WE1A-4

Inter-Satellite Phase and Frequency Synchronization for Software-Defined CubeSat Radio Subsystems

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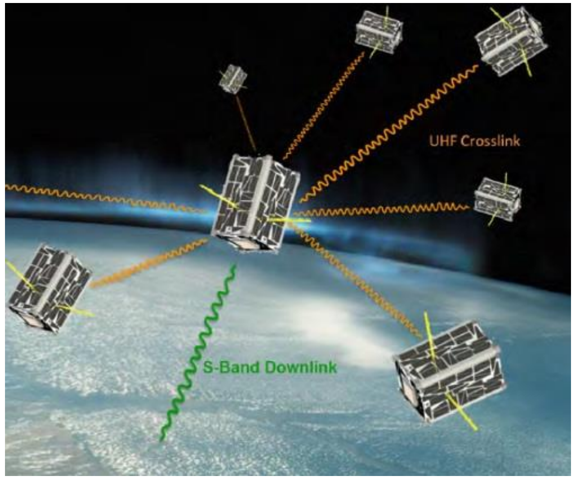
Cooperating Satellites



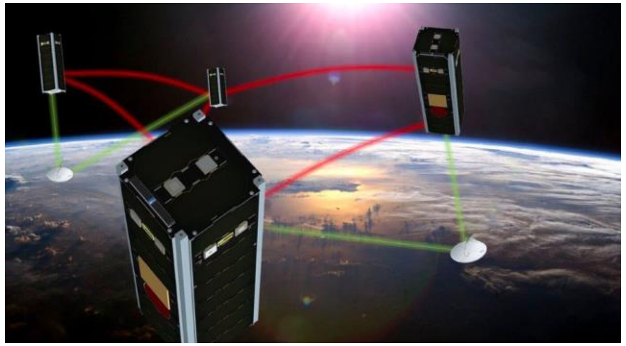
- Cooperating satellites
  - Being used for +12 years
  - Recent interest: LEO small satellites
- Advantages
  - New application areas + improved mission performance
  - Cost savings + system level redundancy
- Common term: *distributed satellite system (DSS)*
- Classes of *cooperating* DSSs*: cluster*, *swarm*, *fractionate spacecraft*, *federated satellite system (FSS)*
- Often require ranging & synchronization, recent overview of methods in[2]

[1]NASA Edison Demonstration of Smallsat Networks (EDSN).

[2]L. M. Marrero et al., “Architectures and Synchronization Techniques for Distributed Satellite Systems: A Survey”, 2022.

CubeSat DSS Mission Examples

NETSAT[1]



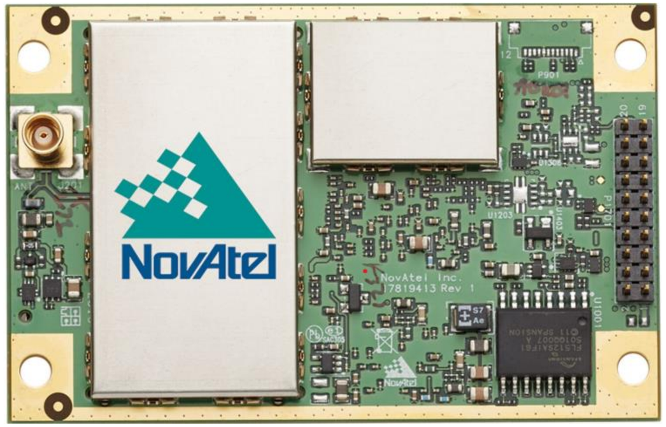
- 4x 3U CubeSats (DSS cluster)
- Objective: analyze different 3D formation topologies
- Launch: 28.09.2020

CloudCT[2]

- 10x 3U CubeSats (DSS cluster)
- Objective: 3D computed tomography of clouds
- Launch planned 2024

[1]Julian Scharnagl et al., “NetSat - Challenges of a Formation Composed of 4 Nano-Satellites”, 2021.
[2]Maximilian von Arnim et al., “The CloudCT Formation Of 10 Nano-Satellites For Computed Tomography To Improve Climate Predictions”, 2022.

