Scheduling of twin telescopes
and its impact on troposphere and UT1 estimation

Armin Corbin\textsuperscript{1}, Rüdiger Haas\textsuperscript{1},
Axel Nothnagel\textsuperscript{2},
Benjamin Niedermann\textsuperscript{2},
Jan-Henrik Haunert \textsuperscript{2}

\textsuperscript{1} Chalmers University of Technology, Sweden
\textsuperscript{2} University of Bonn, Germany

18 March 2019
Motivation

KOKEE12M
WETTZ13N
WETTZ13S
ISHIOKA
ONSA13NE
ONSA13SW
WETTZ13N
WETTZ13S
Overview

Schedule

Simulator

LSA

UT1, ZWD, Clocks

UT1, ZWD, Clocks

UT1, ZWD, Clocks
Overview

Schedule

Simulator

LSA

UT1, ZWD, Clocks

UT1, ZWD, Clocks

UT1, ZWD, Clocks
Scheduling

Strategy

- regular observations: *one observation per minute*
- **optimal** sky coverage

Observations

- duration: 30 s
- minimum SNR: 20
Scheduling

Strategy

• regular observations: *one observation per minute*
• optimal sky coverage

Observations

• duration: 30 s
• minimum SNR: 20

Receiver

• 32 channels @ 32MHz
• 1-bit sampling

Twins

• twins never observe the same source together
• spherical distance $> 60^\circ$
Scheduling

**Strategy**
- regular observations: *one observation per minute*
- optimal sky coverage

**Observations**
- duration: 30 s
- minimum SNR: 20

**Receiver**
- 32 channels @ 32MHz
- 1-bit sampling

**Twins**
- twins never observe the same source together
- spherical distance $> 60^\circ$
Integer Linear Programming

\[ \max \Phi(x) = a^T x \]

subject to linear inequality constraints

\[ Cx \leq b \]

with \( x \in \{0, 1\} \)
Integer Linear Programming

\[
\max \Phi(x) = a^T x
\]

sky coverage

subject to linear inequality constraints

\[Cx \leq b\]

modelling scheduling problem

with \( x \in \{0, 1\} \)
Integer Linear Programming

$$\max \Phi(x) = a^T x$$  \rightarrow \text{sky coverage}

subject to linear inequality constraints

$$Cx \leq b$$  \rightarrow \text{one baseline}

with $x \in \{0, 1\}$

$C \in \mathbb{R}^{61409 \times 7089}$

$x \in \{0, 1\}^{7089}$

$b \in \mathbb{R}^{61409}$
Integer Linear Programming

$$\max \Phi(x) = a^T x$$

subject to linear inequality constraints

$$Cx \leq b$$

one baseline

$$C \in \mathbb{R}^{61409 \times 7089}$$

$$x \in \{0, 1\}^{7089}$$

$$b \in \mathbb{R}^{61409}$$

with $x \in \{0, 1\}$
Sky Coverage Score

- **multiple partitions** of hemisphere into cells of equal size and similar shape
- evaluation period: 20 minutes
- period shift: 5 minutes

\[
\frac{2\pi}{13} \quad \frac{2\pi}{50} \quad \frac{2\pi}{300}
\]

partition 1  
(13 cells)  

partition 2  
(50 cells)  

partition 3  
(300 cells)
Sky Coverage Score

- **multiple partitions** of hemisphere into cells of **equal size** and similar shape
- evaluation period: 20 minutes
- period shift: 5 minutes

\[
2\pi \frac{5}{13} + 2\pi \frac{13}{50} + 2\pi \frac{17}{300}
\]

partition 1
(13 cells)

partition 2
(50 cells)

partition 3
(300 cells)
Simulation

Schedule

Simulator

LSA

UT1, ZWD, Clocks

UT1, ZWD, Clocks

UT1, ZWD, Clocks
\[ \tau_{\text{sim}} = \tau_g + \text{clock}_2 - \text{clock}_1 + Mf(\epsilon_2) \cdot \text{ZWD}_2 - Mf(\epsilon_1) \cdot \text{ZWD}_1 + wn \]

