24th European VLBI Group for Geodesy and Astrometry Working Meeting

Geodetic VLBI observations of lunar radio sources

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Current status & recommendations for future research

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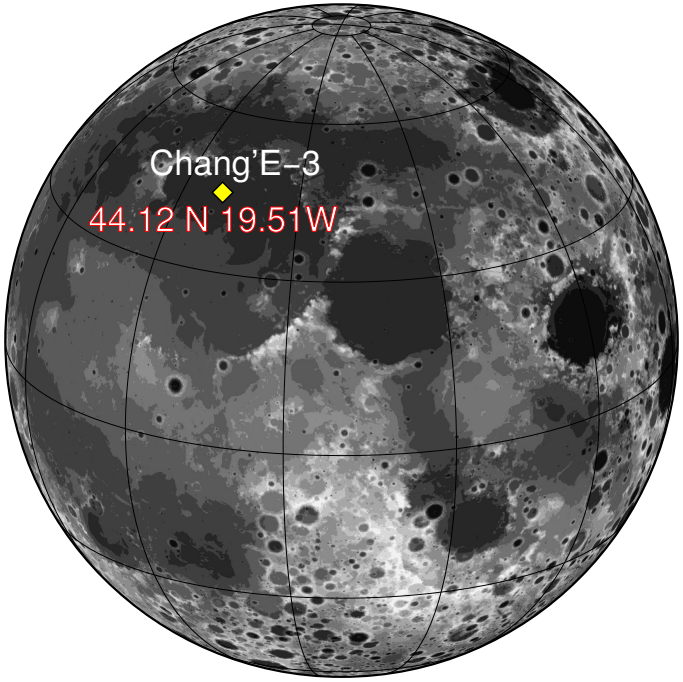
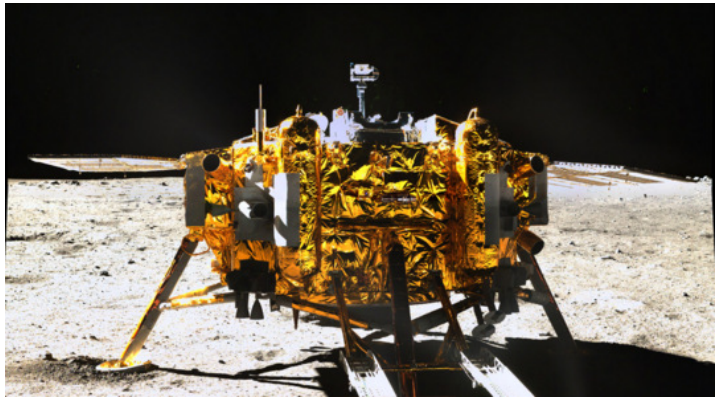
March 19, 2019

Chinese Lunar Exploration Program (CLEP)

Chang'E-3 mission





CE-3 lander photographed by the Yutu rover.
Credit: Chinese Academy of Sciences

Chang'E-3 mission (lander + rover) - late 2013

Lander's signal characteristics:

- 4 Differential-One-way-Ranging (DOR) tones centered at 8.470 GHz:
  $\pm$ 19.25 MHz & $\pm$3.85 MHz
- Communication channel at 8.496 GHz
- X-band-only signals

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Geodetic Very Long Baseline Interferometry (VLBI)

Global observing programs organized by the IVS

Global IVS observing programs:

- Research & development (IVS-R&D): 24 hours - several per year
  - **OCEL(Observing the Chang'E Lander with VLBI):**
    24-hour sessions in 2014, 2015 and 2016 - Twelve in total

OCEL (Observing the Chang'E Lander with VLBI)