CubeSat Synchronization & Ranging



- Typical solution: GNSS
  - Precision and accuracy limited
  - Orbit height limited
  - Requires additional space and energy
- Dedicated sync & ranging subsystem? Additional volume, mass, power consumption, etc.
- Motivation: implement synchronization & ranging with existing subsystems
- There is always: a *communications subsystem*

[1]NovAtel OEM719 Multi-Frequency GNSS Receiver.

Communicaitons Subsystem Trend

- *Software-defined radio*
- Benefits, see e.g. NASA report[1]
  - Increasingly small and efficient
  - Attractive due to flexibility
- Typical CubeSat configuration (up to C-band)
  - 1U PCB size, standardized (e.g. PC104)
  - Analog Devices AD936x TRXs
  - SoCs (FPGA+Processor), e.g. Xilinx Zynq-7000 family
- Commercially available: GOM Space, Alén Space, IQ Spacecom, etc.

[1]NASA, "State of the Art Small Spacecraft Technology (2022)".

[2]Alén Space Totem SDR.

SDR-Based Ranging & Synch

- No CubeSat mission using SDR for (highly precise) synchronization or ranging known to the authors
- State of the Art: Prager et al.[1], two-way time transfer (TWTT) based fine synchronization and ranging
  - Application: distributed MIMO SAR
  - Requires: GPS for coarse synchronization and syntonization
- Can synchronization and ranging be implemented with COTS SDR solutions without pre-synchronization?[2]
- *Can we improve our previous work to bring the system towards carrier phase synchronization?*

[1]S. Prager et al., "Wireless Subnanosecond RF Synchronization for Distributed Ultrawideband Software-Defined Radar Networks," 2020.
[2]M. Gardill et al., "Towards Wireless Ranging and Synchronization using CubeSat Software-Defined Radio Subsystems", 2023.

Two-Way Time Transfer

- Parameters of interest
  - Time of Flight (TOF)

    $T_{\mathsf{ToF}} = d_{\mathsf{A,B}}/c_0$
  - Time offset

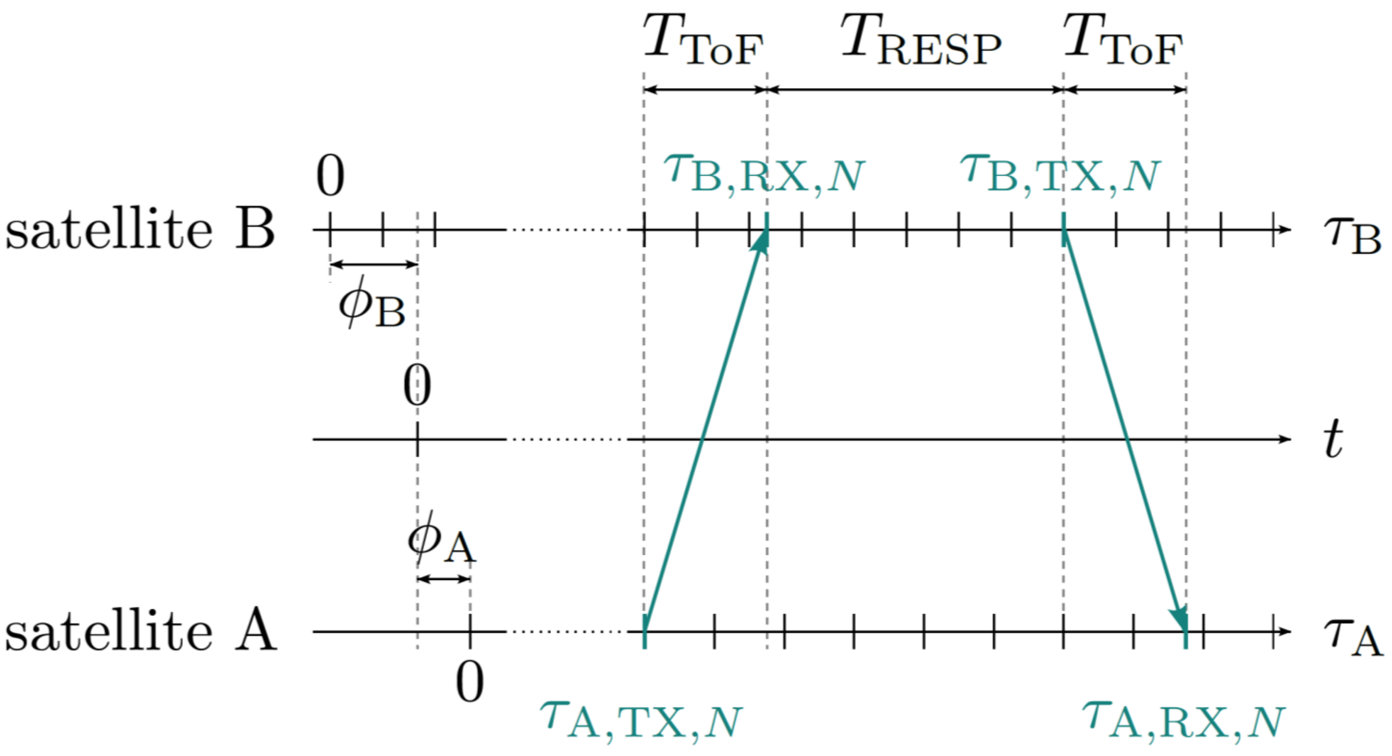
    $\Delta T_{\mathsf{A,B}} = \phi_{\mathsf{B}} - \phi_{\mathsf{A}}$
  - Relative clock skew

