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Observing the APOD satellite with the AuScope VLBI network

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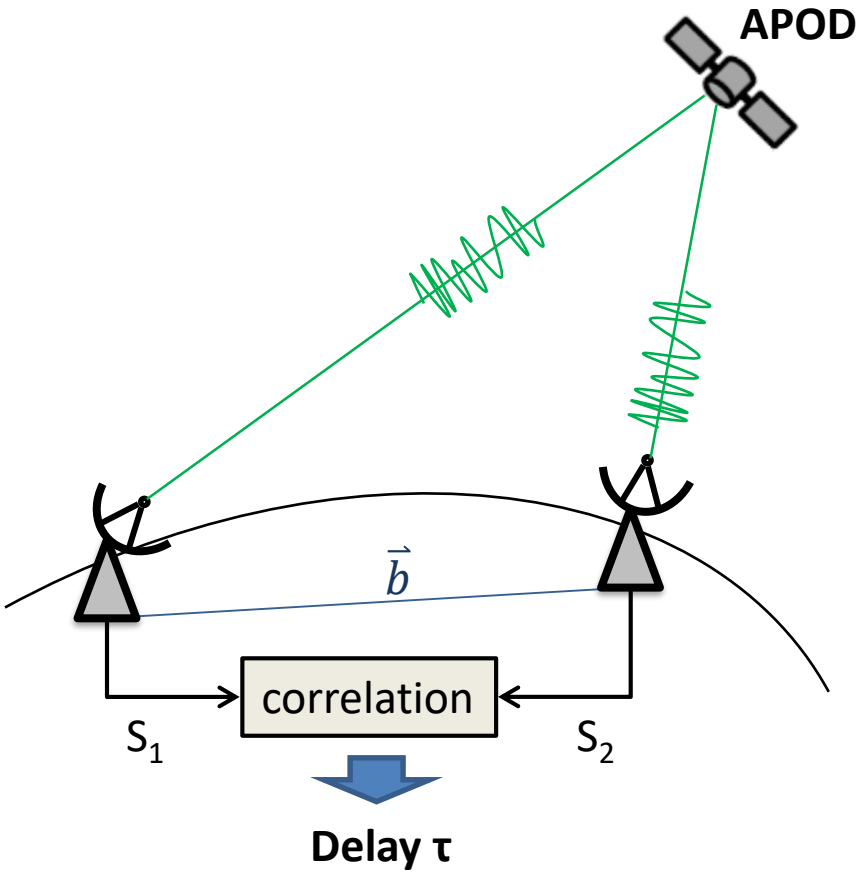
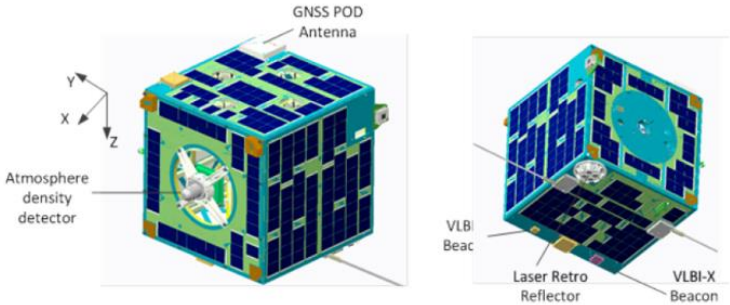
Observation approach

- **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 ≈ 97°)
- Geodetic payload:
  - GNSS receiver (GPS & BD)
  - SLR retroreflector
  - **VLBI S/X beacon (DOR tones)**



Physical layout of APOD-A (Sun et al., 2017)

- **GNSS receiver used for POD partly failed in Jan. 2016**

➢ Final orbit accuracy: **10-20 m**

➢ Orbit predictions: **km-level**

Label	Band	Frequency [MHz]
$Carr_S$	S	2262.010
DOR_{S1}	S	2256.869
DOR_{S2}	S	2260.982
DOR_{S3}	S	2263.038
DOR_{S4}	S	2267.151
$Carr_X$	X	8424.040
DOR_{X1}	X	8404.894
DOR_{X2}	X	8420.211
DOR_{X3}	X	8427.869
DOR_{X4}	X	8443.186

