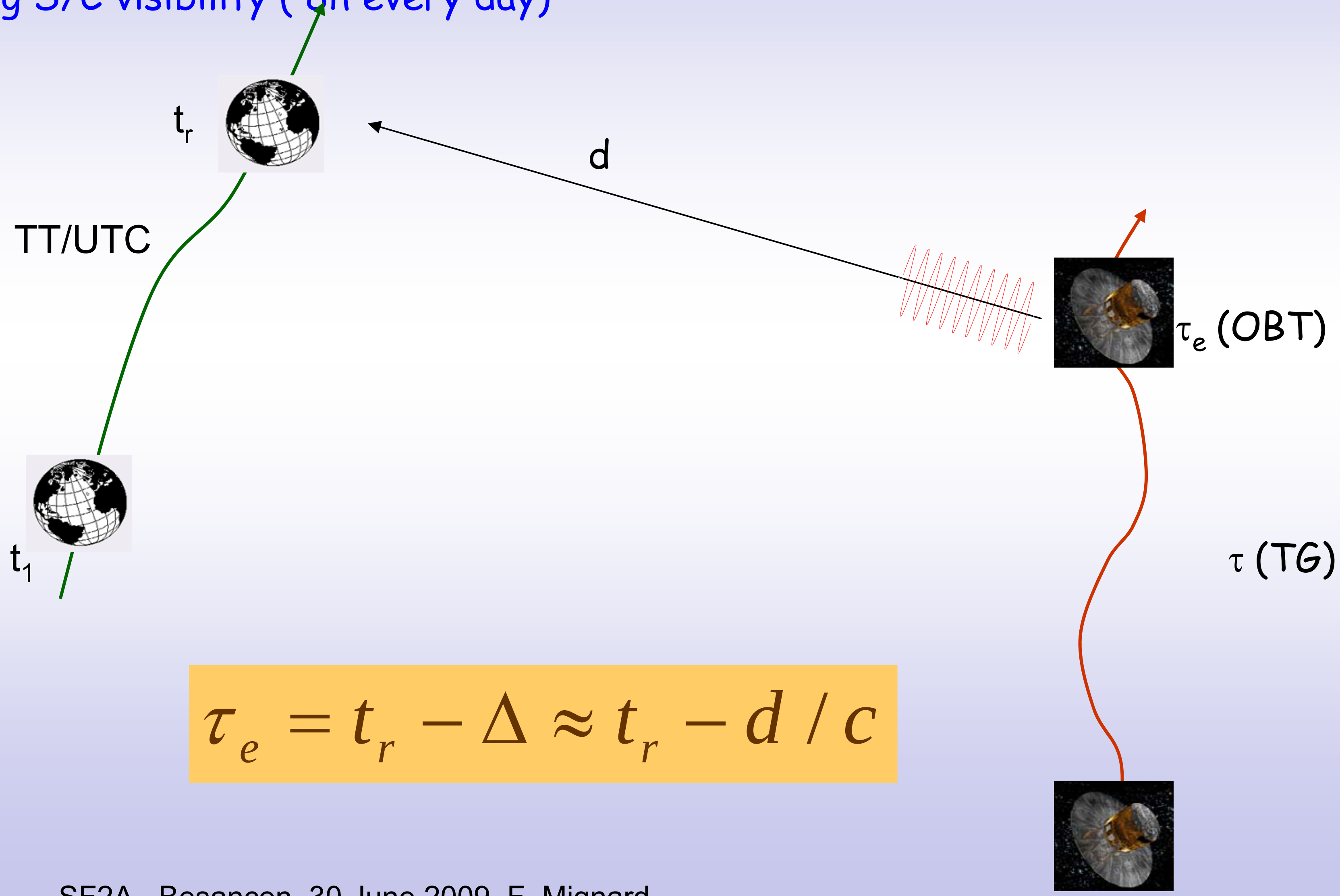
Mignard, Crosta, Klioner, 2004

Time scales in the Gaia operation and processing

- TCB is the coordinate time of BCRS.
  - TCB is intended to be the time argument of final Gaia catalogue, etc.
  - TCB is defined for any event in the solar system and far beyond it.
- TT is a linear function of the coordinate time of GCRS.
  - TT will be used to tag the events at the Earth-bound observing sites
  - The mean rate of TT is close to the mean rate of an observer on the geoid.
  - UTC=TT+32.134 s + leap seconds
- TG is the proper time of Gaia.
  - TG is an ideal form of OBT (an ideal clock on Gaia would show TG)
  - TG is an intermediate step in converting OBT into TCB
- OBT is a realization of TG with all technical errors…
  - OBT will be used to tag the observations