- IERS conventions
- ITRF2014, ICRF2
- polar motion and nutation: IERS C04
- UT1: BKG eopi
\[ \tau_{\text{sim}} = \tau_g + \text{clock}_2 - \text{clock}_1 + Mf(\epsilon_2) \cdot \text{ZWD}_2 - Mf(\epsilon_1) \cdot \text{ZWD}_1 + \text{wn} \]

Allan std.: \(10^{-14} \text{ s @ 50 min}\)
Simulation

\[ \tau_{\text{sim}} = \tau_g + \text{clock}_2 - \text{clock}_1 + Mf(\epsilon_2) \cdot ZWD_2 - Mf(\epsilon_1) \cdot ZWD_1 + wn \]

**partitioning**
- spatial: 209 cells of equal size
- temporal: 1 minute steps

**turbulence model**
- Nilsson & Haas (2010)
- Parameters: Petrachenko et al. (2009)
- initial ZWD = 450 ps / 135 mm
- VMF1
\[ \tau_{\text{sim}} = \tau_g + \text{clock}_2 - \text{clock}_1 + Mf(\epsilon_2) \cdot ZWD_2 - Mf(\epsilon_1) \cdot ZWD_1 + wn \]

**partitioning**
- spatial: 209 cells of equal size
- temporal: 1 minute steps

**turbulence model**
- Nilsson & Haas (2010)
- Parameters: Petrachenko et al. (2009)
- initial ZWD = 450 ps / 135 mm
- VMF1
\[ \tau_{\text{sim}} = \tau_g + \text{clock}_2 - \text{clock}_1 + M_f(\epsilon_2) \cdot ZWD_2 - M_f(\epsilon_1) \cdot ZWD_1 + \text{wn} \]

20 ps white noise
Results

Schedule

Simulator

LSA

UT1, ZWD, Clocks

UT1, ZWD, Clocks

UT1, ZWD, Clocks
Results

<table>
<thead>
<tr>
<th>name</th>
<th>station</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 twin</td>
<td>Wn Is (K2)</td>
</tr>
<tr>
<td>1 twin</td>
<td>Wn Ws Is K2</td>
</tr>
<tr>
<td>2 twin</td>
<td>Ow Oe Wn Ws Is K2</td>
</tr>
</tbody>
</table>
Results

<table>
<thead>
<tr>
<th>name</th>
<th>station</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 twin</td>
<td>Wn Is (K2)</td>
</tr>
<tr>
<td>1 twin</td>
<td>Wn Ws Is K2</td>
</tr>
<tr>
<td>2 twin</td>
<td>Ow Oe Wn Ws Is K2</td>
</tr>
</tbody>
</table>
Results

<table>
<thead>
<tr>
<th>name</th>
<th>station</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 twin</td>
<td>Wn Is (K2)</td>
</tr>
<tr>
<td>1 twin</td>
<td>Wn Ws Is K2</td>
</tr>
<tr>
<td>2 twin</td>
<td>Ow Oe Wn Ws Is K2</td>
</tr>
</tbody>
</table>
Simulation Results: UT1

![Plot](image)

### Results

<table>
<thead>
<tr>
<th>solution</th>
<th>mean (μs)</th>
<th>WRMS(μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>original schedule (S/X)</td>
<td>-0.5</td>
<td>11</td>
</tr>
<tr>
<td>0 twins</td>
<td>0.1</td>
<td>8</td>
</tr>
</tbody>
</table>
Simulation Results: UT1

![Graph showing simulation results with dates from 21-Jan-18 to 08-Oct-18 and corresponding ΔUT1 values in μs.]

### Results

<table>
<thead>
<tr>
<th>solution</th>
<th>mean (μs)</th>
<th>WRMS(μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>original schedule (S/X)</td>
<td>-0.5</td>
<td>11</td>
</tr>
<tr>
<td>0 twins</td>
<td>0.1</td>
<td>8</td>
</tr>
<tr>
<td>1 twins</td>
<td>0.4</td>
<td>6</td>
</tr>
<tr>
<td>2 twins</td>
<td>0.2</td>
<td>4</td>
</tr>
</tbody>
</table>
Exemplary ZWD time series
Exemplary ZWD time series