    $\alpha_{\mathsf{A}}/\alpha_{\mathsf{B}}$
  - Carrier phase offset

    $\gamma^{\mathrm{err}}_{\mathrm{A,B}} = \gamma_{\mathrm{A}} - \gamma_{\mathrm{B}}$

- Clock of satellite i

  $\tau_i = \alpha_i t + \phi_i$



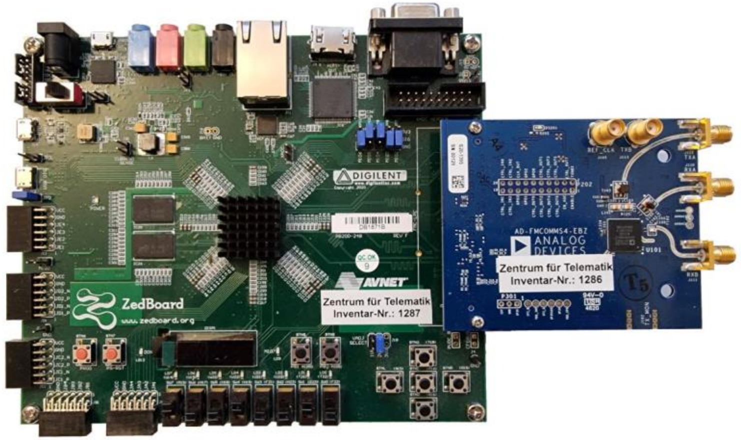
TWTT-Requirements

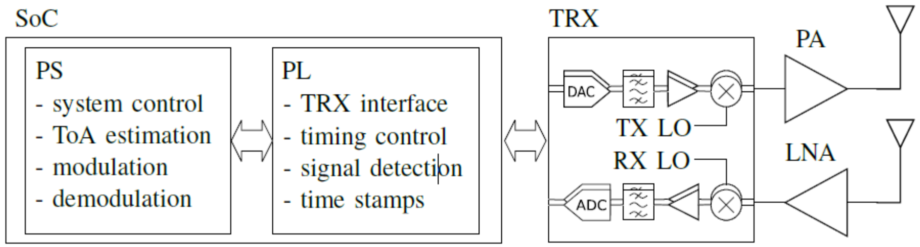
- Required to solve for parameters of interest[1]
  - $\tau_{\mathrm{A,TX},n}$, $\tau_{\mathrm{B,RX},n}$, $\tau_{\mathrm{B,TX},n}$, $\tau_{\mathrm{A,RX},n}$
  - For two successive TWTT measurements $n \in N, N+1$
- What the radio subsystem needs to implement
  - Highly precise time-triggered transmit for $\tau_{\mathrm{A,TX},n}$, $\tau_{\mathrm{B,TX},n}$
  - Time stamping for received samples
  - Highly precise time-of-arrival estimation for $\tau_{\mathrm{B,RX},n}$, $\tau_{\mathrm{A,RX},n}$
  - Exchange of timing information in between satellites

[1] M. Gardill et al., “Towards Wireless Ranging and Synchronization using CubeSat Software-Defined Radio Subsystems”, 2023.

