RF Phase Drift Measurements Using Two-tone Scheme

Maciej Grzegrzółka, Andžej Šerlat, Krzysztof Czuba

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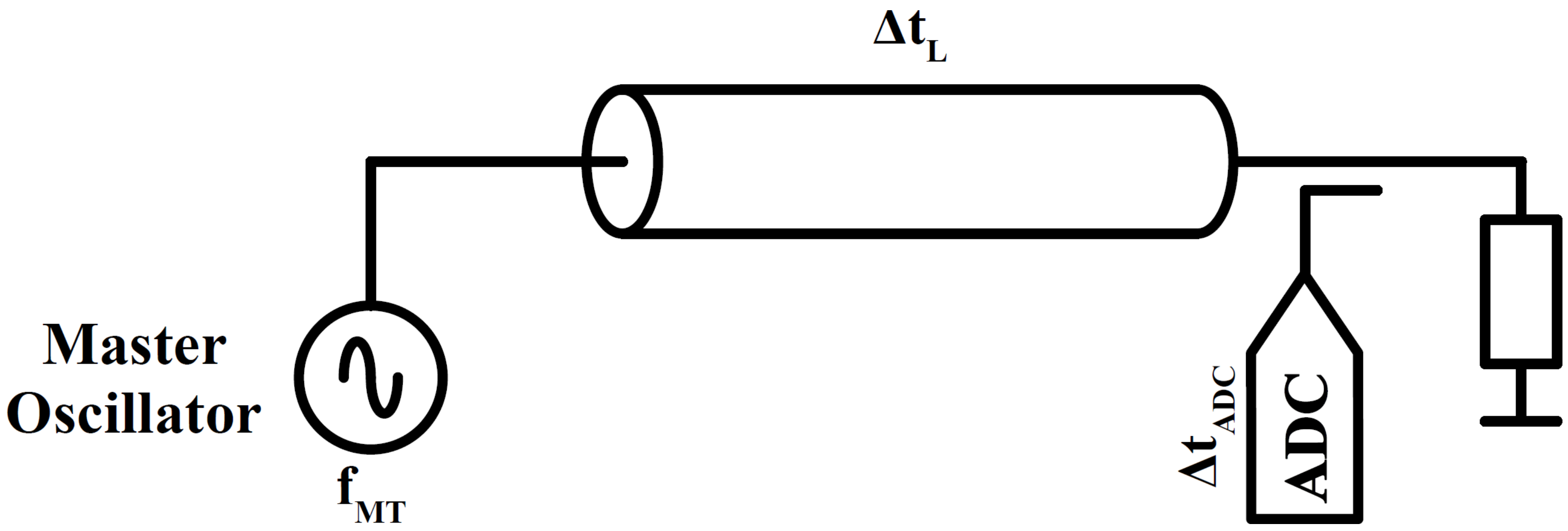
Introduction

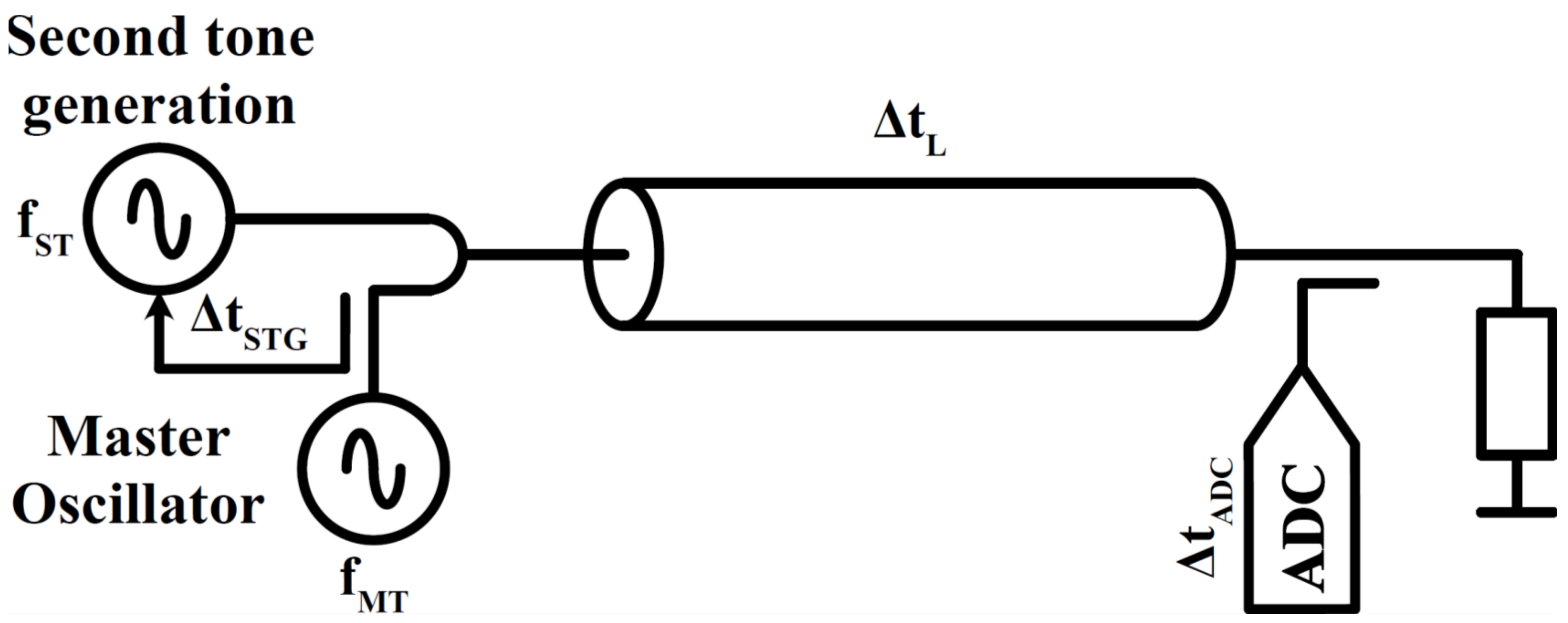
- Phase drift of cables, couplers, and other components is a significant issue in phase reference line design.
- Manufacturers rarely provide information about component phase drifts.
- Characterizing the components is important to select the best available ones.
- Several measurement methods exist, but their performance is often insufficient.
- We aim to test a two-tone method and verify its performance.

Single Tone Measurement



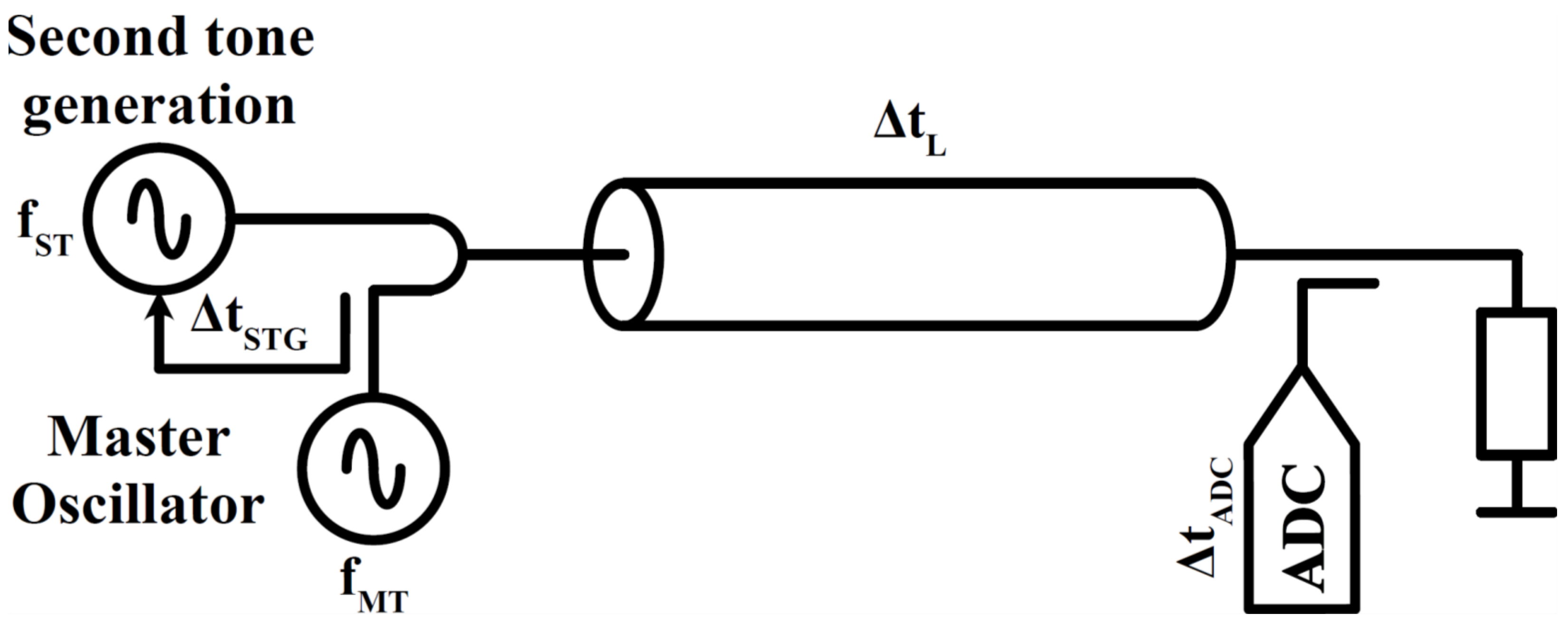
$$\Delta\varphi = (\Delta t_L + \Delta t_{ADC}) f_{MT}$$