Combination of lunar and quasar observations

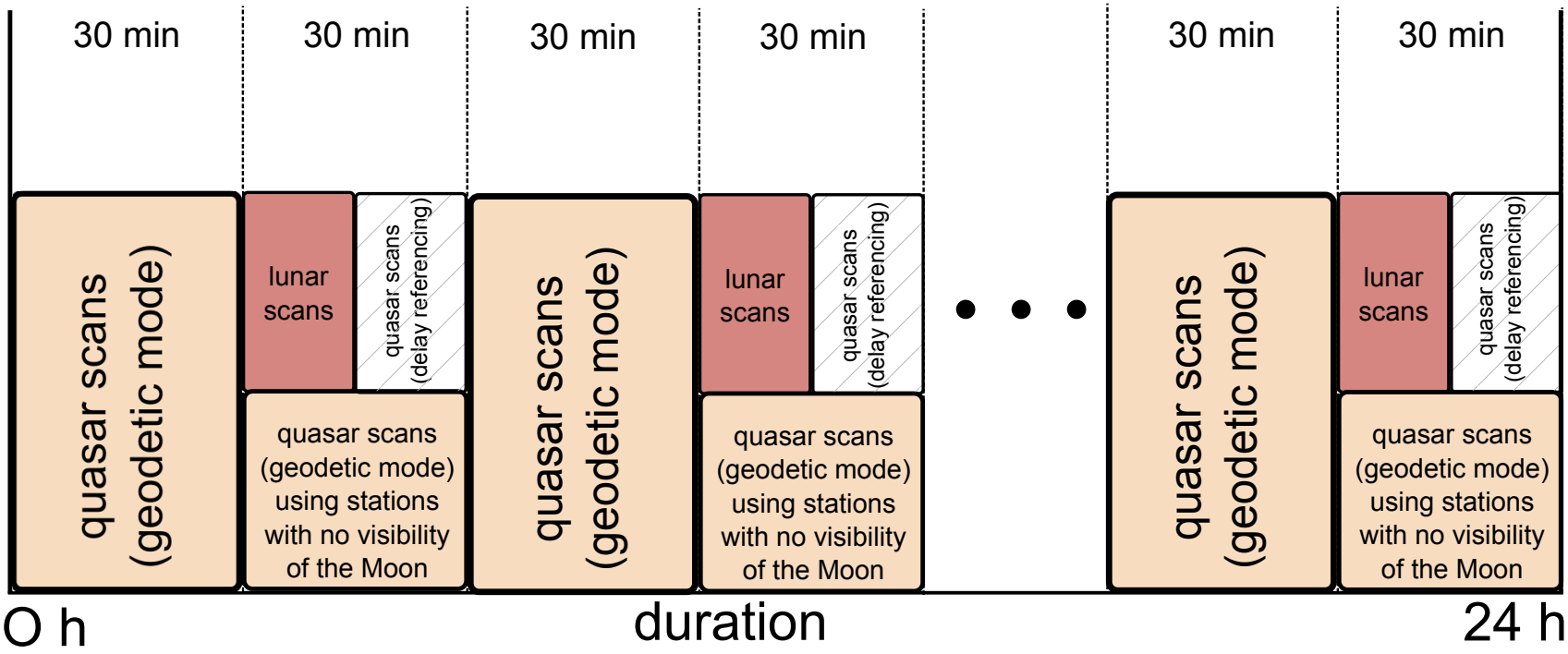

Fig.1 from Klopotek et al. (2019)

Observations:

- Automatic scheduling of 30-minute quasar-only scans with *Sked*
- Manual combination of quasar and lunar observations for the other 30-minute blocks of scans
- Quasar scans for referencing - not considered in this study