one-way synchronisation

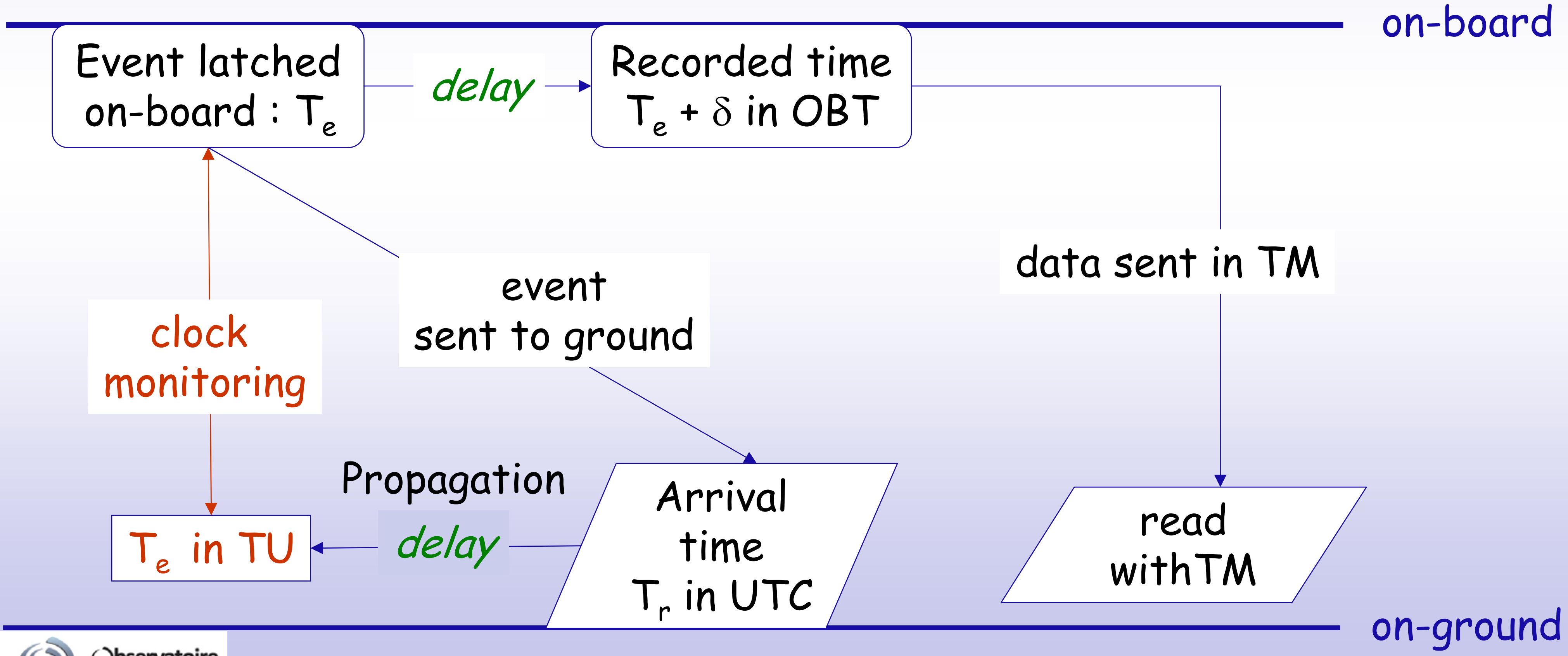
- Method adopted for Gaia
  - during S/C visibility (8h every day)



$$\tau_e = t_r - \Delta \approx t_r - d/c$$

On-way Gaia clock synchronisation

- Production of an synchronisation event on board ➔ T_e
- Event strobe sent to telemetry packet immediately
- It is time tagged on board on near real time ➔ $T_e + \delta$ on-board clock
- Data sent with TM
- Received on the ground after propagation ➔ T_r on-ground clock