Two Tone Measurement (1)



$$\Delta\varphi_{MT} = (\Delta t_L + \Delta t_{ADC}) f_{MT}$$

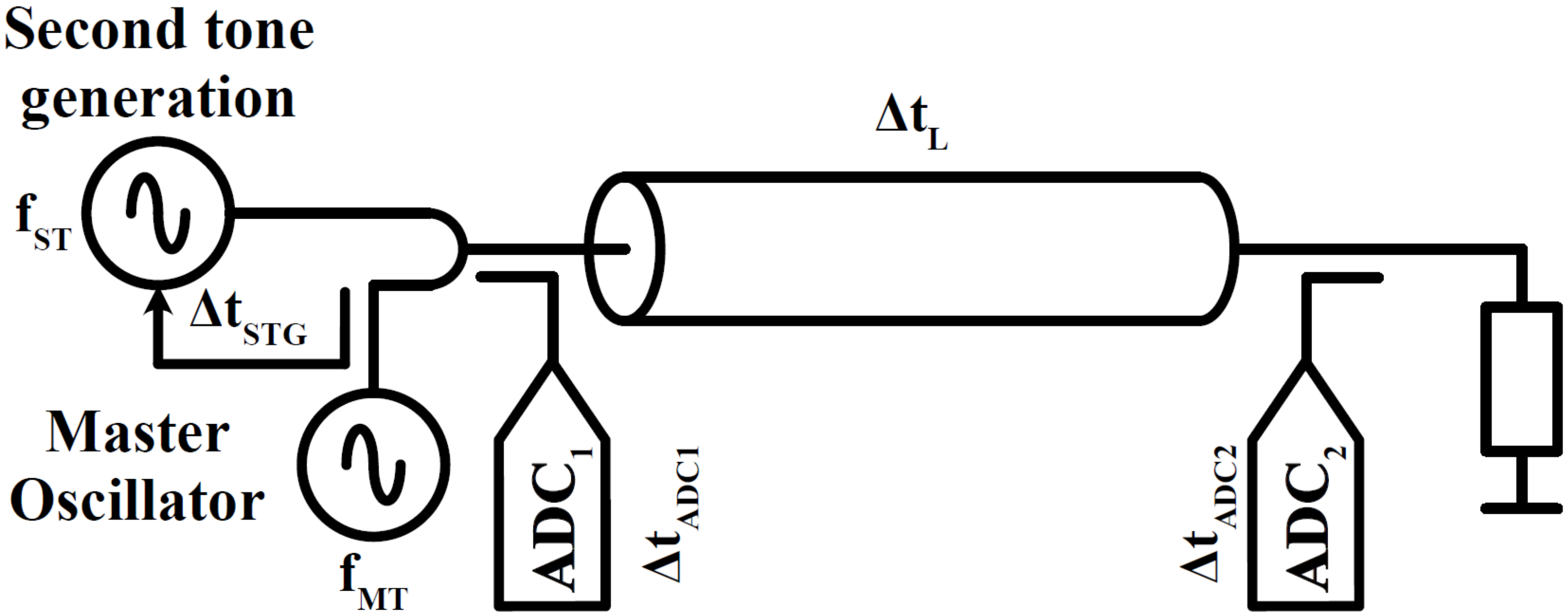
Two Tone Measurement (1)



$$\Delta\varphi_{MT} = (\Delta t_L + \Delta t_{ADC}) f_{MT}$$

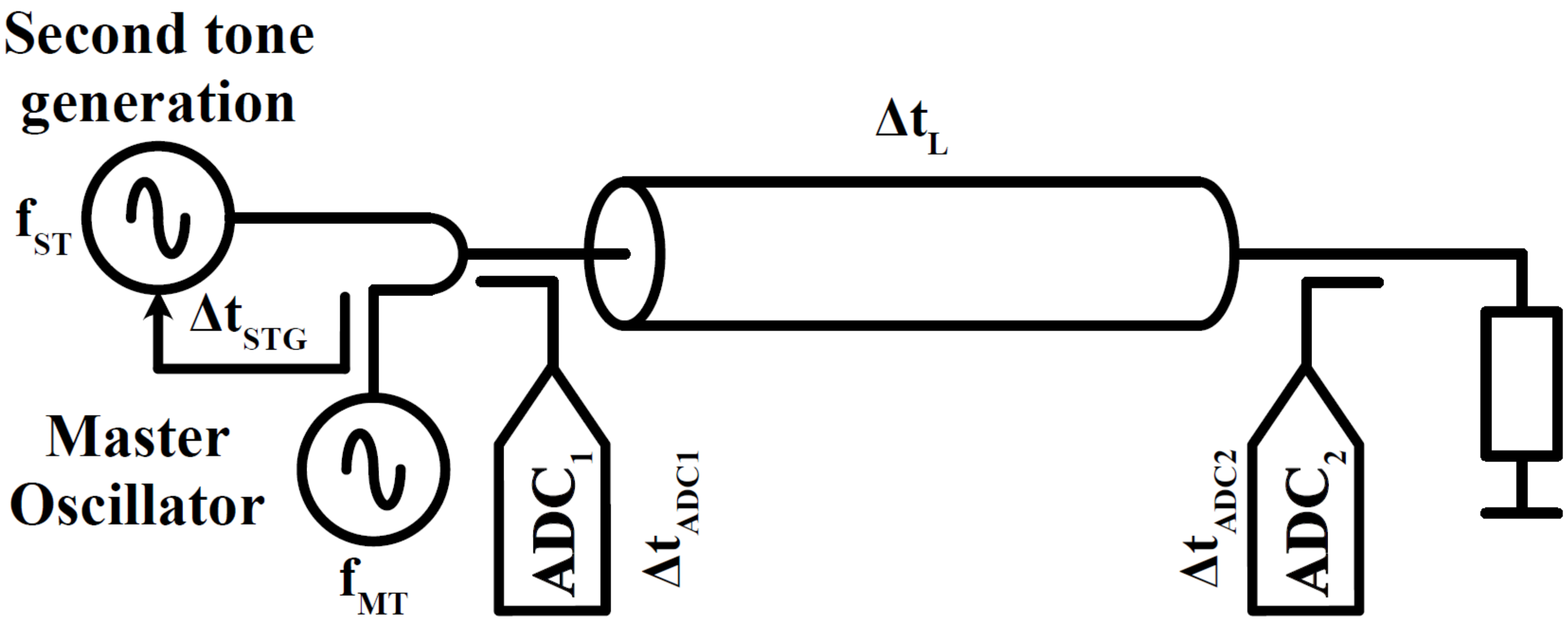
$$\Delta\varphi_{ST} = (\Delta t_{STG} + \Delta t_L + \Delta t_{ADC}) f_{ST}$$

Two Tone Measurement (2)



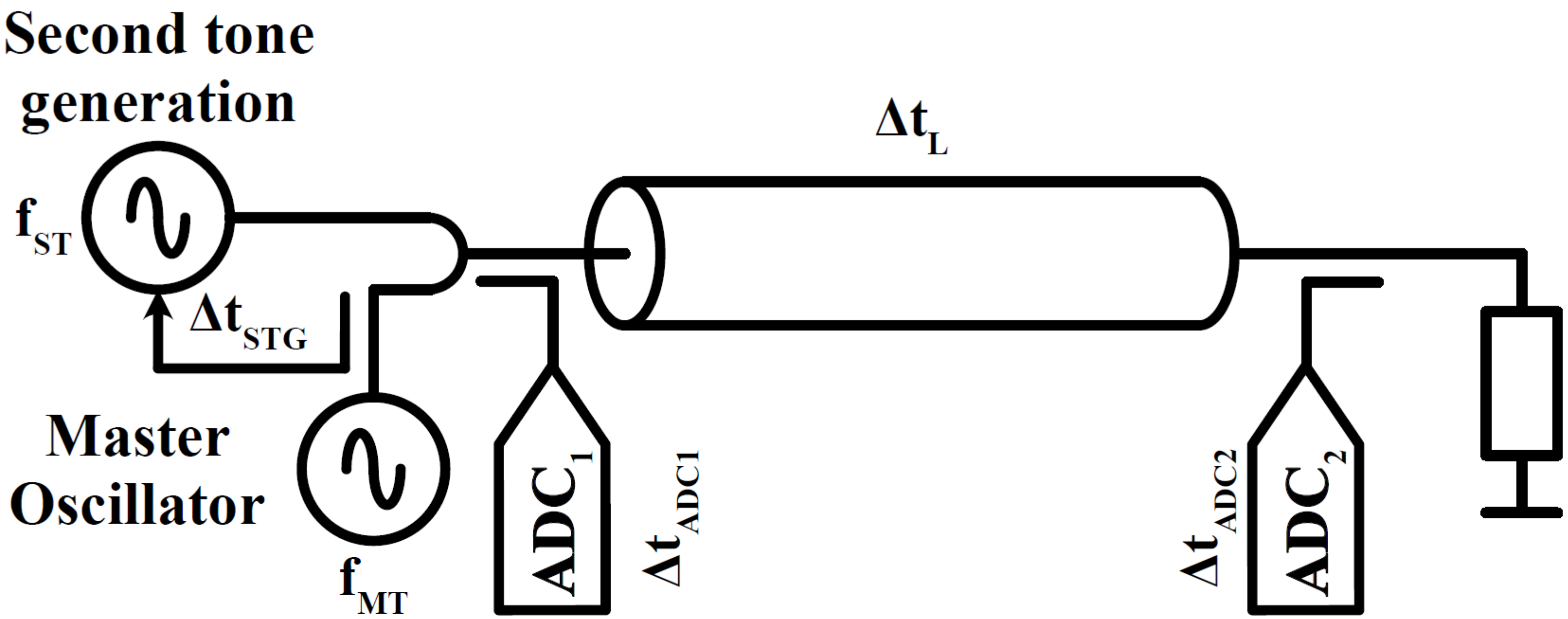
$$\Delta\varphi_{MT1} = (\Delta t_{ADC1}) f_{MT}$$