Implementation

- Target platform: Alén Space Totem SDR
- Development board/Breadboard setup
  - Zedboard with Zynq-7000 SoC
    - PS: Dual-Core ARM Cortex-A9
    - PL: Artix-7 (Logic Cells, Block RAM, DSPs)
  - AD-FMCOMMS4-EBZ with AD9364 TRX
    - 1TX/1RX
    - Wideband 70 MHz - 6 GHz
    - $f_{s,max}$: 61.44 MHz; Max. Bandwidth B_{max}: 50 MHz

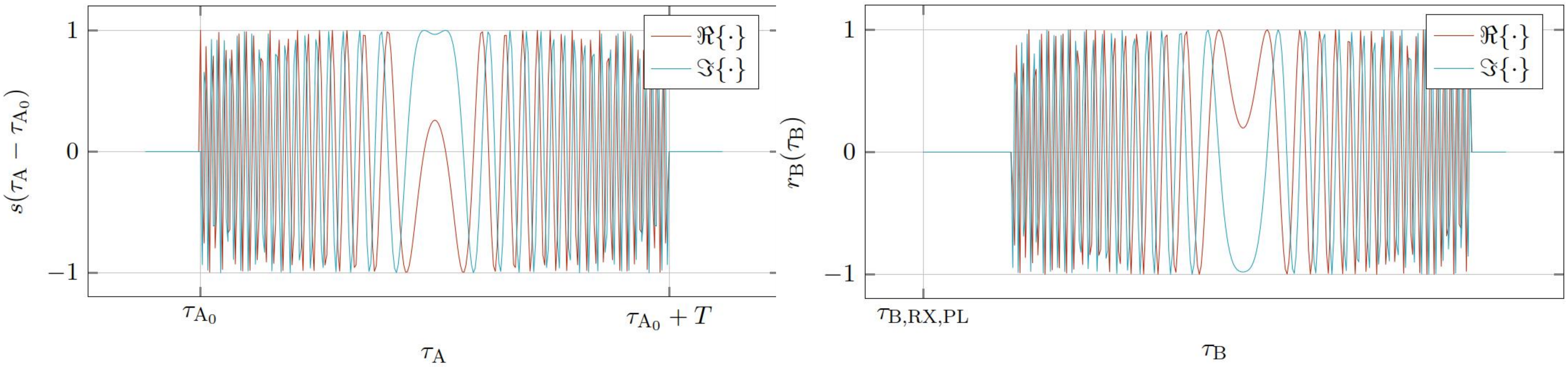




Time of Arrival Estimation

- TX signal: linear FMCW chirp, $s(t) = \exp\left(j2\pi\left(\frac{B_c f_s}{2 l_c} t - \frac{B_c}{2}\right) t\right), \quad 0 \leq t \leq T_c$
- RX signal model: time-scaling and delay, frequency offset, phase shift