on-board

Event latched on-board : T_e

delay

Recorded time $T_e + \delta$ in OBT

event sent to ground

data sent in TM

clock monitoring

Propagation delay

T_e in TU

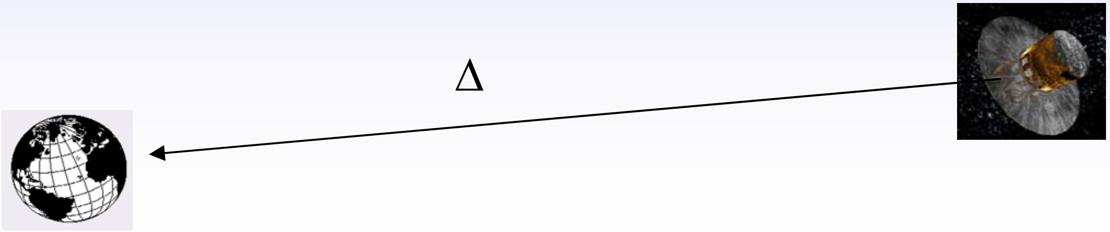
Arrival time T_r in UTC

read withTM

on-ground

Full time transfer equation

- Based on the computation of propagation delay
  - needs several calibrations and significant modelling



UTC t_r

Δ

τ_e (OBT)

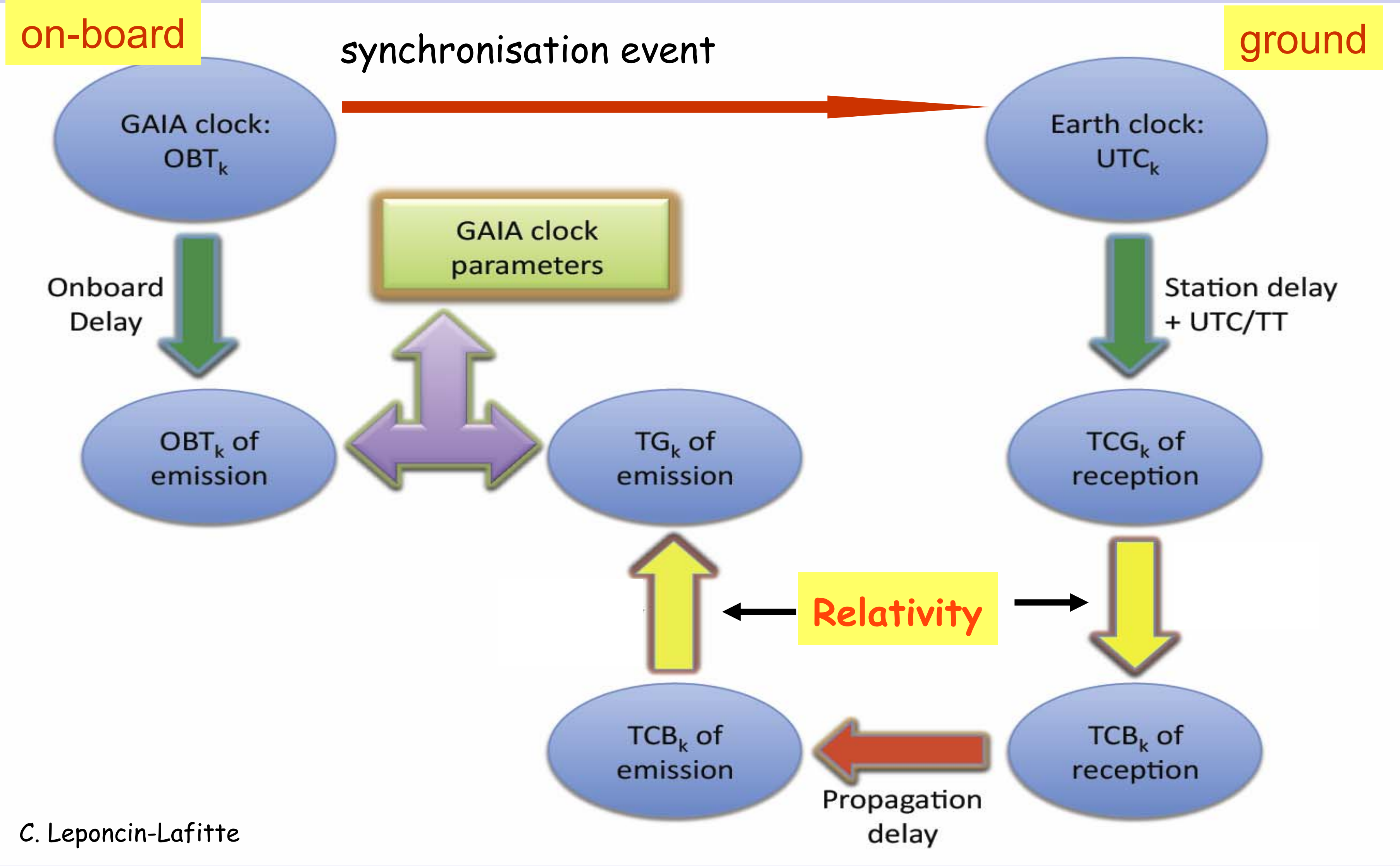
$$\Delta = d/c + \delta_T + \delta_I + S + R$$