Two Tone Measurement (2)



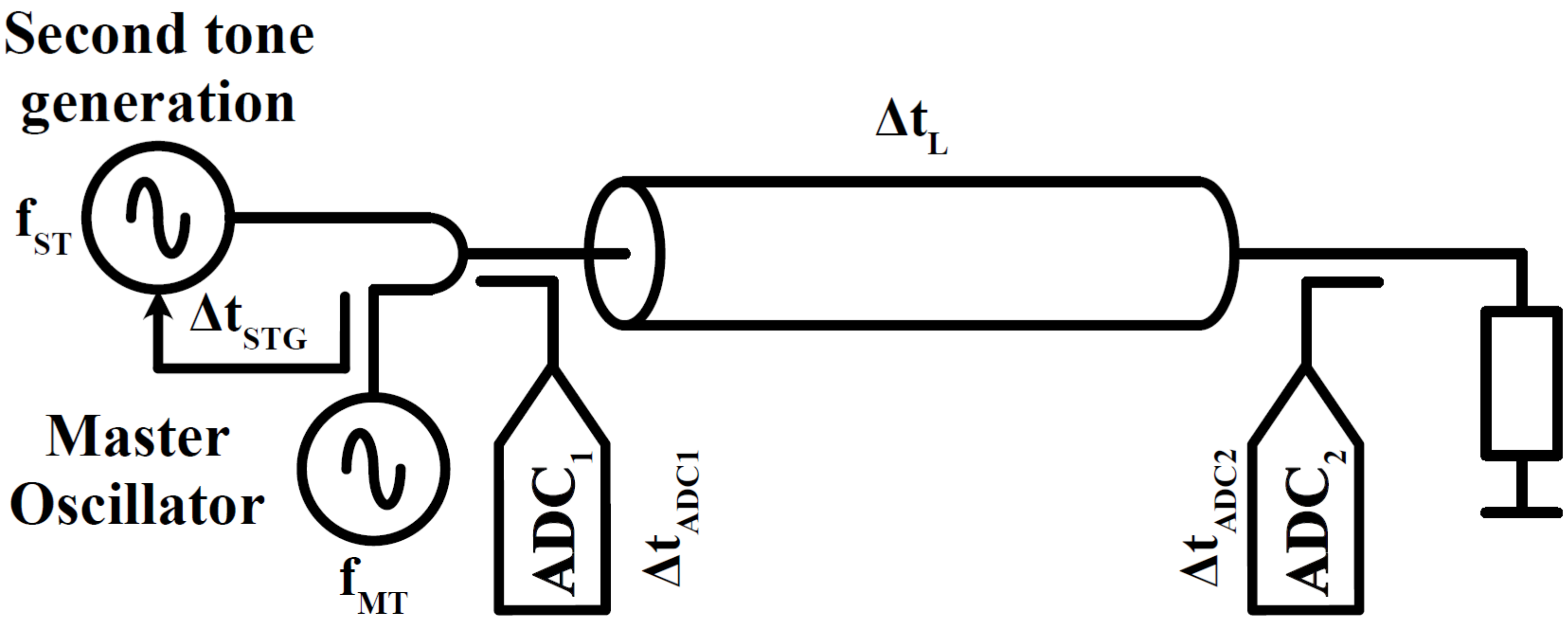
$$\Delta\varphi_{MT1} = (\Delta t_{ADC1}) f_{MT}$$
$$\Delta\varphi_{ST1} = (\Delta t_{STG} + \Delta t_{ADC1}) f_{ST}$$

Two Tone Measurement (2)



$$\Delta\varphi_{MT1} = (\Delta t_{ADC1}) f_{MT}$$
$$\Delta\varphi_{ST1} = (\Delta t_{STG} + \Delta t_{ADC1}) f_{ST}$$
$$\Delta\varphi_{MT2} = (\Delta t_L + \Delta t_{ADC2}) f_{MT}$$

Two Tone Measurement (2)



$$\Delta\varphi_{MT1} = (\Delta t_{ADC1}) f_{MT}$$
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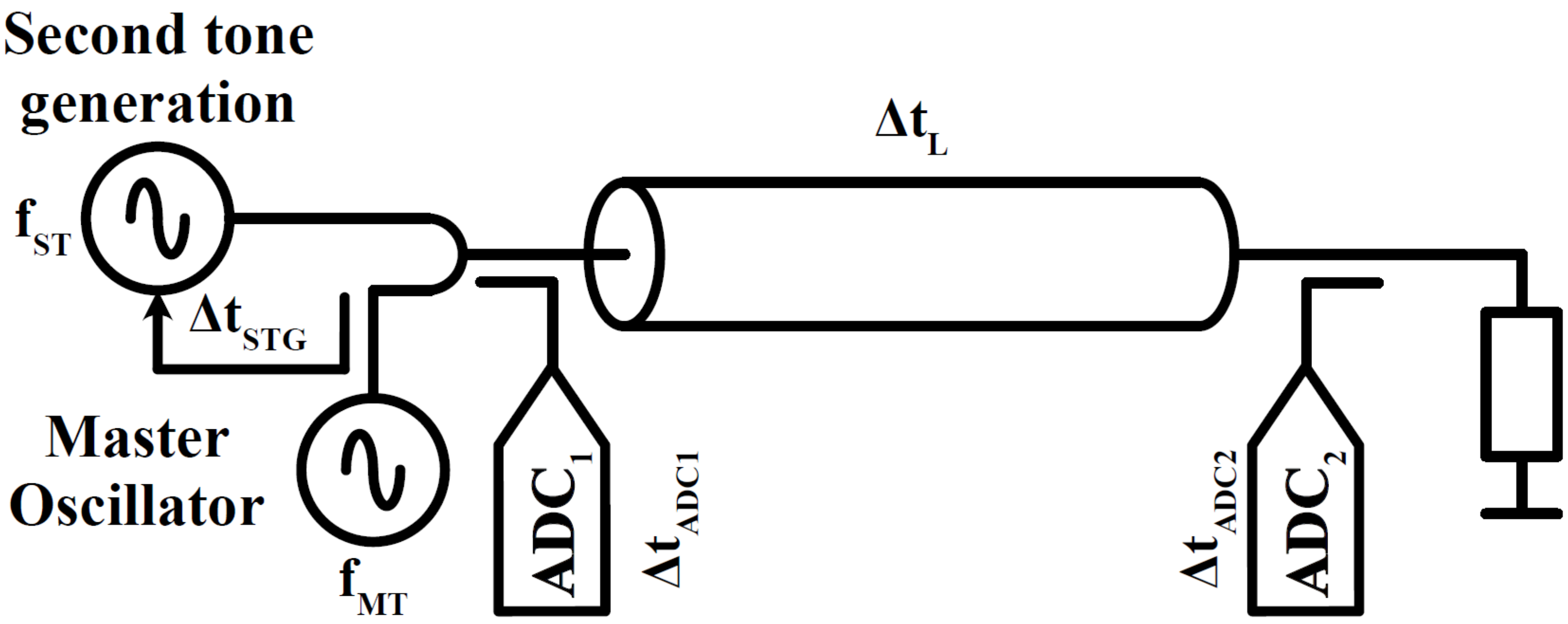
$$\Delta\varphi_{MT2} = (\Delta t_L + \Delta t_{ADC2}) f_{MT}$$
$$\Delta\varphi_{ST2} = (\Delta t_{STG} + \Delta t_L + \Delta t_{ADC2}) f_{ST}$$

Two Tone Measurement (2)