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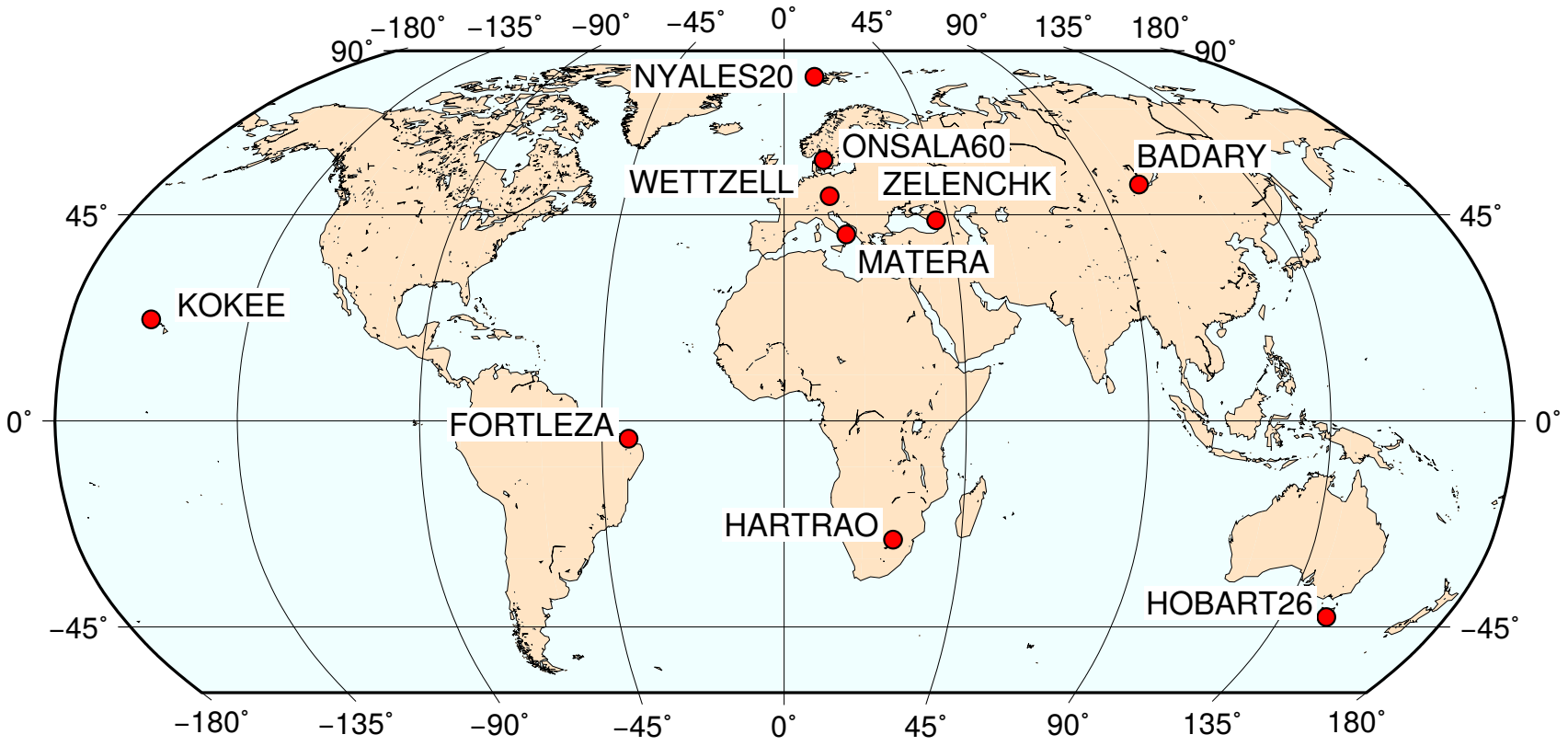
OCEL - Observations

VLBI telescopes participating in OCEL08 (RD1510) & OCEL09 (RD1601)



OCEL08 (RD1510): 2015-12-01 17:30 UTC – 2015-12-02 17:30 UTC

- No. of utilized quasar/**lunar** observations: 3523 / **856**

OCEL09 (RD1601): 2016-01-20 18:00 UTC – 2016-01-21 18:00 UTC

- No. of utilized quasar/**lunar** observations: 3791 / **1302**

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OCEL - Observations

Performance overview

Table 1 Characteristics of OCEL sessions and problems encountered during the analysis, shown for the selected experiments

Session	Quasar data	Lunar data
RD1405 (OCEL01)	Stations used (8): Bd, Hh, Ho, Ny, On, Sh, Wz, Zc	(6): Bd, Ny, Ho, On, Wz, Zc
	No. of usable/scheduled obs.: 2622/6585	301 /1018
	Mc scheduled, but not participated	Most obs. during the last 6 h
	Ny participating during the first 10 h	
RD1506 (OCEL06)	Stations used (11): Bd, Ft, Hh, Ho, Kk, Mt, Ny, On, Sh, Wz, Zc	(8): Bd, Ft, Hh, Ho, Kk, Mt, Sh, Wz
	No. of usable/scheduled obs.: 5064/6912	520/870
	Manual phase calibration applied to all stations	19-h observation period
	RFI at S band (Ft, Ho, Mt, Sh, Zc)	
	Problems at X band (Ho, Ny, Sh)	
RD1510 (OCEL08)	Stations used (10): Bd, Ft, Ho, Ht, Kk, Mt, Ny, On, Wz, Zc	(9): No On
	No. of usable/scheduled obs.: 3523/6045	856/1524
	Manual phase calibration (Kk)	22-h obs. period
	RFI at S band (Ft, Mt, Zc)	
	Problems at X band (Ft, Ny)	
RD1601 (OCEL09)	Stations used (10): Bd, Ft, Ho, Hh, Kk, Mt, Ny, On, Wz, Zc	All
	No. of usable/scheduled obs.: 3791/6094	1302/1427
	Manual phase calibration (Ho, Kk)	24-h obs. period
	RFI at S band (Ft, Ho, Mt, Zc)	
	Problems at X band (Ny)	
RD1604 (OCEL10)	Stations used (10): Bd, Ft, Hh, Ho, Mc, Ny, On, Sh, Wz, Zc	(7): Bd, Ft, Hh, Wz, On, Sh, Zc
	No. of usable/scheduled obs.: 2617/7272	547/1629
	Manual phase calibration (Ho, Mc)	Most obs. during the first 8 h
	RFI at S band (Zc, Ft, Mc)	
	Poor data quality at Mc: not used	Poor data quality at Mc: not used
RD1613 (OCEL12)	Stations used (9): Bd, Hh, Kk, Mt, Ny, On, Ft, Wz, Zc	(8): No Ft
	No. of usable/scheduled obs.: 3022/5339	345/1355
	No signal in the last four X-band channels at Ft, Mt and Ny	16-h obs. period
	RFI at S band (Ft, Mt, Zc)	
	Manual phase calibration (Kk)	
	Ho and Ur - not correlated	