$$R \approx \int \left(\frac{v^2}{2c^2} + \frac{\Delta U}{c^2} \right) dt$$

$$S = \text{Shapiro delay}$$

- For Gaia d/c ~ 5s
  - D to 1 μs ➔ d to 0.3 km !
    - with current tracking performance OK in **radial direction**
  - but details depend of the tracking error spectrum

Overall synchronisation scheme



on-board

synchronisation event

ground

GAIA clock: OBT_k

Earth clock: UTC_k

GAIA clock parameters

Onboard Delay

Station delay + UTC/TT

OBT_k of emission

TG_k of emission

TCG_k of reception

Relativity

TCB_k of emission

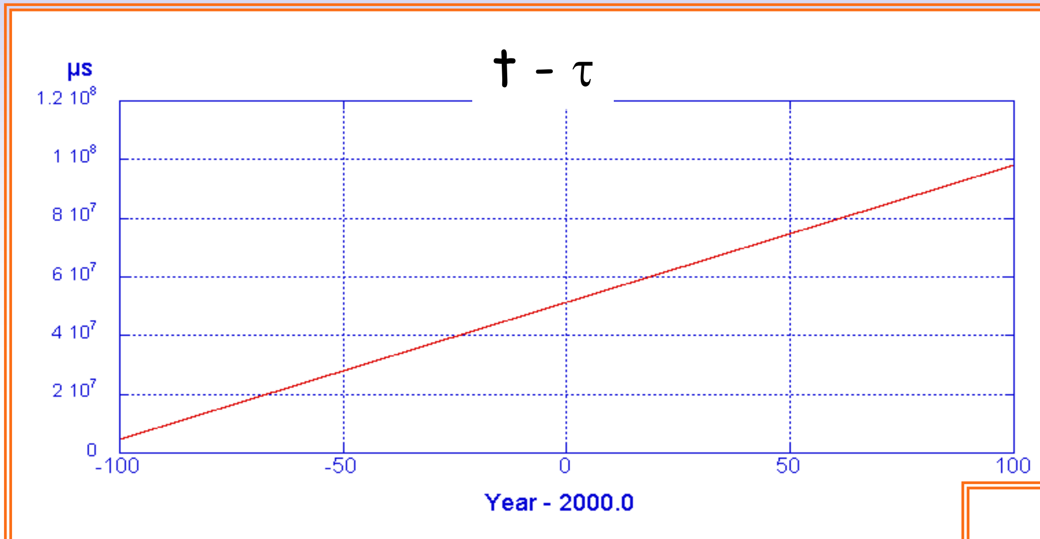
TCB_k of reception

Propagation delay

C. Leponcin-Lafitte

Raw difference TCB – TG

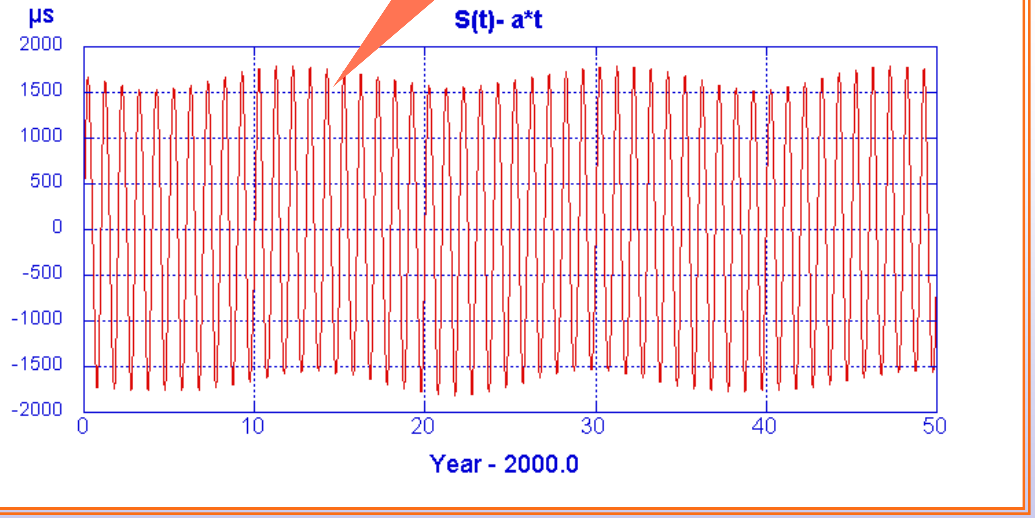
- Makes sense over a long term



Secular term :

TCB - τ = 1.481259949x10^{-8} (JD-J2010)