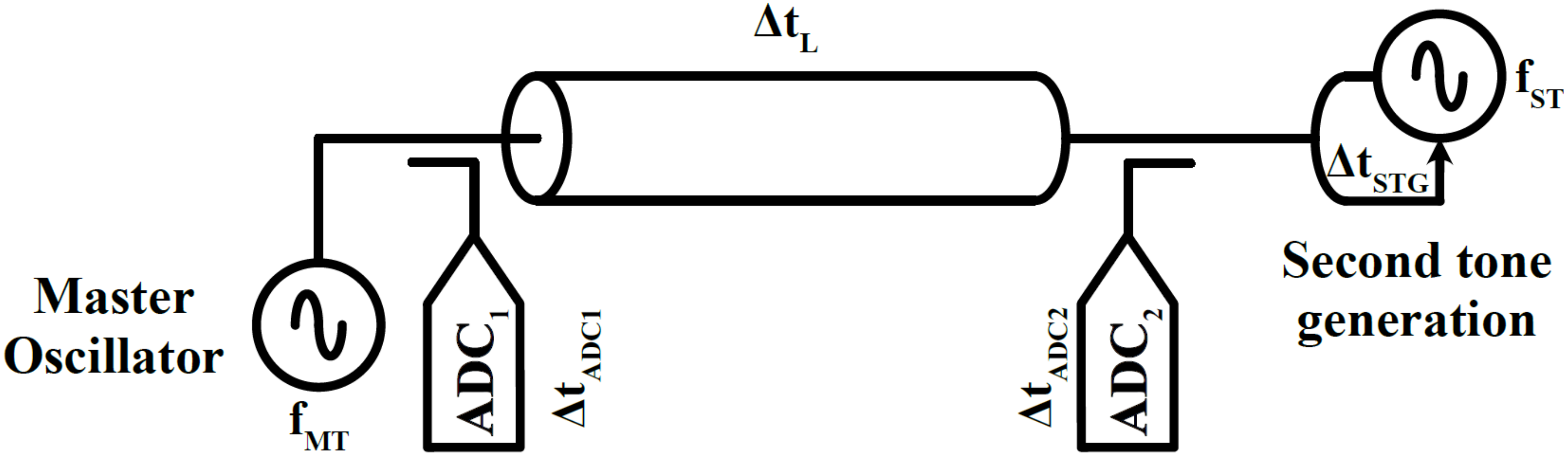
$$\Delta\varphi_{MT1} = (\Delta t_{ADC1}) f_{MT}$$

$$\Delta\varphi_{ST1} = (\boldsymbol{\Delta t_{STG}} + \Delta t_{ADC1}) f_{ST}$$

$$\Delta\varphi_{MT2} = (\Delta t_L + \Delta t_{ADC2}) f_{MT}$$

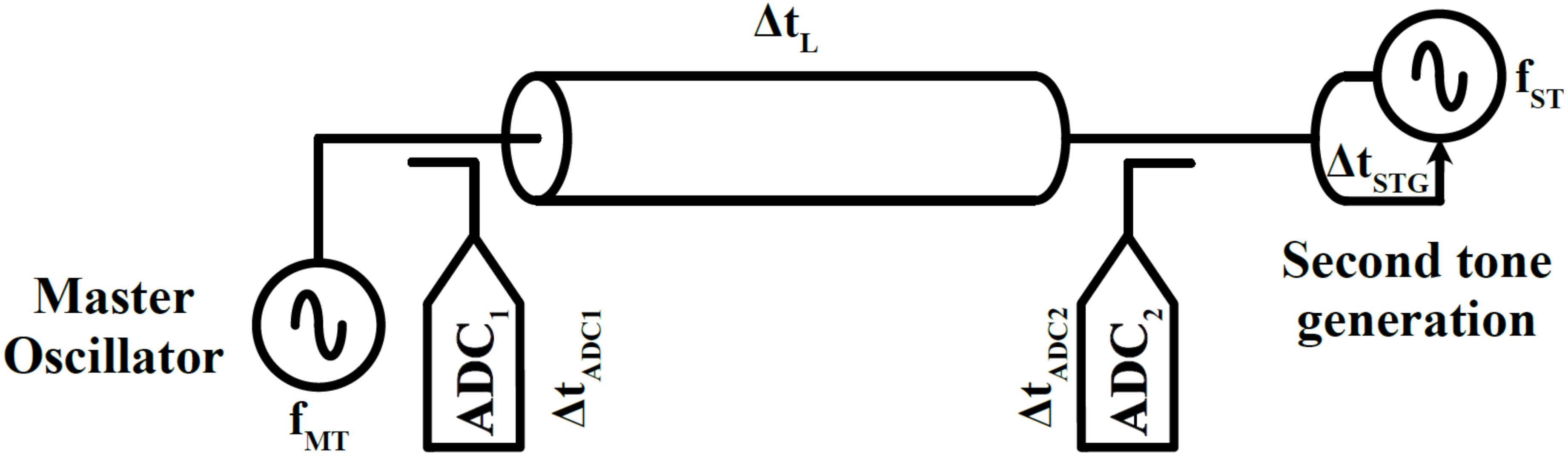
$$\Delta\varphi_{ST2} = (\boldsymbol{\Delta t_{STG}} + \Delta t_L + \Delta t_{ADC2}) f_{ST}$$

Two Tone Measurement (3)



$$\Delta\varphi_{MT1} = (\Delta t_{ADC1}) f_{MT}$$

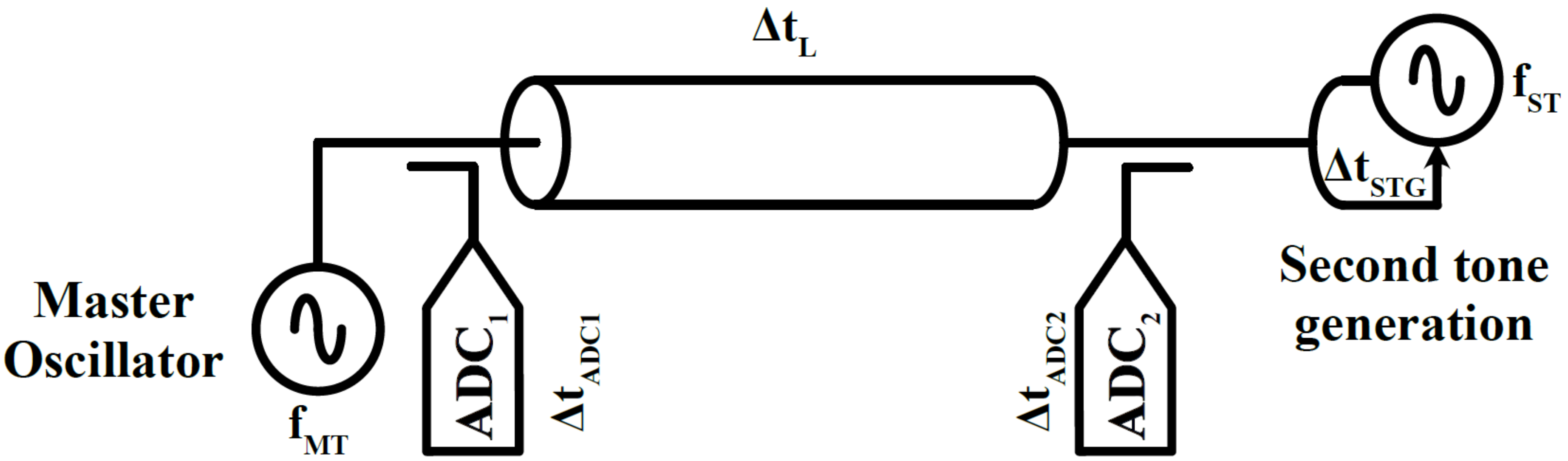
Two Tone Measurement (3)



$$\Delta\varphi_{MT1} = (\Delta t_{ADC1}) f_{MT}$$

$$\Delta\varphi_{ST1} = (\Delta t_{STG} + 2\Delta t_L + \Delta t_{ADC1}) f_{ST}$$

Two Tone Measurement (3)

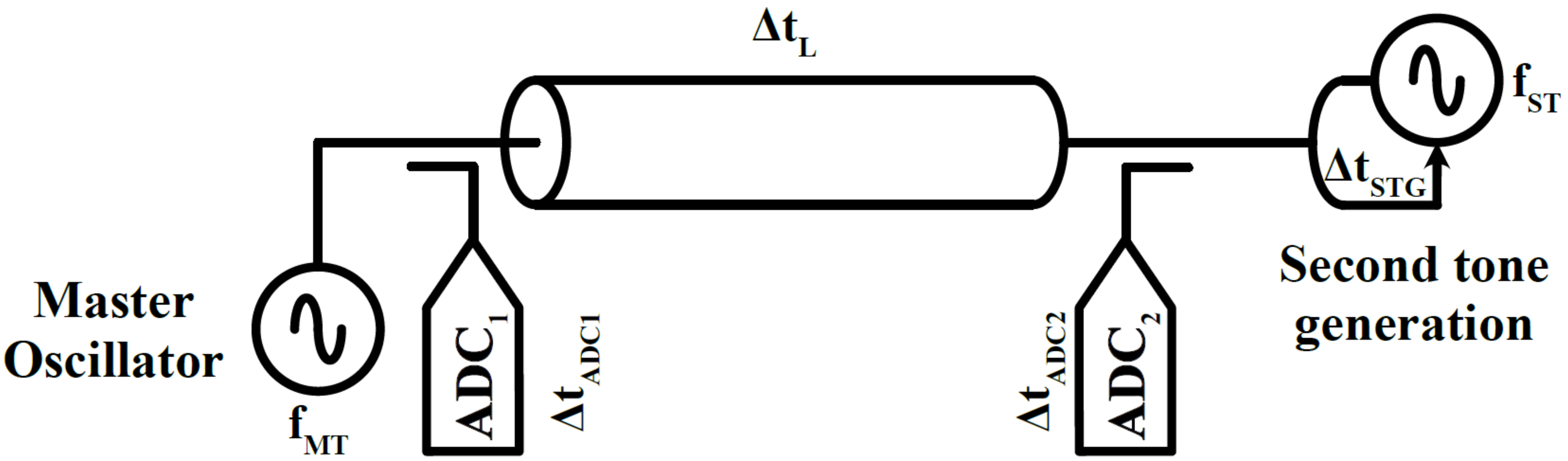


$$\Delta\varphi_{MT1} = (\Delta t_{ADC1}) f_{MT}$$

$$\Delta\varphi_{ST1} = (\Delta t_{STG} + 2\Delta t_L + \Delta t_{ADC1}) f_{ST}$$