Δf=10.3 MHz

Δf=38.3 MHz

DOR tones emittel by the S/X beacon

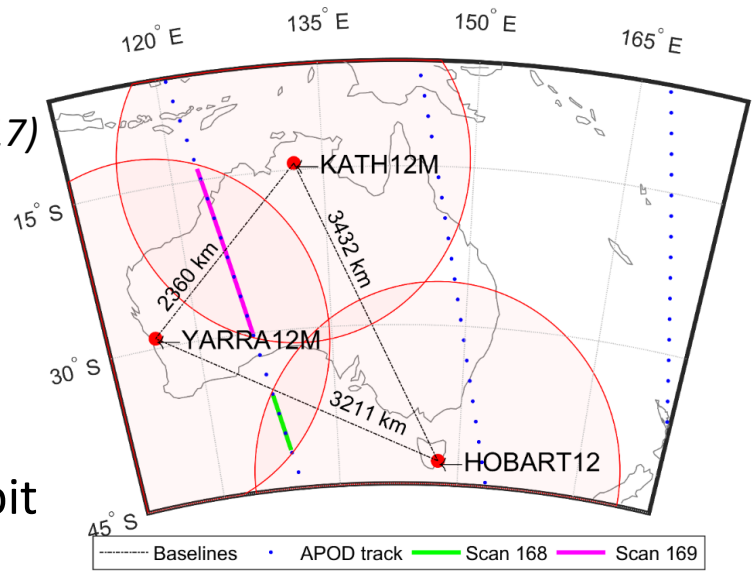
Experiements in November 2016

Date	Duration	Code	Stations	Targets
11.11.2016	33 min	316a	Ke, Yg	APOD + quasars
12.11.2016	41 min	317a	Hb, Ke	APOD + quasars
12.11.2016	35 min	317b	Hb, Ke, Yg	APOD + quasars
13.11.2016	26 min	318b	Hb, Ke, Yg	APOD + quasars
13.11.2016	26 min	318c	Hb, Ke	APOD + quasars
13.11.2016	23 min	318d	Ke, Yg	APOD + quasars
14.11.2016	40 min	319a	Hb, Ke, Yg	APOD + quasars
27.11.2016	**24 h**	a332	Hb, Ke, Yg	APOD + quasars

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

Scheduling

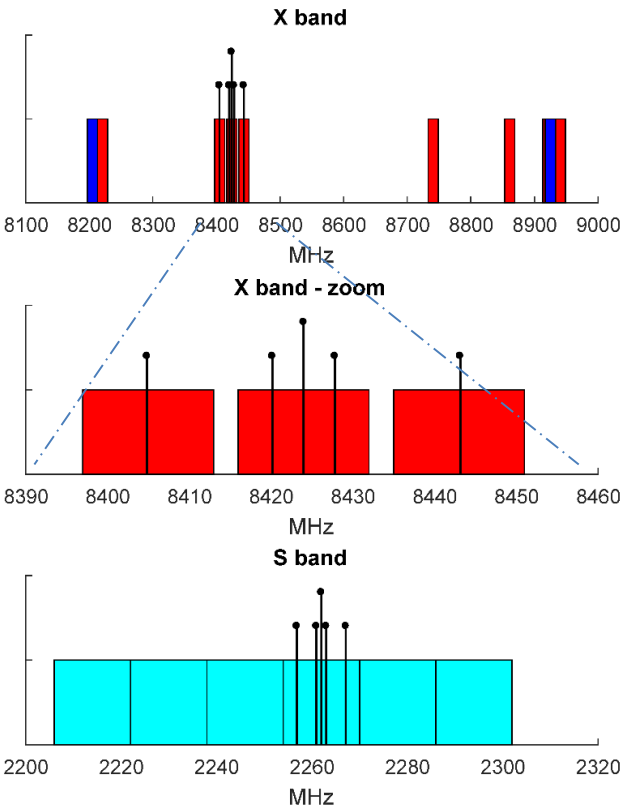
- **Scheduling** with **VieVS Satellite Scheduling Module** *(Hellerschmied et al., 2017)*
  - ➢ Control files for stations (antennas & recorders) and correlator
- **Experiment design**
  - – Continental-wide baselines and LEO ortbit
  - ➢ Limited common visibility
  - ➢ Only single-baseline scans
  - ➢ 1 to 3 observable ovserpasses per day