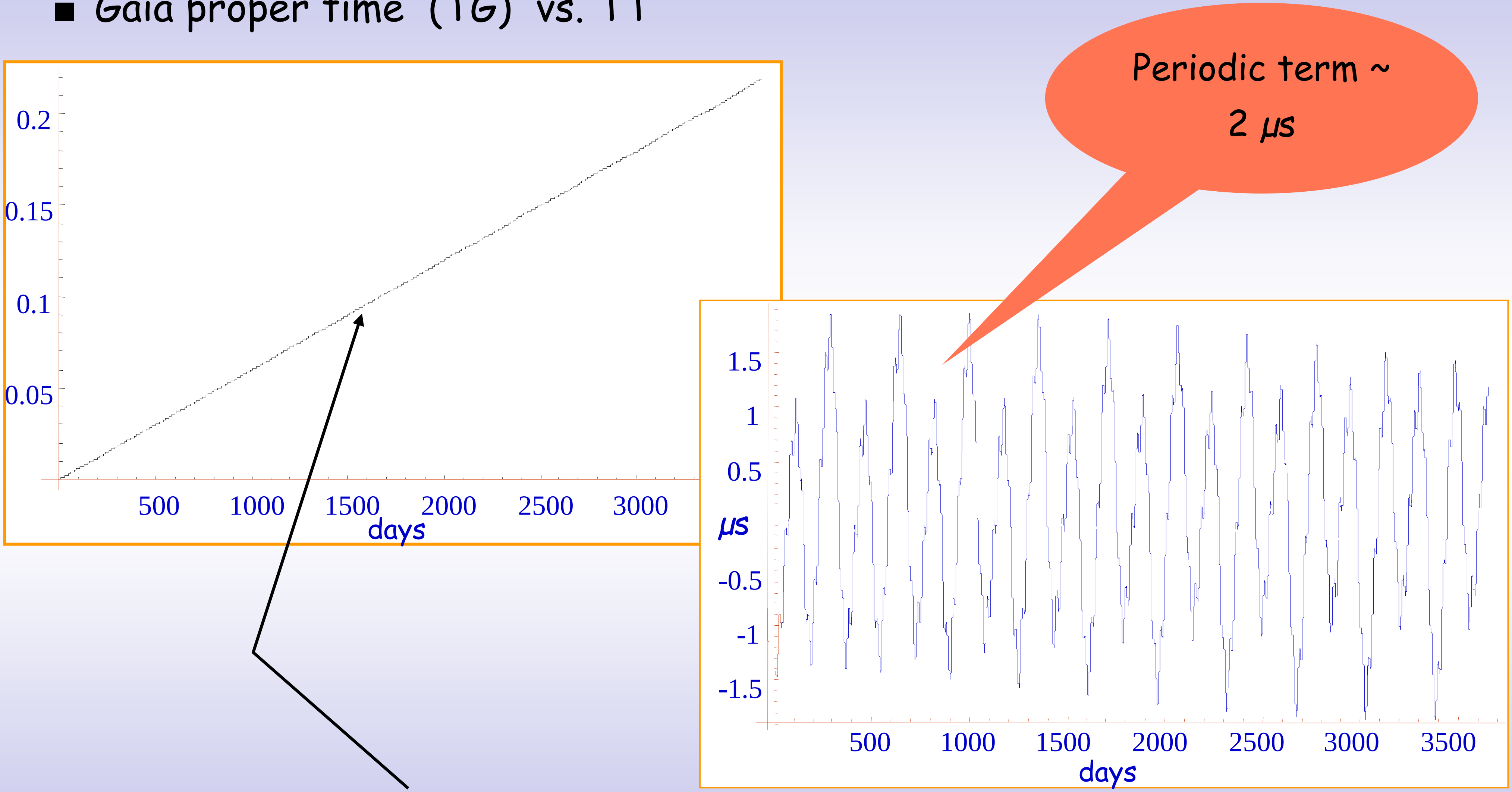
amplitude : 1.66 ms + modulation



Mignard et al., 2006

TT - TG

- Gaia proper time (TG) vs. TT



Periodic term ~ 2 μs

Secular term : TT - τ = 6.93…x10^{-10} (JD-J2010)