The italic font indicates sessions used in this study. Two-letter telescope codes: BADARY (Bd), FORTLEZA (Ft), HARTRAO (Hh), HART15M (Ht), HOBART26 (Ho), KOKEE (Kk), KUNMING (Km), MATERA (Mt), MEDICINA (Mc), NYALES20 (Ny), ONSALA60 (On), SESHAN25 (Sh), URUMQI (Ur), WETTZELL (Wz), ZELENCHK (Zc)

Tab. 1 from Klopotek et al. (2019)

OCEL - Observations

Performance overview

Table 1 Characteristics of OCEL sessions and problems encountered during the analysis, shown for the selected experiments

Session	Quasar data	Lunar data
RD1405 (OCEL01)	Stations used (8): Bd, Hh, Ho, Ny, On, Sh, Wz, Zc	(6): Bd, Ny, Ho, On, Wz, Zc
	No. of usable/scheduled obs.: 2622/6585	301 /1018
	Mc scheduled, but not participated	Most obs. during the last 6 h
	Ny participating during the first 10 h	
RD1506 (OCEL06)	Stations used (11): Bd, Ft, Hh, Ho, Kk, Mt, Ny, On, Sh, Wz, Zc	(8): Bd, Ft, Hh, Ho, Kk, Mt, Sh, Wz
	No. of usable/scheduled obs.: 5064/6912	520/870
	Manual phase calibration applied to all stations	19-h observation period
	RFI at S band (Ft, Ho, Mt, Sh, Zc)	
	Problems at X band (Ho, Ny, Sh)	
RD1510 (OCEL08)	Stations used (10): Bd, Ft, Ho, Ht, Kk, Mt, Ny, On, Wz, Zc	(9): No On
	No. of usable/scheduled obs.: 3523/6045	856/1524
	Manual phase calibration (Kk)	22-h obs. period
	RFI at S band (Ft, Mt, Zc)	
	Problems at X band (Ft, Ny)	
RD1601 (OCEL09)	Stations used (10): Bd, Ft, Ho, Hh, Kk, Mt, Ny, On, Wz, Zc	All
	No. of usable/scheduled obs.: 3791/6094	1302/1427
	Manual phase calibration (Ho, Kk)	24-h obs. period
	RFI at S band (Ft, Ho, Mt, Zc)	
	Problems at X band (Ny)	
RD1604 (OCEL10)	Stations used (10): Bd, Ft, Hh, Ho, Mc, Ny, On, Sh, Wz, Zc	(7): Bd, Ft, Hh, Wz, On, Sh, Zc
	No. of usable/scheduled obs.: 2617/7272	547/1629
	Manual phase calibration (Ho, Mc)	Most obs. during the first 8 h
	RFI at S band (Zc, Ft, Mc)	
	Poor data quality at Mc: not used	Poor data quality at Mc: not used
RD1613 (OCEL12)	Stations used (9): Bd, Hh, Kk, Mt, Ny, On, Ft, Wz, Zc	(8): No Ft
	No. of usable/scheduled obs.: 3022/5339	345/1355
	No signal in the last four X-band channels at Ft, Mt and Ny	16-h obs. period
	RFI at S band (Ft, Mt, Zc)	
	Manual phase calibration (Kk)	
	Ho and Ur - not correlated	

The italic font indicates sessions used in this study. Two-letter telescope codes: BADARY (Bd), FORTLEZA (Ft), HARTRAO (Hh), HART15M (Ht), HOBART26 (Ho), KOKEE (Kk), KUNMING (Km), MATERA (Mt), MEDICINA (Mc), NYALES20 (Ny), ONSALA60 (On), SESHAN25 (Sh), URUMQI (Ur), WETTZELL (Wz), ZELENCHK (Zc)