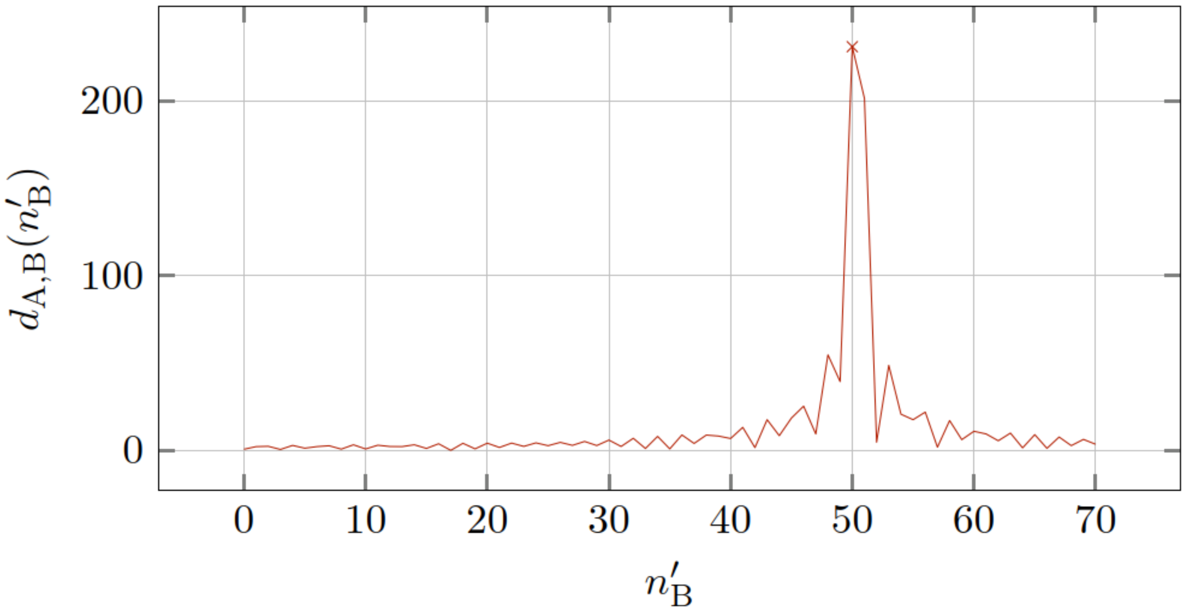
$$r_B(\tau_B) = s\left(\frac{\alpha_A}{\alpha_B}(\tau_B - \tau_{B,RX})\right) e^{j2\pi f_{err} \tau_B} e^{-j2\pi f_c \left(\alpha_B^{-1} \alpha_A \left(\phi_B + \tau_{B_{ToF}}\right) - \phi_A\right)} e^{j \gamma_{A,B}^{err}}$$