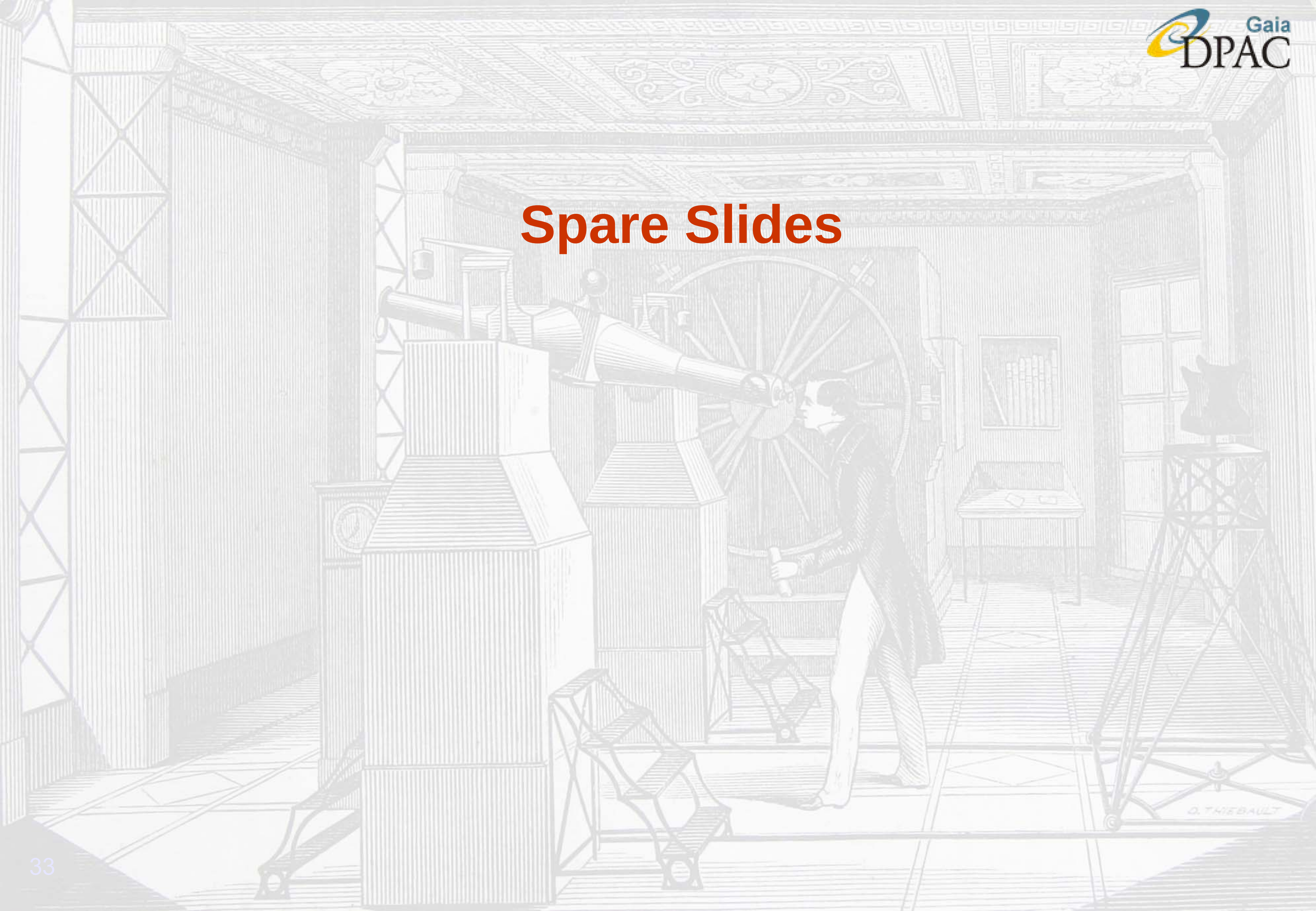
S. Klioner, 2006

Conclusions

- No good astrometry without dedicated metrology
  - two outstanding examples presented in detail

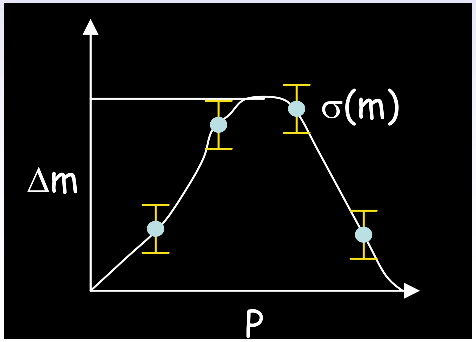
- Instrument calibration is a major activity of the Data Processing
  - optics
  - detectors throughput
  - CCD large and medium scale mapping
  - spin-rate
  - photometric system
  - RVS reference wavelength
  - zero point radial velocity
  - …

Spare Slides



Accuracy: Variable phenomena

- Astrometry of standard stars
  - No timing problem (~ 1 minute for the nearest or fastest stars)
- Variable stars : $\sigma(t) < P\,\sigma(m)/2\Delta m$
  - No resolution better than few seconds needed
- Radial velocity, spect. binaries : $\sigma(t) < P\,\sigma(V_r)/2\Delta V_r$