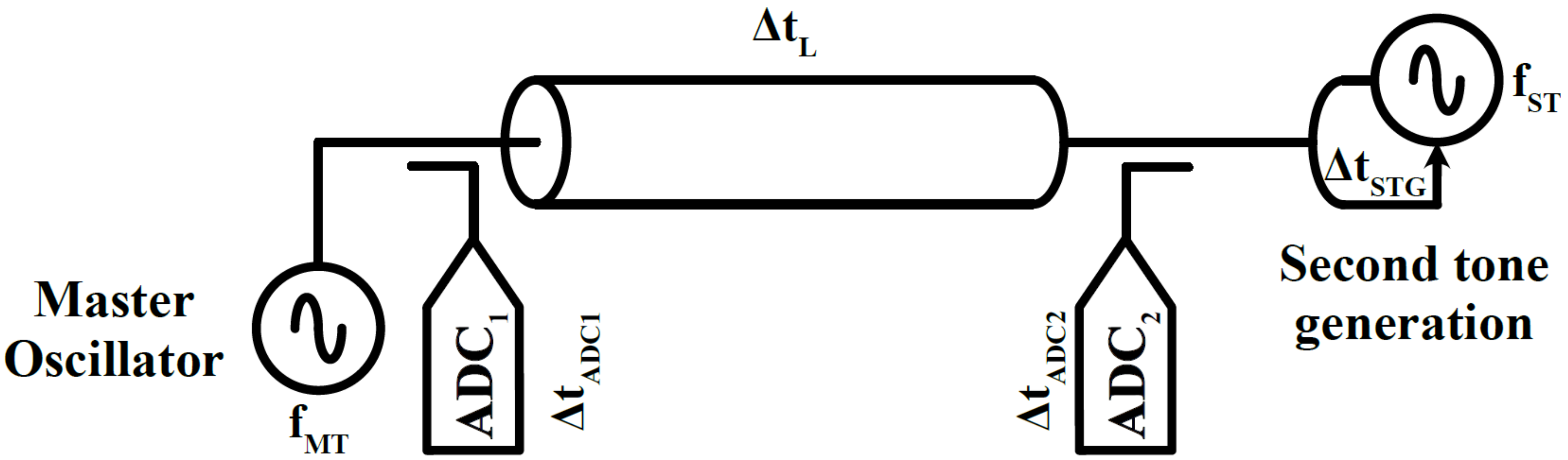
$$\Delta\varphi_{MT2} = (\Delta t_L + \Delta t_{ADC2}) f_{MT}$$

Two Tone Measurement (3)



$$\Delta\varphi_{MT1} = (\Delta t_{ADC1}) f_{MT}$$
$$\Delta\varphi_{ST1} = (\Delta t_{STG} + 2\Delta t_L + \Delta t_{ADC1}) f_{ST}$$
$$\Delta\varphi_{MT2} = (\Delta t_L + \Delta t_{ADC2}) f_{MT}$$
$$\Delta\varphi_{ST2} = (\Delta t_{STG} + \Delta t_L + \Delta t_{ADC2}) f_{ST}$$

Two Tone Measurement (3)

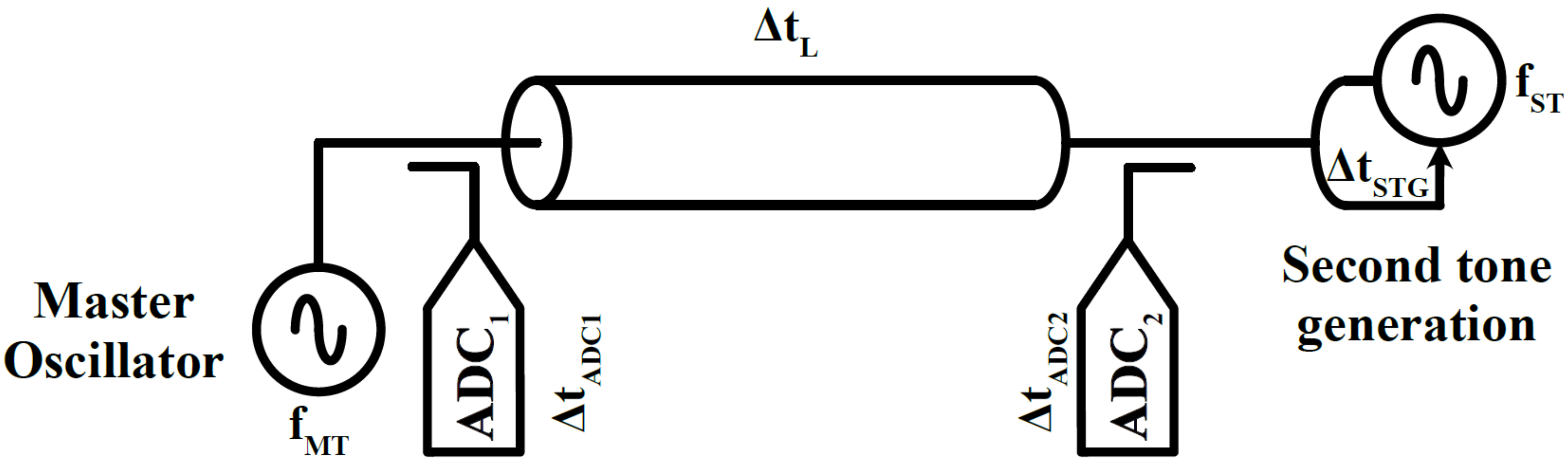


$$\Delta t_{STG} + 2\Delta t_L = \frac{\Delta\varphi_{ST1}}{f_{ST}} - \frac{\Delta\varphi_{MT1}}{f_{MT}}$$

$$\Delta\varphi_{MT2} = (\Delta t_L + \Delta t_{ADC2}) f_{MT}$$

$$\Delta\varphi_{ST2} = (\Delta t_{STG} + \Delta t_L + \Delta t_{ADC2}) f_{ST}$$

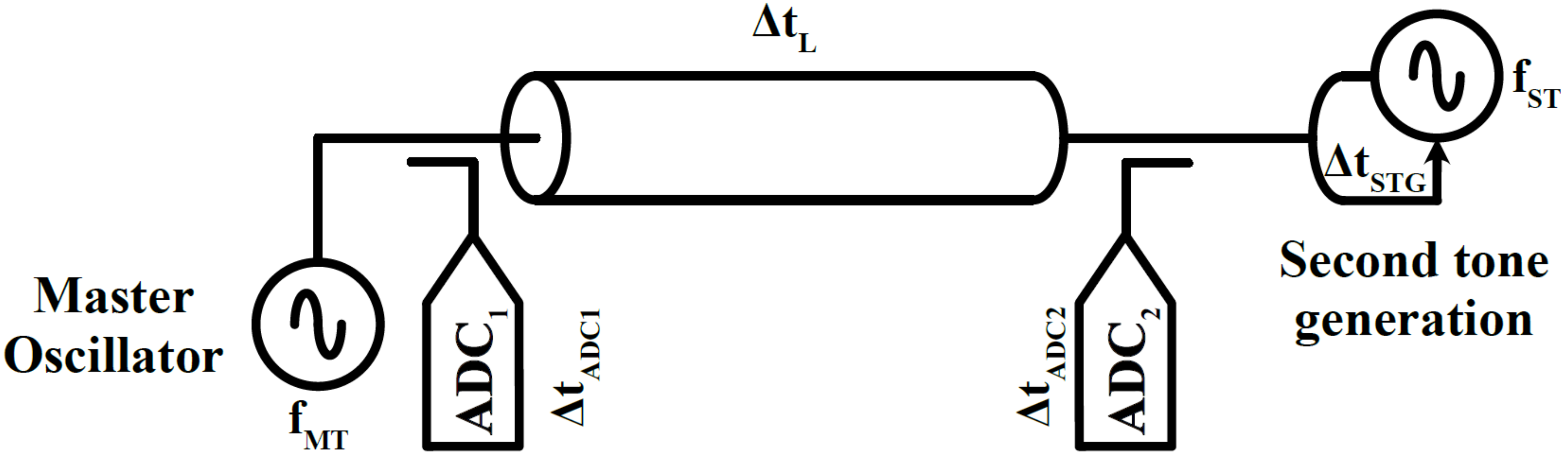
Two Tone Measurement (3)



$$\Delta t_{STG} + 2\Delta t_L = \frac{\Delta\varphi_{ST1}}{f_{ST}} - \frac{\Delta\varphi_{MT1}}{f_{MT}}$$