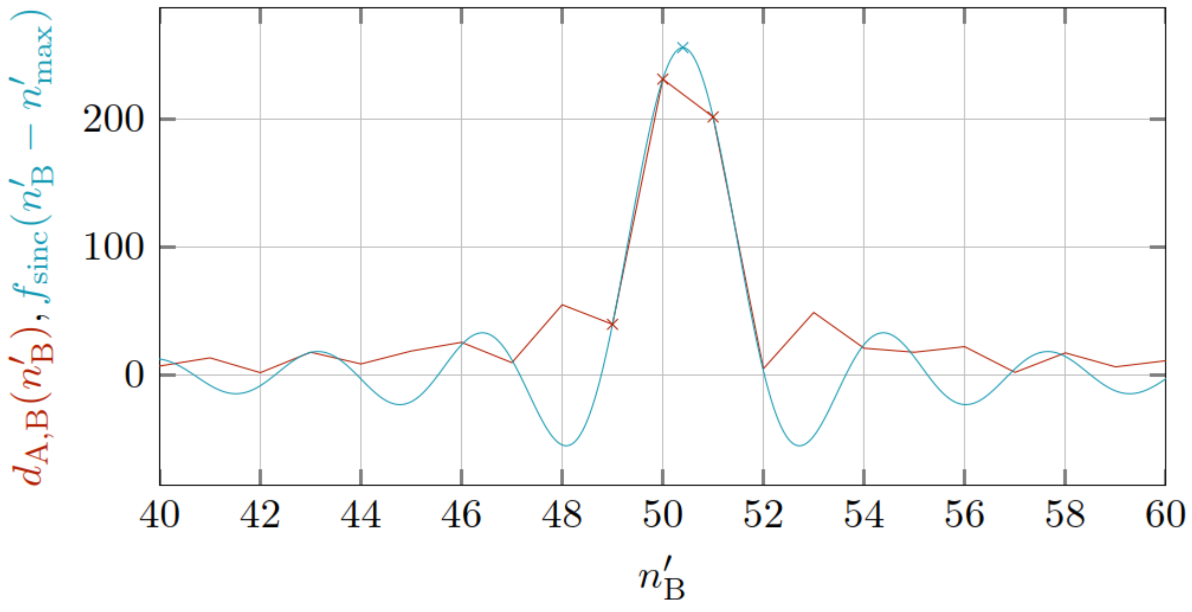


Time of Arrival Estimation

- RX processing: correlation, peak detection, peak interpolation

$\tau_{\mathrm{B,RX}}$





The Phase

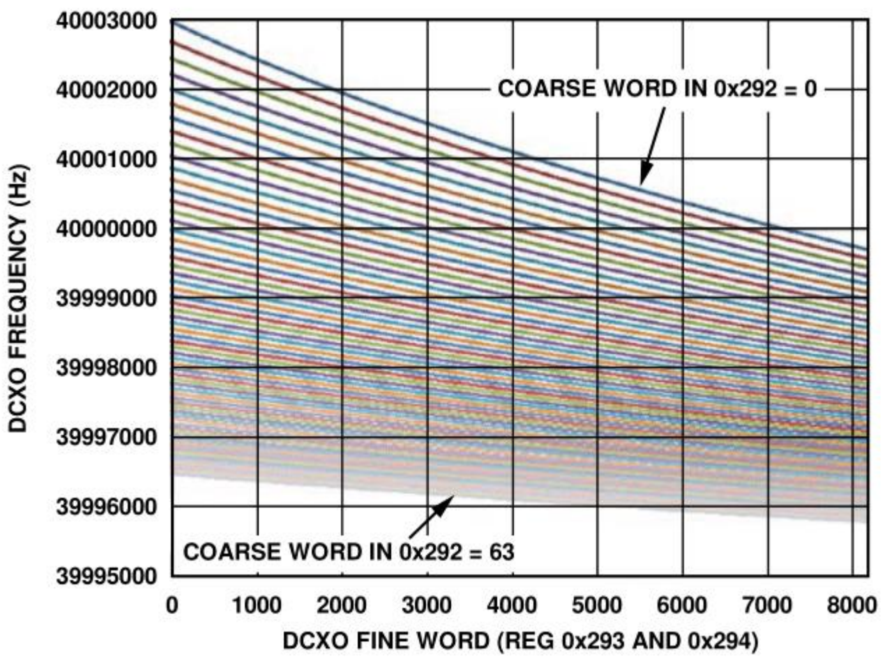
- Also use phase information from correlation: frequency offset, phase shift

$$\angle d_{\mathrm{A,B}}(\hat{\tau}_{\mathrm{B,RX}}) = 2\pi f_{\mathrm{err}} \hat{\tau}_{\mathrm{B,RX}} - 2\pi f_{\mathrm{c}} \left(\frac{\alpha_{\mathrm{A}}}{\alpha_{\mathrm{B}}} (\phi_{\mathrm{B}} + \tau_{\mathrm{B_{ToF}}}) - \phi_{\mathrm{A}} \right) + \gamma_{\mathrm{A,B}}^{\mathrm{err}}$$

- Idea: Use phase difference $\Delta\varphi = \angle d_{\mathrm{A,B},N+1}(\hat{\tau}_{\mathrm{B,RX},N+1}) - \angle d_{\mathrm{A,B},N}(\hat{\tau}_{\mathrm{B,RX},N})$ from two TWTT measurements for better estimate of $\alpha_{\mathsf{A}}/\alpha_{\mathsf{B}}$ then calculate $\gamma_{\mathrm{A,B}}^{\mathrm{err}}$
- Problem: Phase ambiguity if f_{err} too big.
- Solution: DCXO

Syntonization

- DCXO: digitally programmable on-chip variable capacitor + external crystal oscillator
- Coarse word + fine word
- Worst case resolution: 0.0125 ppm
- Total range: ± 60 ppm
- Goal: minimize error $e_{A,B} = \frac{\alpha_A}{\alpha_B} - 1$
- Implementation: Two-level linear proportional controller



[1]Analog Devices, *AD9364 Reference Manual*, 2014, rev.0.

