Observing the APOD satellite with the AuScope VLBI network

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Observation approach

• Direct observations of artificial satellite signals
  – „Geodetic“ observation mode using the standard VLBI signal chain
  – Satellite signals treated like noise
  ➢ Computation of group delays
The APOD-A Nano Satellite

- Chinese Cube satellite mission by BACC launched in Sept. 2015
- LEO orbit (~450 km, $i \approx 97^\circ$)
- Geodetic payload:
  - GNSS receiver (GPS & BD)
  - SLR retroreflector
  - VLBI S/X beacon (DOR tones)

- GNSS receiver used for POD partly failed in Jan. 2016
  - Final orbit accuracy: **10-20 m**
  - Orbit predictions: **km-level**

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<table>
<thead>
<tr>
<th>Label</th>
<th>Band</th>
<th>Frequency [MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carr$_S$</td>
<td>S</td>
<td>2262.010</td>
</tr>
<tr>
<td>DOR$_{S1}$</td>
<td>S</td>
<td>2256.869</td>
</tr>
<tr>
<td>DOR$_{S2}$</td>
<td>S</td>
<td>2260.982</td>
</tr>
<tr>
<td>DOR$_{S3}$</td>
<td>S</td>
<td>2263.038</td>
</tr>
<tr>
<td>DOR$_{S4}$</td>
<td>S</td>
<td>2267.151</td>
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<tr>
<td>Carr$_X$</td>
<td>X</td>
<td>8424.040</td>
</tr>
<tr>
<td>DOR$_{X1}$</td>
<td>X</td>
<td>8404.894</td>
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<tr>
<td>DOR$_{X2}$</td>
<td>X</td>
<td>8420.211</td>
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<tr>
<td>DOR$_{X3}$</td>
<td>X</td>
<td>8427.869</td>
</tr>
<tr>
<td>DOR$_{X4}$</td>
<td>X</td>
<td>8443.186</td>
</tr>
</tbody>
</table>

$\Delta f = 10.3$ MHz

$\Delta f = 38.3$ MHz

DOR tones emitte by the S/X beacon
## Experiments in November 2016

<table>
<thead>
<tr>
<th>Date</th>
<th>Duration</th>
<th>Code</th>
<th>Stations</th>
<th>Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.11.2016</td>
<td>33 min</td>
<td>316a</td>
<td>Ke, Yg</td>
<td>APOD + quasars</td>
</tr>
<tr>
<td>12.11.2016</td>
<td>41 min</td>
<td>317a</td>
<td>Hb, Ke</td>
<td>APOD + quasars</td>
</tr>
<tr>
<td>12.11.2016</td>
<td>35 min</td>
<td>317b</td>
<td>Hb, Ke, Yg</td>
<td>APOD + quasars</td>
</tr>
<tr>
<td>13.11.2016</td>
<td>26 min</td>
<td>318b</td>
<td>Hb, Ke, Yg</td>
<td>APOD + quasars</td>
</tr>
<tr>
<td>13.11.2016</td>
<td>26 min</td>
<td>318c</td>
<td>Hb, Ke</td>
<td>APOD + quasars</td>
</tr>
<tr>
<td>13.11.2016</td>
<td>23 min</td>
<td>318d</td>
<td>Ke, Yg</td>
<td>APOD + quasars</td>
</tr>
<tr>
<td>14.11.2016</td>
<td>40 min</td>
<td>319a</td>
<td>Hb, Ke, Yg</td>
<td>APOD + quasars</td>
</tr>
<tr>
<td>27.11.2016</td>
<td>24 h</td>
<td>a332</td>
<td>Hb, Ke, Yg</td>
<td>APOD + quasars</td>
</tr>
</tbody>
</table>

→ APOD was tracked by AuScope whenever possible from Nov. 11 to 14, 2016
Scheduling

• **Scheduling with VieVS Satellite Scheduling Module** *(Hellerschmied et al., 2017)*
  - Control files for stations (antennas & recorders) and correlator

• **Experiment design**
  - Continental-wide baselines and LEO orbit
  - Limited common visibility
  - Only single-baseline scans
  - 1 to 3 observable overpasses per day

*Observation geometry in session a332. The antenna’s projected field of views are indicated as red circles.*
Observations

• **Satellite tracking**
  – **AZEL tracking mode** of the AuScope ACUs
  – Input: 1 sec time-series of AzEl positions
  – Tracking data based on orbit predictions by BACC (accuracy on the km level only!)