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

Observations

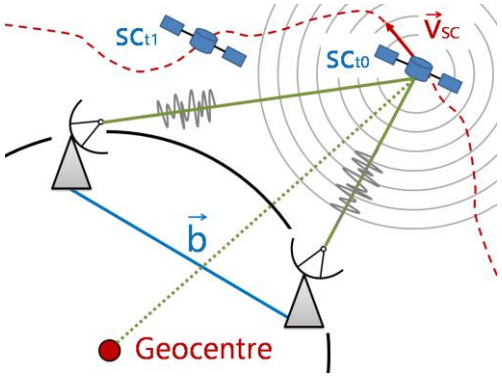
- **Satellite tracking**
  - **AZEL tracking mode** of the AuScope ACUs
  - Input: 1 sec time-series of AzEl positions
  - Tracking data based on orbit predictions by BACC (accuracy on the km level only!)
- **Observation mode**
  - Aim: capture APOD tone & to compute MBDs for quasar
  - 16 x 16 MHz channels (10 in X, 6 in S)
  - 2 bit sampling (64 Mbps/channel)



Observation mode. APOD's DOR tones are indicated by black lines.

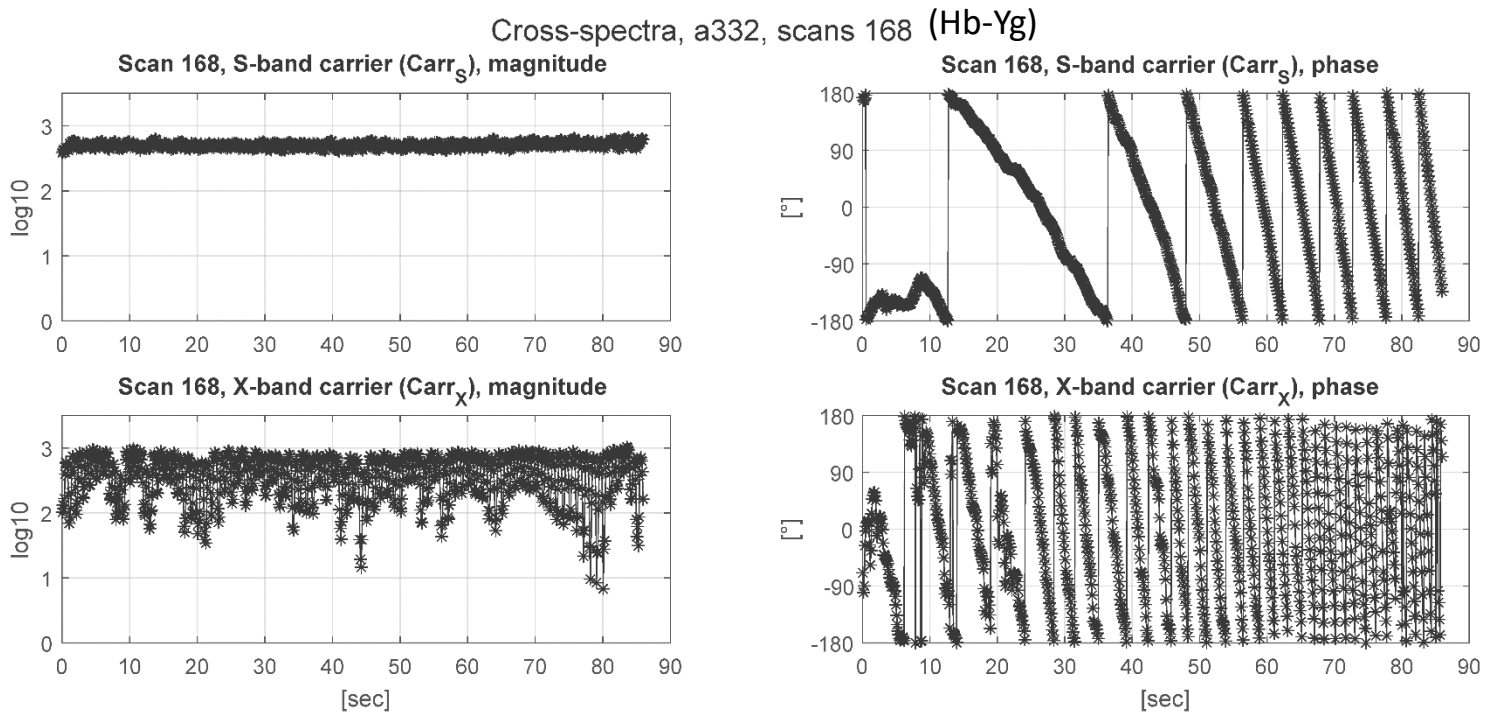
Correlation with DiFX Software

- 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

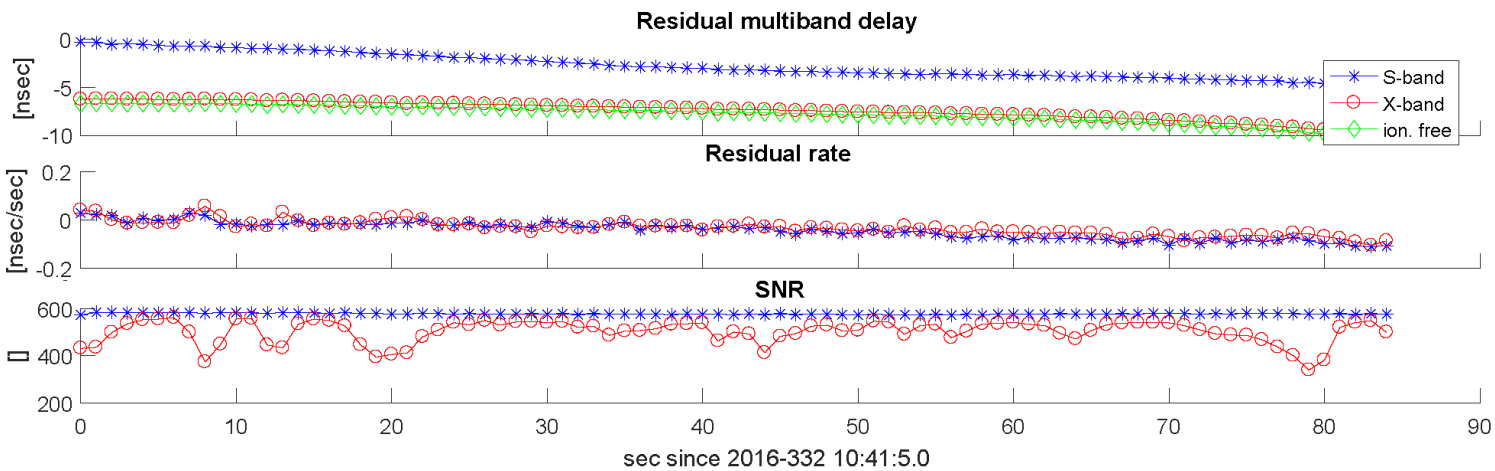


- **Amplitude variations** due to **slight mispoint** more pronounced in X-band (narrow beam-width of ~10‘ vs. ~40‘ in S-band)
- Correlator model not accurate enough to stop **phase wrapping**

Inaccurate orbit data!