Clock Skew Phase based Estimation

- Under the assumption that
  - α_A/α_B approx. linear during measurement
  - Relative movement in between satellites is negligible in comparison to frequency difference, or known elsehow
- … α_A/α_B can be estimated from the phase difference by

$$\frac{\alpha_A}{\alpha_B} = \frac{\Delta\varphi}{2\pi\, f_c\left(\hat{\tau}_{B,RX,N+1} - \hat{\tau}_{B,RX,N}\right)} + 1.$$

Carrier Phase Offset

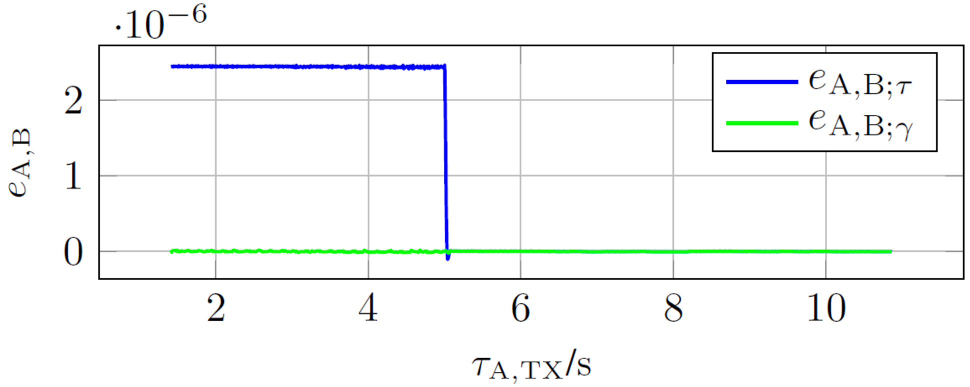
- Considering that $f_{\text{err}} = \left(\frac{\alpha_i}{\alpha_j} - 1\right) f_{\text{c}},$
- and using a transformation $t_{i,\text{RX,N}} = 0$ (TWTT measurement starts at 0 global time)
- the relative carrier phase difference is

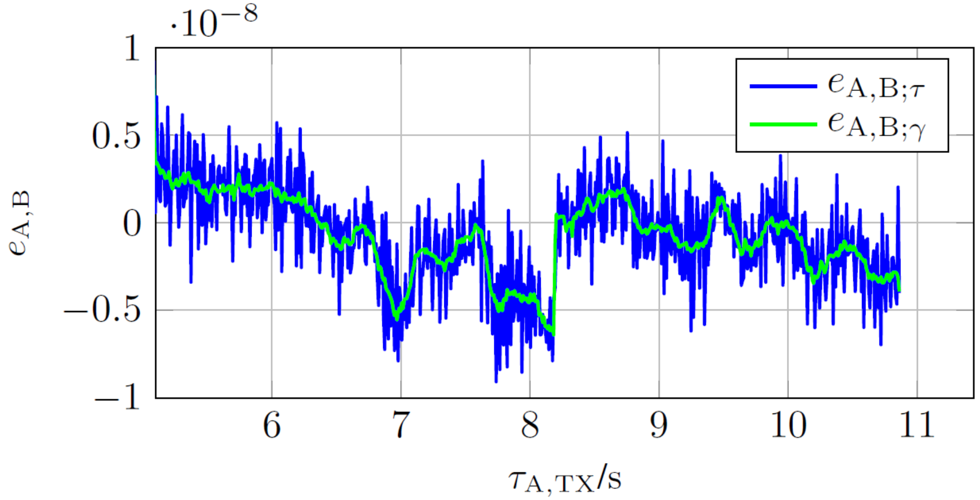
$$\gamma_{i,j}^{\text{err}} = \angle d_{i,j}(\hat{\tau}_{i,j}) - 2\pi f_{\text{c}} \left[\phi_i - \phi_j - \frac{\alpha_i}{\alpha_j} \tau_{j\text{ToF}} - \left(\frac{\alpha_i}{\alpha_j} - 1\right) (\tau_{j,\text{RX}} - \tau_{j,\text{TX}}) \right].$$

- Note: $\Delta T_{i,j} = \phi_j - \phi_i$, α_i / α_j, $\tau_{j\text{TOF}}$, $\tau_{j,\text{RX}}$, $\tau_{j,\text{TX}}$ are known.