• **Observation mode**
  – Aim: capture APOD tone & to compute MBDs for quasar
  – 16 x 16 MHz channels (10 in X, 6 in S)
  – 2 bit sampling (64 Mbps/channel)

*Observation mode. APOD’s DOR tones are indicated by black lines.*
Correlation with DiFX Software

- The standard a priori delay model was replaced by „near field delay model“ calculated in VieVS
  - Low quality of the final orbit solution (10 - 20 m) degrades the accuracy of the modeled delays
- **Zoom bands** (32 kHz wide) centered on the DOR tones used to extract the APOD signals from recorded 16 MHz bands

Near-filed delay modeling based on a light-time solution plus relativistic corrections (Klioner, 1991)
Correlation: cross-specra

- **Amplitude variations** due to slight mispoint more pronounced in X-band (narrow beam-width of ~10′ vs. ~40′ in S-band)
- Correlator model not accurate enough to stop phase wrapping

Inaccurate orbit data!
Fringe Fitting with HOPS/fourfit

- Calculation of multiband delays based on zoom bands in S/X
  - 1 sec integration time

  ![Residual multiband delay graph]

  ![Residual rate graph]

  ![SNR graph]

- Smooth residual delays and delay rates
- **Lower and more variable SNR in X band** reflect the tracking issues

**Typical values**

- ±10 ns
- < 0.5ns/s
- S: 500-800
- X: 200-700

*Fringe fitting results of scan 168 in session a332 by HOPS/fourfit*
Analysis with VieVS

- „Observed“
  - Ionosphere-free linear combination of S/X delays (e.g. Alizadeh et al., 2013)
- „Computed“
  - Near-field delay model by Klioner (1991)
  - Standard geophysical modeling in VieVS

- O-C residuals typically on the level of ~10 ns
- Systematic signature in O-C explainable by along-track offset (~8 m, this example)
- Mandatory to estimate orbit parameters along with other parameters
Analysis: Parameter estimation – test case

- Least-squares adjustment
  - Based on APOD observations
  - Const. Offsets estimated

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>Formal error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clock offset, Hb</td>
<td>14.0m</td>
<td>2.3m</td>
</tr>
<tr>
<td>Clock offset, Ke</td>
<td>−1.1m</td>
<td>1.9m</td>
</tr>
<tr>
<td>ZWD, Hb</td>
<td>3.4cm</td>
<td>1.7cm</td>
</tr>
<tr>
<td>ZWD, Ke</td>
<td>14.3cm</td>
<td>2.1cm</td>
</tr>
<tr>
<td>ZWD, Yg</td>
<td>7.3cm</td>
<td>1.7cm</td>
</tr>
<tr>
<td>Orbit, radial</td>
<td>1.2m</td>
<td>0.3m</td>
</tr>
<tr>
<td>Orbit, along-track</td>
<td>−7.8m</td>
<td>0.3m</td>
</tr>
<tr>
<td>Orbit, cross-track</td>
<td>−1.9m</td>
<td>1.3m</td>
</tr>
</tbody>
</table>

Parameter estimation results from scans 168 and 169 in experiment a332.

Post-fit residuals of scans 168 and 169 in session a332

WRMS = 9.5 cm
Summary

✓ Series of APOD observations in November 2016 with AuScope
  – Challenging due to the low satellite orbit and the inaccurate orbit data
  ➢ O-C residuals on level of a few ns for all tracks

• Limitations:
  – Global tracking network required for estimation of high quality orbit parameters
  – Small number of single baseline tracks due to observation geometry
  ➢ Observations still not sufficient to study frame ties

• For further details see Hellerschmied et al. (2018), doi: 10.3390/s18051587
Thank you for your attention!

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References:
Hellerschmied et al. (2018), Observing APOD with the AuScope VLBI array, Sensors
Plank et al. (2017), VLBI observations to satellites of the GNSS: from scheduling to analysis, J Geod, Vol 91, pp 867-880.
Sun et al. (2017), VLBI observations to the APOD satellite, Advances in Space Research Vol 61, pp 823-829