  - Period of few hours : resolution of ~ 1 mn.
- Astrometry of solar system objects
  - accuracy of ~ 10 μas .
  - largest motion of 200 mas/s : $\sigma(t) < 10 - 100$ μs

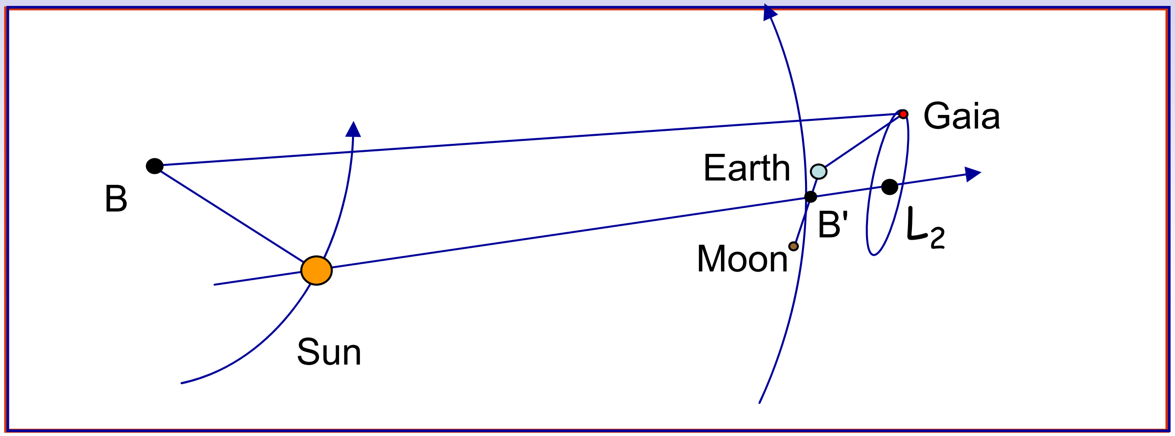


Accuracy: Use of the ephemeris

- Solar system bodies
  - Jupiter needed to 1 km ➔ $\sigma(t) < 0.05$ s
- Position of Gaia
  - Earth/Gaia to 0.1 km, $V \sim 30$ km/s ➔ $\sigma(t) < 0.01$ s
- Velocity of Gaia
  - Earth to 1 mm/s, $\Gamma \sim 6$ mm/s^2 ➔ $\sigma(t) < 0.1$ s
  - Gaia/L2 to 1 mm/s, $\Gamma \sim 0.04$ mm/s^2 ➔ $\sigma(t) < 10$ s
- Attitude of Gaia
  - A posteriori computation of the image location
    - $\sigma_{pos} < 1$ mas, $V \sim 60$ "/s ➔ $\sigma(t) < 10\ \mu s$
    - 1px = 10 μas, $V \sim 60$ "/s ➔ $\sigma(t) < 100$ ns