Experimental Evaluation

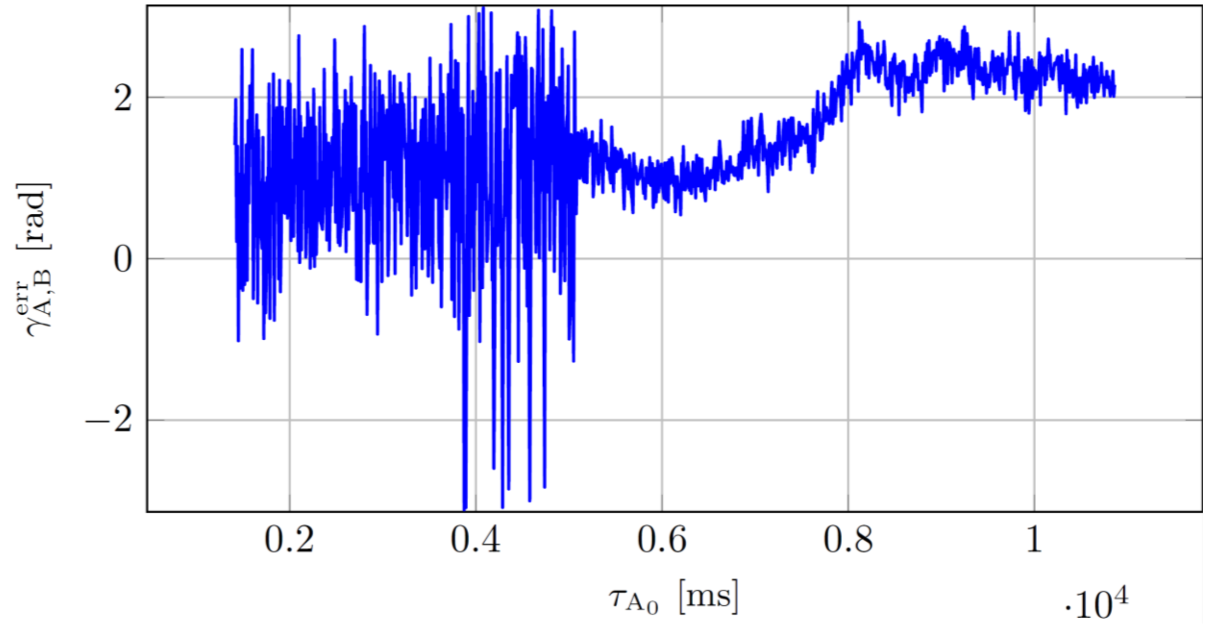
- Using two development kits at a distance of approx. 1.8m
- Evaluation using $n_{\text{trial}} = 1000$ TWTT measurements
- Syntonization inactive during first 5 seconds, then frequency matching using DCXO
- $f_c = 2\,\text{GHz},\ B_c = 34\,\text{MHz},\ l_c = 1024$ and $f_s = 61.44\,\text{MHz}$
- Settling time $\Delta t = 80\,\text{ms}$





Experimental evaluation

- Settling time possibly caused by PLLs
- Standard deviation $\sigma_{\gamma_{i,j}^{\mathrm{err}}} \approxeq 0.21\,\mathrm{rad}$ from 289 samples (corresponds to 3.3% of the wavelength)



Summary & Next Steps

- Summary
  - Synchronization, ranging and carrier phase offset estimation on commercial CubeSat SDR platform
  - Measurement results show promising performance
- Next steps
  - Use measurements for carrier-phase synchronization
  - Make system more robust and extend to more nodes
  - Test under more realistic conditions: ISL link budget, Doppler, free-space, etc.
  - Bring it into a mission!