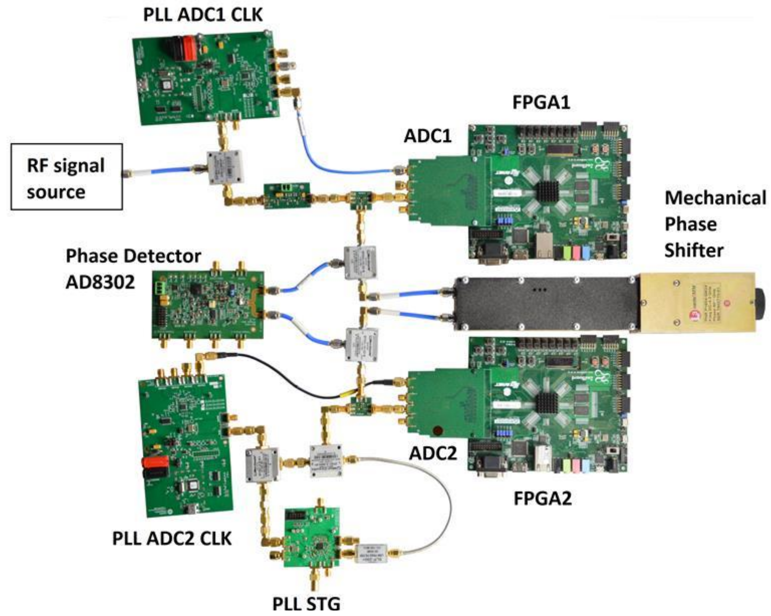
$$\Delta t_{STG} = \frac{\Delta\varphi_{ST2}}{f_{ST}} - \frac{\Delta\varphi_{MT2}}{f_{MT}}$$

Two Tone Measurement (3)

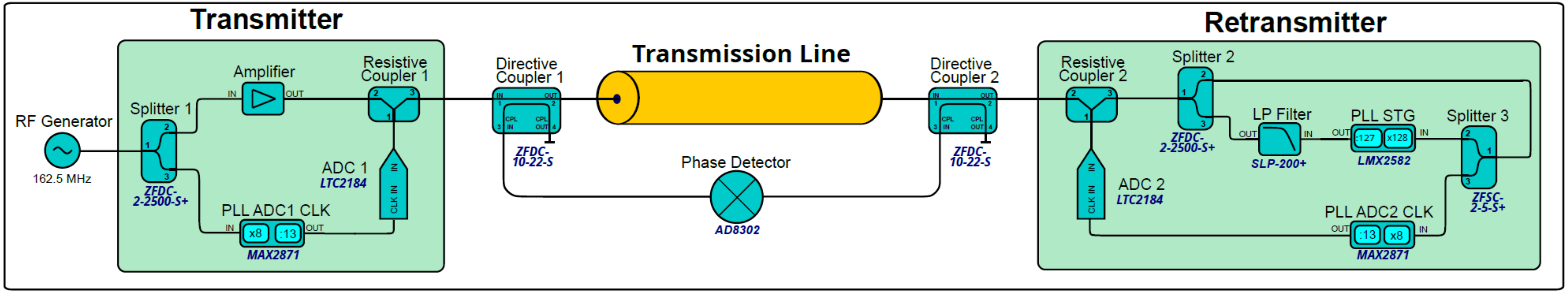


$$\Delta t_L = \frac{\Delta\varphi_{ST1} - \Delta\varphi_{ST2}}{2f_{ST}} - \frac{\Delta\varphi_{MT1} - \Delta\varphi_{MT2}}{2f_{MT}}$$

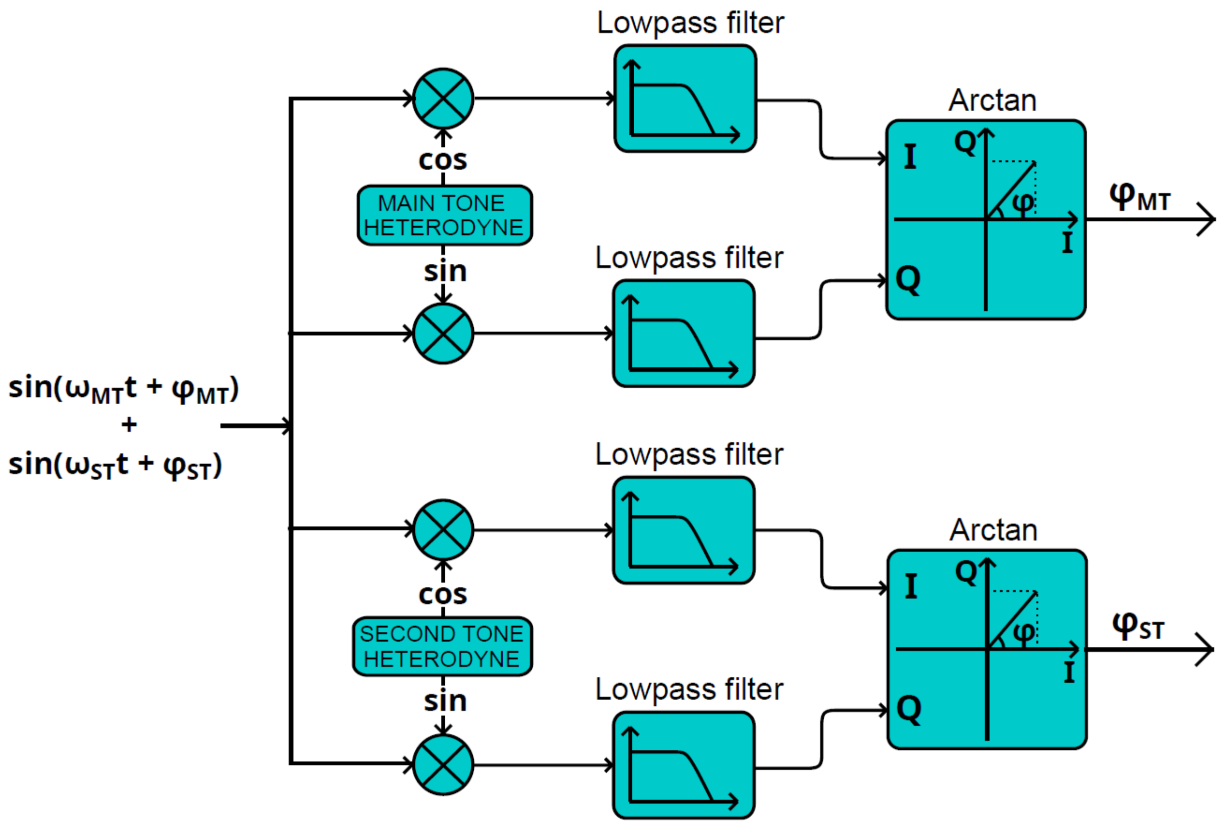
Test System

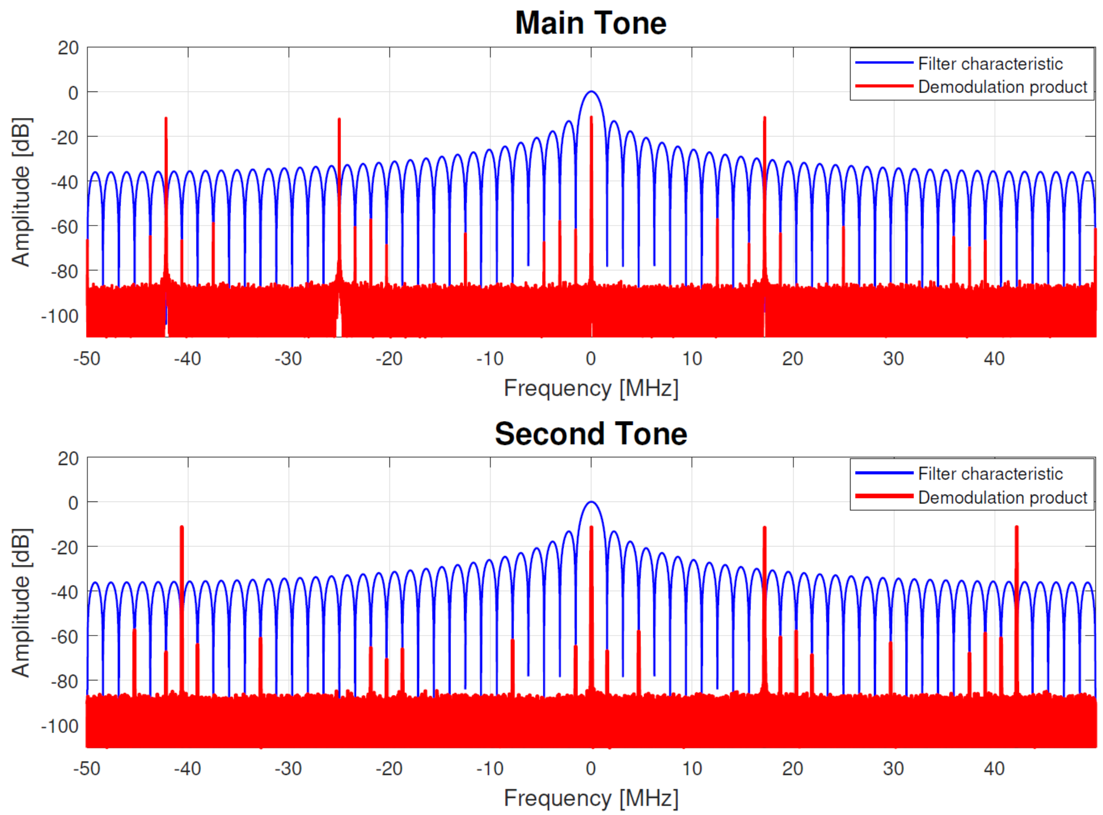


- Test system assembled to evaluate method performance
- Mechanical phase shifter simulating line drifts
- Main tone: 162.5 MHz
- Second tones tested:
  - 20.3125 MHz → 142.1875 MHz separation
  - 161.32 MHz → 1.18 MHz separation