Motion of Gaia : TCB - TG

- Orbit of Gaia around L2



$$\frac{d\tau}{dt} \approx 1 - \frac{1}{c^2}\left[\frac{V^2}{2} + U\right] + \frac{1}{c^4}\left[-\frac{V^4}{8} - \frac{3}{2}V^2U + \frac{U^2}{2} + 4\mathbf{V.W}\right]$$

$$t - \tau = \int\left(\frac{V^2}{2c^2} + \frac{U}{c^2}\right)dt + \int\left(\frac{1}{8}\frac{V^4}{c^4} + \frac{3}{2}\frac{V^2U}{c^4} - \frac{U^2}{2c^4} - 4\mathbf{V.W}\right)dt$$

- Numerical quadrature + solar system ephemerides

Practical method for TCB ←→ TG 1/2

- Solution for a period of few years

τ = TG

t = TCB

$$\frac{d\tau}{dt} = 1 + \frac{1}{c^2}\,\alpha'(t) + \frac{1}{c^4}\,\beta'(t)$$

→ motion of the Gaia clock in BCRS

$$\alpha' = -\frac{1}{2}\,v_o^2 - \sum_A \frac{GM_A}{r_{oA}}$$

→ from the BCRS metric with Gaia **r**, **v**

$$\beta' = -\frac{1}{8}\,v_o^4 + \left(\beta - \frac{1}{2}\right)\left(\sum_A \frac{GM_A}{r_{oA}}\right)^2 + (2\beta - 1)\sum_A \left(\frac{GM_A}{r_{oA}} \sum_{B\neq A} \frac{GM_B}{r_{AB}}\right)$$
$$+ \sum_A \frac{GM_A}{r_{oA}}\left(2(1+\gamma)v_A^i v_o^i - \left(\gamma + \frac{1}{2}\right) v_o^2 - (1+\gamma)v_A^2 + \frac{1}{2} a_A^i r_{oA}^i + \frac{1}{2}(v_A^i r_{oA}^i / r_{oA})^2\right)$$

Practical method for TCB ←→ TG 2/2

- One determined two small corrections

$\tau = \mathrm{TG}$

$t = \mathrm{TCB}$

$$\boxed{\begin{aligned} \tau &= t + \delta t(t), \\ t &= \tau - \delta\tau(\tau) \end{aligned}}$$

$$\boxed{\frac{d\delta t}{dt} = \frac{1}{c^2}\,\alpha'(t) + \frac{1}{c^4}\,\beta'(t)}$$

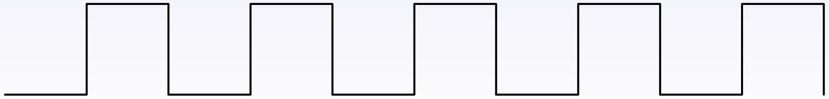
➔ direct transformation

$$\boxed{\frac{d\delta\tau}{d\tau} = \frac{1}{c^2}\,\alpha'(\tau - \delta\tau) + \frac{1}{c^4}\,\Big(\beta(\tau - \delta\tau) - \alpha^2(\tau - \delta\tau)\Big)}$$

- The initial conditions $\delta t(t_0) = 0$ for some fixed t_0 during the mission
- Solution represented in Chebyshev polynomials

On-board time and clock

- There will be a stable frequency standard ➔ RB clock
  - f = 10 MHz
- It will be used to tune the master clock at 20 MHz
  - 1 clock cycle = 50 ns
  - cycle number coded over 64 bits (~ 10^{19} states)



- This will control the TDI clocking (TDI = 982.8 μs)
  - 1 TDI period = 19656 clock cycles
- Therefore OBT = 19656*TDI index
  - OBT will be embedded in the TDI data stream
- The CDU generates clock signals and synchronisation pulses which inherit from the main clock short term and long term stability properties.
- Any CDU generated signal is synchronous and phased with the others and consequently with the main clock.