Fringe Fitting with HOPS/fourfit

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



Typical values

±10 ns

< 0.5ns/s

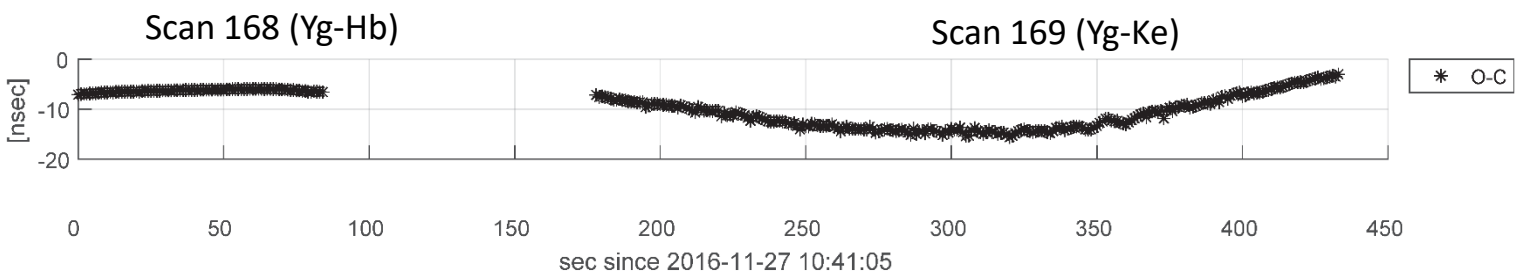
S: 500-800
X: 200-700

Fringe fitting results of scan 168 in session a332 by HOPS/fourfit

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

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



Scans 168 and 169 in session a332

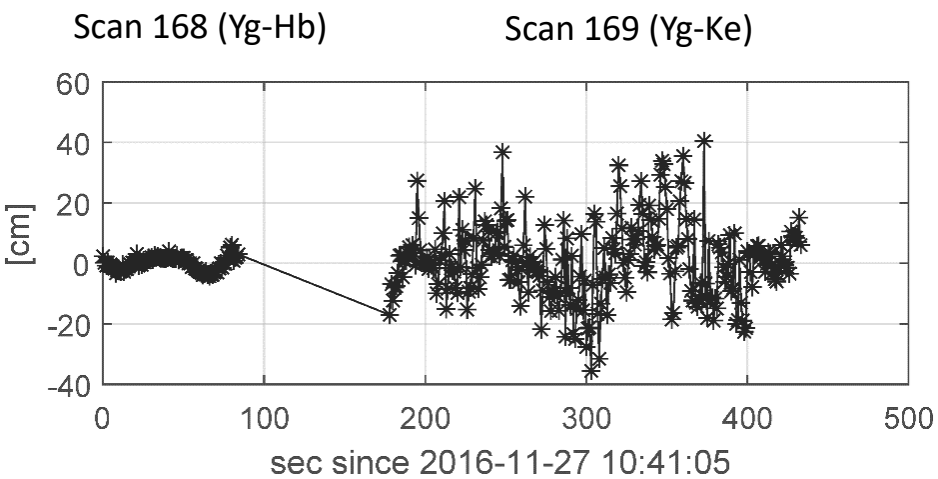
- O-C residuals typically on the level of ~10 ns
- **Systematic signature in O-C** explainable by along-track offset (-8 m, this example)
- Mandatory to **estimate orbit parameters along with other parameters**

Analysis: Parameter estimation – test case

- **Least-squares adjustmnent**
  - Based on APOD observations
  - Const. Offsets estimated

Parameter	Estimate	Formal error
Clock offset, Hb	$14.0m$	$2.3m$
Clock offset, Ke	$-1.1m$	$1.9m$
ZWD, Hb	$3.4cm$	$1.7cm$
ZWD, Ke	$14.3cm$	$2.1cm$
ZWD, Yg	$7.3cm$	$1.7cm$
Orbit, radial	$1.2m$	$0.3m$
Orbit, along-track	$-7.8m$	$0.3m$
Orbit, cross-track	$-1.9m$	$1.3m$

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:

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AuScope