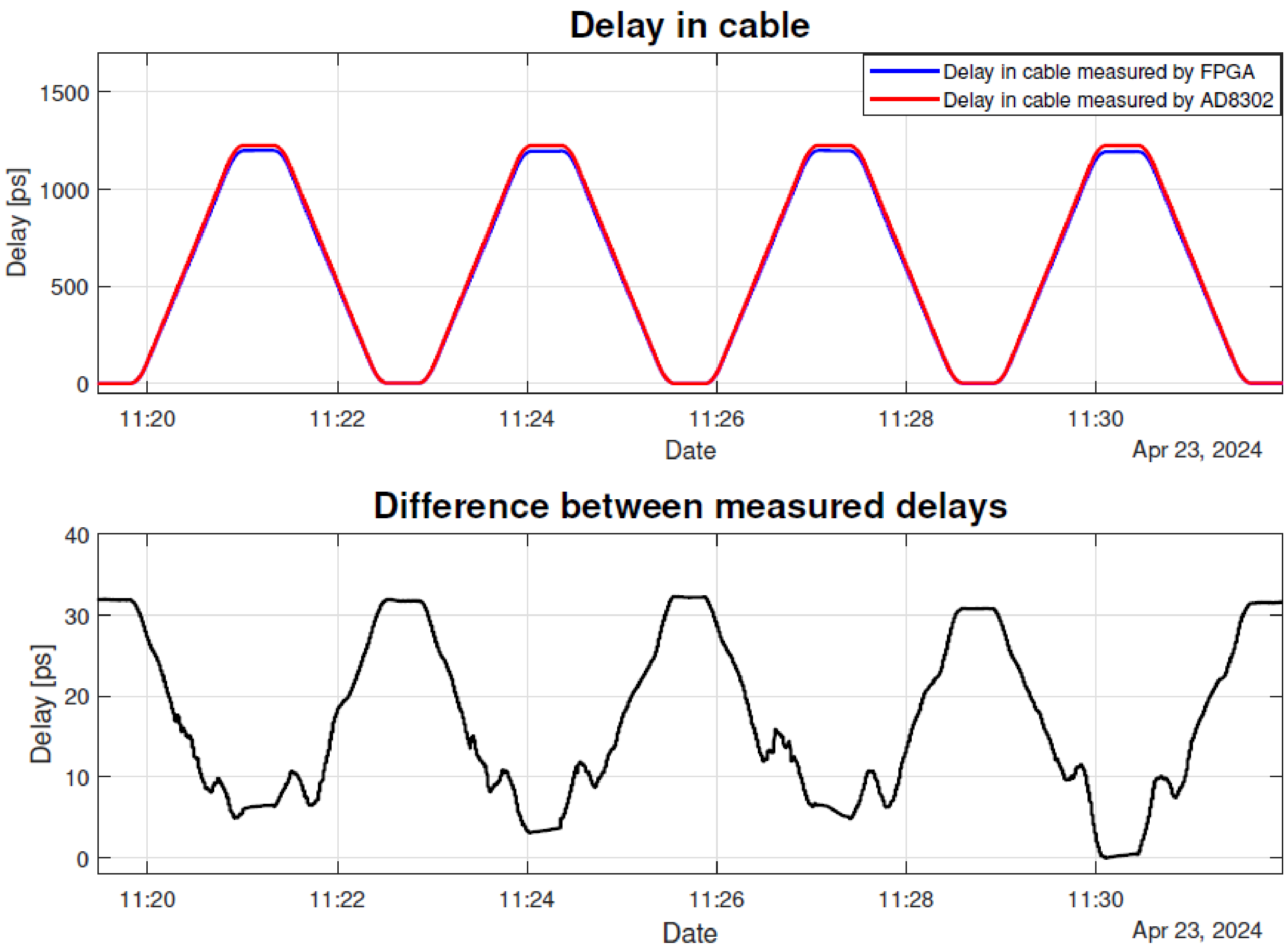


Signal processing



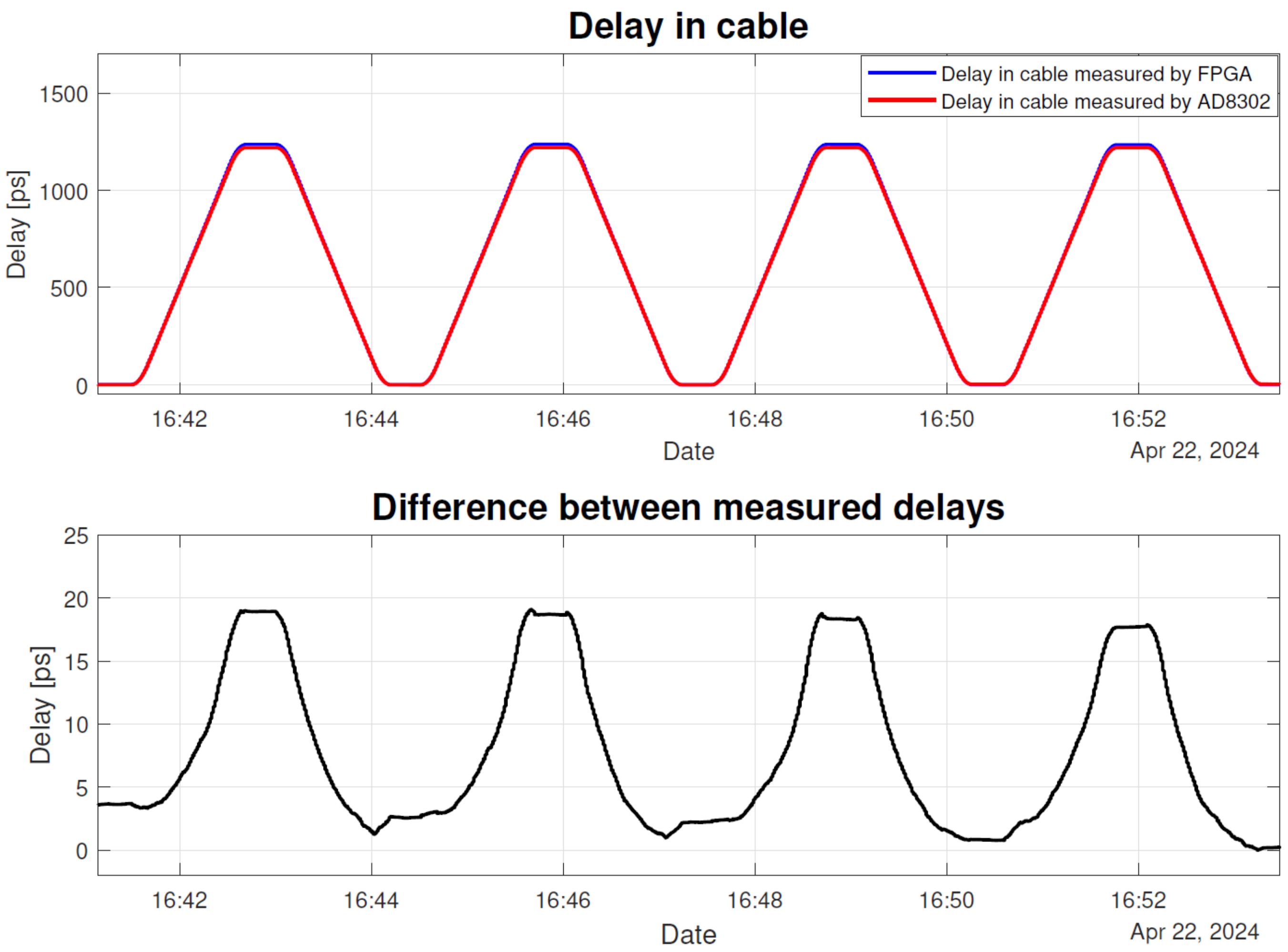


Measurements – Comparison to AD8302



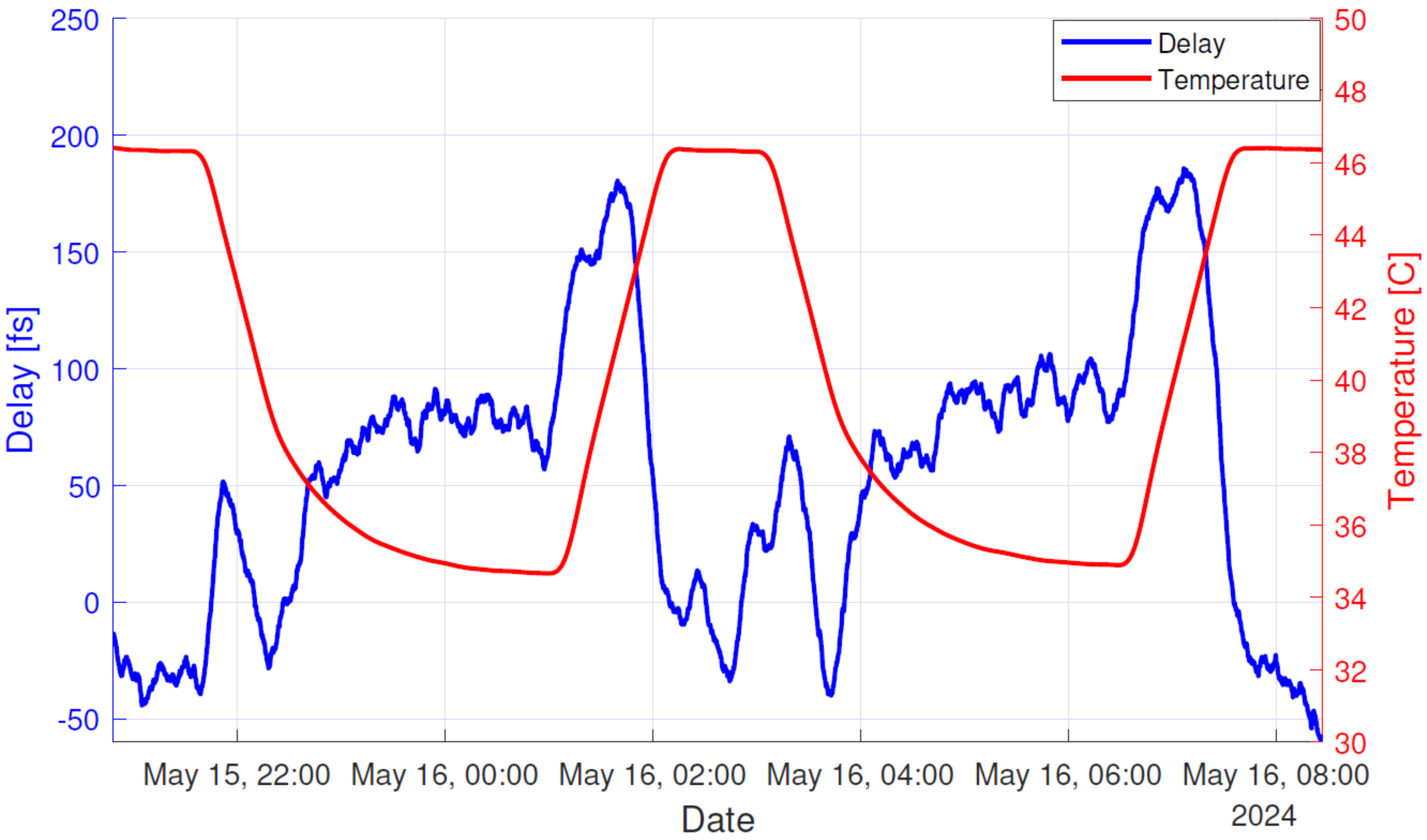
- Second tone: 20.3125 MHz
- Measured error: < 2.6 %

Measurements – Comparison to AD8305



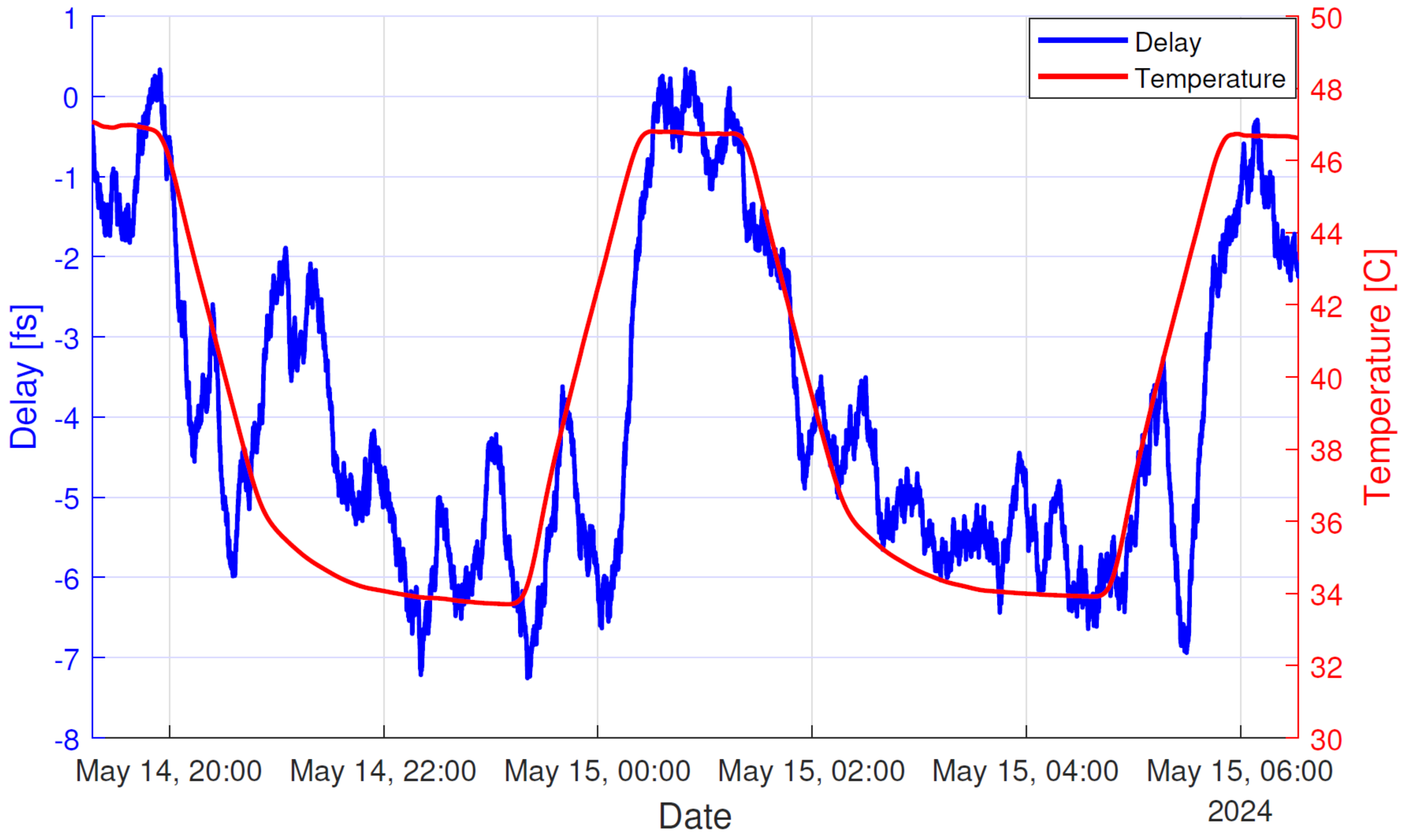
- Second tone: 161.32 MHz
- Measured error: < 1.5 %

Measurements - Selfdrifts



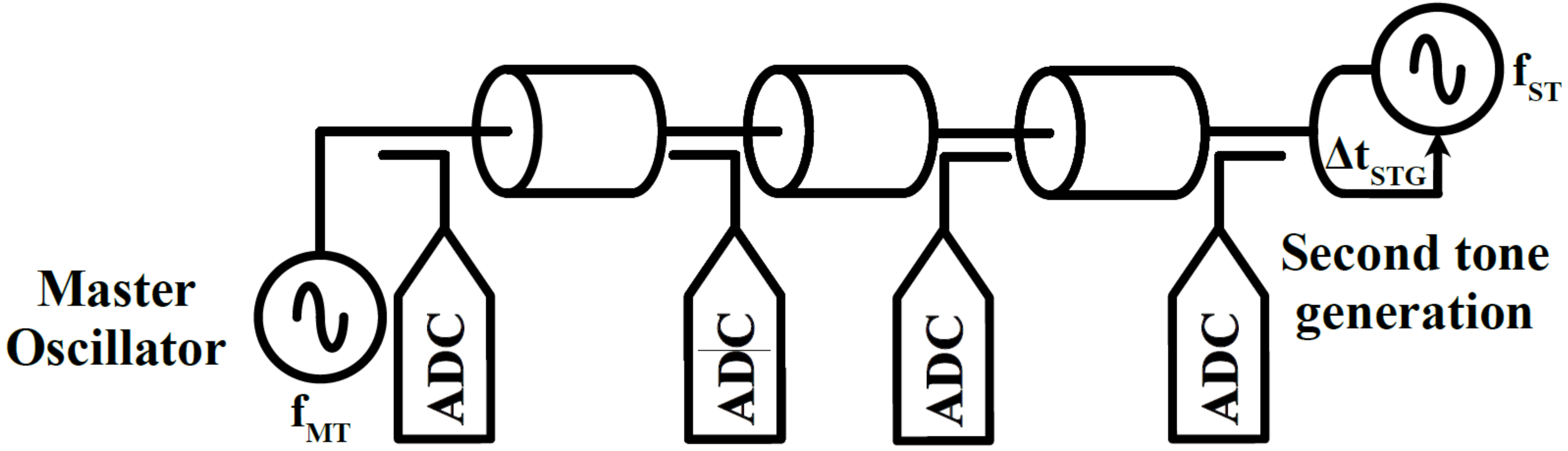
- Second tone: 20.3125 MHz
- Temperature change: 12 °C
- Drift: 250 fs
- Drift coefficient: 20.83 fs/°C

Measurements - Selfdrifts



- Second tone: 161.32 MHz
- Temperature change: 12 °C
- Drift: 8 fs
- Drift coefficient: 667 as/°C

Plans for future



- Two-tone system planned for PIP-II phase reference distribution
- Dedicated hardware developed and in production
- New test setup with this hardware to be assembled this year

Summary

- Two-tone phase drift measurement system developed and tested
- Performance:
  - 2.6% error – 142.1875 MHz separation
  - 1.5% error – 1.18 MHz separation
- Self-drift:
  - 20.83 fs/°C – 142.1875 MHz separation
  - 667 as/°C – 1.18 MHz separation
- More information can be found in:

Šerlat, Andžej, Maciej Grzegrzółka, and Krzysztof Marek Czuba. 2025. “Two-Tone RF Signal Phase Drift Measurement System.” Measurement 243. https://doi.org/10.1016/j.measurement.2024.116183

Thank you for attention!