- simulated (true) ZWD
  - 0 twins
  - 1 twins
  - 2 twins

Results
Exemplary ZWD time series

- simulated (true) ZWD
  - 0 twins
  - 1 twins
  - 2 twins

Results
Simulation Results: ZWD

<table>
<thead>
<tr>
<th>solution</th>
<th>Wn</th>
<th>Ws</th>
<th>Kk</th>
<th>Is</th>
<th>On</th>
<th>Os</th>
<th>#baselines</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 twin</td>
<td>9.2</td>
<td>-</td>
<td>16.5</td>
<td>11.7</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>1 twin</td>
<td>8.8</td>
<td>8.9</td>
<td>16.7</td>
<td>11.0</td>
<td>-</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>8.1</td>
<td>16.7</td>
<td>11.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 twin</td>
<td>8.8</td>
<td>9.0</td>
<td>15.8</td>
<td>10.1</td>
<td>7.4</td>
<td>7.1</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>8.0</td>
<td>15.6</td>
<td>10.3</td>
<td></td>
<td>6.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Simulation Results: ZWD

**Average difference true - estimated ZWD (ps)**

<table>
<thead>
<tr>
<th>solution</th>
<th>Wn</th>
<th>Ws</th>
<th>Kk</th>
<th>Is</th>
<th>On</th>
<th>Os</th>
<th>#baselines</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 twin</td>
<td>9.2</td>
<td>-</td>
<td>16.5</td>
<td>11.7</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>1 twin</td>
<td>8.8</td>
<td>8.9</td>
<td>16.7</td>
<td>11.0</td>
<td>-</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>8.1</td>
<td>16.7</td>
<td>11.1</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 twin</td>
<td>8.8</td>
<td>9.0</td>
<td>15.8</td>
<td>10.1</td>
<td>7.4</td>
<td>7.1</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>8.0</td>
<td>15.6</td>
<td>10.3</td>
<td>6.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Simulation Results: ZWD

**Average difference true - estimated ZWD (ps)**

<table>
<thead>
<tr>
<th>solution</th>
<th>Wn</th>
<th>Ws</th>
<th>Kk</th>
<th>Is</th>
<th>On</th>
<th>Os</th>
<th>#baselines</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 twin</td>
<td>9.2</td>
<td>-</td>
<td>16.5</td>
<td>11.7</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>1 twin</td>
<td>8.8</td>
<td>8.9</td>
<td>16.7</td>
<td>11.0</td>
<td>-</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>8.1</td>
<td></td>
<td>16.7</td>
<td>11.1</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2 twin</td>
<td>8.8</td>
<td>9.0</td>
<td>15.8</td>
<td>10.1</td>
<td>7.4</td>
<td>7.1</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>8.0</td>
<td></td>
<td>15.6</td>
<td>10.3</td>
<td></td>
<td>6.0</td>
<td></td>
</tr>
</tbody>
</table>

\[ C_n \times 10^{-7} m^{-\frac{1}{3}} \]

|          | 0.94 | 2.30 | 1.46 | 0.72 |
Conclusion

Twin Telescopes in intensive sessions

- twin stations improve UT1 estimations
  - more observations
  - more baselines with large east-west component
- ZWD only slightly improved
  - troposphere is not rotational symmetric
  - mapping functions can not model turbulence adequately
Thank you for your attention!

armin.corbin@chalmers.se


Validation of Simulation

INT1 INT2 Schedules

observed

Simulator

LSA

UT1, ZWD, Clocks

UT1, ZWD, Clocks

ILP scheduling

References
Validation of Simulation

-50
-25
0
25
50
75
UT1 [micros]
observed - simulated

WRMS 14 µs
Median: -3 µs
ILP 2D-Example

\[2x_1 - x_2 \leq 5\]

\[x_2 \leq 3.5\]

\[x_1 + x_2 \geq 1\]

References
ILP 2D-Example

\[ \begin{array}{c}
2x_1 - x_2 \leq 5 \\

x_2 \leq 3.5 \\

x_1 + x_2 \geq 1
\end{array} \]

References
ILP 2D-Example

\[ 2x_1 - x_2 \leq 5 \]

\[ x_2 \leq 3.5 \]

\[ x_1 + x_2 \geq 1 \]
Detail Networks
0 twins
Detail Networks

1 twins
Detail Networks

2 twins

References

24th EVGA Working Meeting 2019, 17-19 March