Advanced Concepts for Ranging and Time Transfer

Applications and Mission Support

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Outline

• Evolution of Clock Technology
• Time Transfer and Ranging
• Missions and Applications
  – PRARE, ACES, ELT, EGE, LEO, T2L2
• Integrated Mission Concepts
  – Reference Satellite in GEO
  – GEO – LEO Tracking
  – Extension to Moon and Deep Space
• Link Design
  – GRACE – like mission
• Recommendations
• Summary and Conclusions
Primary Cs Reference Clocks, define SI unit „1s“ operated by National Matrological Institutes (NMI)

Frequency Uncertainty:

CS2: \( \sim 10^{-14} \)

CSF1: \( \sim 10^{-15} \)

Essen‘s Cs Clock, 1955 \( \sim 10^{-10} \)

Commercial clock (tube) \( \sim 10^{-13} \)
Active Hydrogen Maser
Excellent excellent short stability (ground and space)

Maser Electronics Temperature, 1 month

Phase Noise, 100 MHz: -130 dBc @ 100 Hz offset
Cryo-cooled Sapphire Oscillator, ESA DSA-3
Best short term stability, ground use only

Work performed by femto-st, NPL UK and TimeTech under ESA/ESTEC contract
Cryo-cooled Sapphire Oscillator
10 GHz Synthesiser, intrinsic performance

1 fs ⇔ 0.3 µm

Phase @ 10 GHz 8000 s, 1 Sa/s
1 vert div: 1 fs ~ 0.4 µm

Time Deviation (TDEV): 5E-17s @ 1s (0.017 µm)
⇒ Instrumentation and components exceed GRACE-type requirements
⇒ Optimise Link Budget, select appropriate LO based on phase noise

Note on limitations:
1) Ideal case, hardware only
2) „infinite S/N“ ⇒ Link Budget
3) „noise-free“ local Osc.
Comparison of best short-term stable sources

Best USO

cryo: sapphire oscillator

cavity: stabilised laser
Two-Way Satellite Time & Frequency Transfer (TWSTFT)

- Established method to compare primary clocks since 1980
- Stability: 100..200 ps / month
- Uncertainty B: 1 ns
- Calibration interval: 1 year
Combine Satellite Positioning and Time Transfer

**Satellite Ranging: receive own signal**
- Round Trip signal delay
- Sum of up- and downlink delay
- Depends on link delay effects

**Time Transfer: receive remote signal**
- Bi-Directional link
- Difference of up- and downlink delay
- Independent from link and sat position

Same equipment is used for ranging and time transfer
- Simultaneous availability of results, same data set
- Real-time operation
- Independent orbit determination and clock comparison

“+” Satellite Ranging    “-” Time Transfer
PRARE on-board ERS-2, 12 years of operation
Space-Based PN Ranging, emphasis on Geodesy

Ranging noise, all stations
0.9 cm @ 15s normal points

Velocity noise, all stations
0.015 mm/s @ 15s normal points

PRARE / ERS was selected to support Radar Altimeter operations over oceans
Atomic Clock Ensemble in Space

- **PHARAO** (CNES, France); Cold atom Cs Primary Frequency Standard (1E-16)
- **Active Hydrogen Maser** (Switzerland)
- ESA Mission on ISS 2013
- Prime contractor: ASTRIUM Friedrichshafen, D
ACES-MWL: Architecture and Links

Ku-Band, Up-link
Power Tx: 2 W
Carrier: 13.475 GHz
PN-Code: 100 MChip/s
1pps: 1 time marker /s
S/C: 4 Receiver Channels

Ku-Band, Down-link
Power Tx: 0.5 W
Carrier: 14.70333 GHz
PN-Code: 100 MChip/s
1pps: 1 time marker /s
Data: 2.5 kBit/s

S-Band, Down-link
Power Tx: 0.5 W
Carrier: 2248 MHz
PN-Code: 1 MChip/s
1pps: 1 time marker /s
Data: 2.5 kBit/s

Ku-Band: 2-way Bi-directional Link
Pseudo-Noise 100 MChip/s
Carrier Phase
Carrier Cycle Identification

MWL FS internal delays applied

Requirements:
230 fs @ 300 s
1.2 ps @ 5000 s
5.5 ps @ 1d
10 ps @ 10d

Δ-Configuration

D1 = D2
ACES-MWL & FCDP
Elements for Ranging and Clock Comparison

• FCDP
  – Frequency Comparison and Distribution Package
  – On-board comparison between PHARO and Hydrogen Maser

• MWL Flight Segment (EM)
  – With ultra-stable oscillator (USO) based on BVA resonator (Oscilloquartz)
  – May be operated in stand-alone mode using built-in USO

• MWL Ground Terminal
  – Prototype development and manufacturing
  – Highly stable thermal conditions
Carrier TDEV, C=-95dBm, C/No = 76 dBHz
4 receiver channels DLL1..4

- Thermal noise: \( \sim 1/\sqrt{\tau} \)
- Instrument flicker
- Noise floor
- Thermally induced

1 Sample / s, BW = 1 Hz

70 fs @ 60s
0.4 µm/s @ 60s
ACES - ELT: European Laser Timing (ELT) Concept

Time transfer using SLR laser stations

- All clocks synchronised / known wrt UTC
- Common Clock on-board
- Microwave-based Time-Transfer: 100 ps uncertainty, all weather
- Laser-based Time Transfer: target: 50 ps or better
- 1-way Laser-Ranging from any Laser station synchronised to UTC

Additional Payload elements:
- Laser Photo-Detector with Event Timer
- Passive corner-cube reflector
ACES-ELT: Key components
Small and simple add-on to any mission

- **ELT** (European Laser Timing) is now considered within the baseline ACES instrumentation

- Preparational experiment successfully performed in Wettzell

- Expect the formal go-ahead within FM project phase (start 2009)

- Optics on a boom together with GNNS reflectometry receiver

- Electronics within the Microwave Link (MWL with USO)
German LEO Mission (DLR)
PRARE-L: Lunar Gravity Field Determination

X-Band, Down-link
Power Tx: 2 W
Carrier: 7.2 GHz
PN-Code: 10 MChip/s
1pps: 1 time marker /s
Datent: 5 kBit/s

X-Band, Up-link
Power Tx: 20 W
Carrier: 7.2 GHz
PN-Code: 10 MChip/s
1pps: 1 time marker /s
Datent: 1 kBit/s/Channel
G/S: 2 Rx Kanäle

Ka-Band, Sat1 - Sat2
Power Tx: 50 mW
Carrier: 34 GHz
PN-Code: 100 MChip/s
1pps: 1 time mark
Datent: 5 kBit/s

Inter-Satellite Link:
Ka-Band Carrier
Pseudo-noise, 100 MChip/s

Moon-Earth Ranging
X-Band Carrier
Pseudo-noise, 10 MChip/s

Ranging stability:
better than 4 cm

Time-Synchronisation stability
Ground - Space: 30 ps / 1 day
Space - Space: 1 ps @ 1000s
6 ps @ 1 day

Target: Gravity field to 50th order
Measure Rel. Velocity with Accuracy better than

← Distance: 50 .. 65 km →

Flechtner, F. et al, Simulation study for the determination of the lunar gravity field from PRARE-L tracking onboard the German LEO mission, EGU 2008, Vienna

Diameter: > 15 m
Sensor co-location on ground and in space
Use multiple sensors to search for systematic errors
GEO – LEO tracking via (optical) data link / dedicated links or combination
Integrated On-Board Design, „add-on“
Refer any signal to common USO, distance to several AU

- Determine phase of any signal wrt common USO
- Comparison of on-board signals (various options)
- „Continuous“ operation of µWave an Laser link
Link Design: GRACE – like inter-satellite Link

- Short term stability (1s .. 5 s)
  - link budget -> use highest possible carrier frequency
  - LO phase noise -> use USO with improved phase noise
- Long term stability (10s .. > 1 orbit)
  - Technology aspects and thermal stabilisation

- Carrier: 100 GHz
- RF Power: 100 mW
- Antennae: 25 dBi, 2° dB beam width
- Target C/No: 63 dBHz
- Precision: $\lambda / 3000$
- USO contribution: 0.027 $\mu$m @ 1s
- Link stability: 1 $\mu$m, i.e. flicker noise floor to ~1000s
- Link performance: 1 $\mu$m/s @ 1s, 0.6$\mu$m/s @ 5s
- Optical data link: 0.15 $\mu$m @ 1s (TERRASAR, LEO -> GEO)
Recommendations, Equipment

- Re-use existing equipment and technologies to best extent, like
  - ACES on-board frequency comparison
  - ACES 2-way link space to ground, ranging & time transfer
  - ACES Ground Terminal
  - ACES ELT (European Laser Time Transfer)
- Add existing clocks / frequency sources
  - ACES USO
  - ACES active hydrogen maser
  - Galileo passive hydrogen maser
  - Others?
- Re-use existing communication channels (Optical and RF)
- Optional Equipment
  - Optical frequency source for improved short-term performance
  - Frequency Comb with interface to μWave
  - Interface to optical communication channels
Recommendations, Infrastructure

• Consider and optimise the whole time- and signal flow:
  – NMIs (UTC) – G/S – link – S/C – link S/C
• Synchronise all clocks to UTC, incl. standard TM/TC stations
• Install short-term stable oscillators on board
  – USO, USO with clean-up, act. or pass. Maser, stabilised opt. source
• Add calibration & delay monitoring to all elements
• Re-use hing-rate data links instead of dedicated links
• Consider both µWave and Optical Data Links (high S/N!)
• Consider GEO – LEO links in addition to LEO-LEO
• Co-locate different sensors on ground and on board
• Consider Laser one-way ranging based on synchronised clocks
• Specify Link stability using established methods, i.e. TDEV
Summary and Conclusions

- µWave do not reach precision of dedicated optical links
- µWave is readily available and ideal complement to laser-based systems
- µWave links can be “tailored” to match requirements (to ~1µm @ 1s)
- More detailed time-dependent link-stability requirements highly desirable
- Use highest possible carrier and modulation rates
- Local oscillators crucial for µWave and optical links
- Infrastructure easily augmented by add-ons, on ground and in space
- Consider combination data links and dedicated ranging links
- Co-locate sensors on ground and in space
- Extend and apply these technologies to distances of Moon (orbiter and surface) and beyond to several AU