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OCEL - Observations

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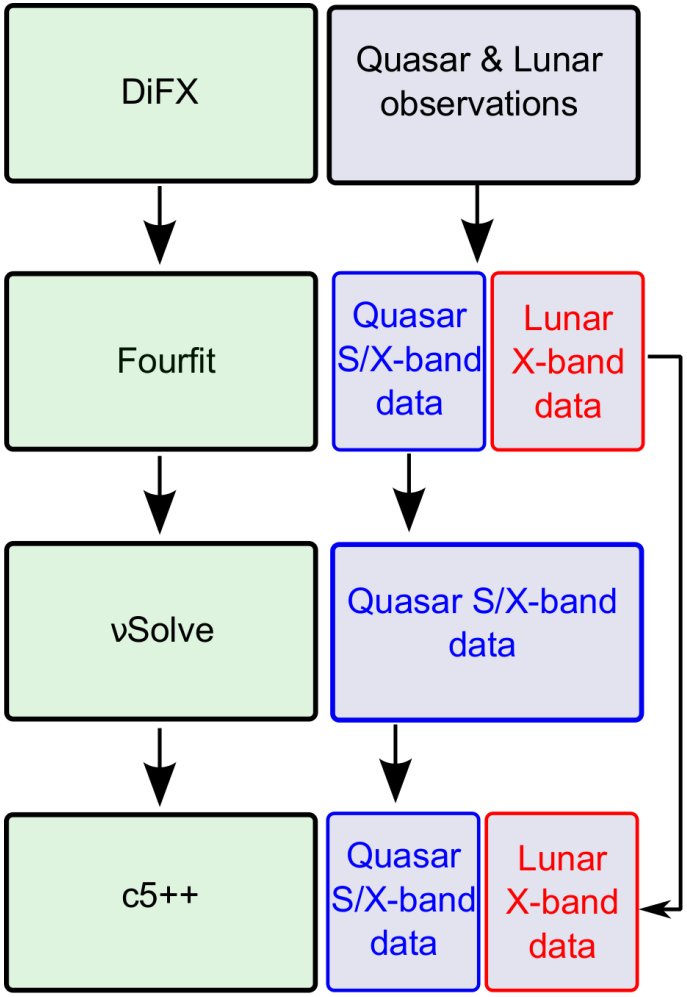
RD1405 (OCEL01)	Stations used (8): Bd, Hh, Ho, Ny, On, Sh, Wz, Zc	(6): Bd, Ny, Ho, On, Wz, Zc
	No. of usable/scheduled obs.: 2622/6585	301 /1018
	Mc scheduled, but not participated	Most obs. during the last 6 h
	Ny participating during the first 10 h	
RD1506 (OCEL06)	Stations used (11): Bd, Ft, Hh, Ho, Kk, Mt, Ny, On, Sh, Wz, Zc	(8): Bd, Ft, Hh, Ho, Kk, Mt, Sh, Wz
	No. of usable/scheduled obs.: 5064/6912	520/870
	Manual phase calibration applied to all stations	19-h observation period
	RFI at S band (Ft, Ho, Mt, Sh, Zc)	
	Problems at X band (Ho, Ny, Sh)	
RD1510 (OCEL08)	Stations used (10): Bd, Ft, Ho, Ht, Kk, Mt, Ny, On, Wz, Zc	(9): No On
	No. of usable/scheduled obs.: 3523/6045	856/1524
	Manual phase calibration (Kk)	22-h obs. period
	RFI at S band (Ft, Mt, Zc)	
	Problems at X band (Ft, Ny)	
RD1601 (OCEL09)	Stations used (10): Bd, Ft, Ho, Hh, Kk, Mt, Ny, On, Wz, Zc	All
	No. of usable/scheduled obs.: 3791/6094	1302/1427
	Manual phase calibration (Ho, Kk)	24-h obs. period
	RFI at S band (Ft, Ho, Mt, Zc)	
	Problems at X band (Ny)	
RD1604 (OCEL10)	Stations used (10): Bd, Ft, Hh, Ho, Mc, Ny, On, Sh, Wz, Zc	(7): Bd, Ft, Hh, Wz, On, Sh, Zc
	No. of usable/scheduled obs.: 2617/7272	547/1629
	Manual phase calibration (Ho, Mc)	Most obs. during the first 8 h
	RFI at S band (Zc, Ft, Mc)	
	Poor data quality at Mc: not used	Poor data quality at Mc: not used
RD1613 (OCEL12)	Stations used (9): Bd, Hh, Kk, Mt, Ny, On, Ft, Wz, Zc	(8): No Ft
	No. of usable/scheduled obs.: 3022/5339	345/1355
	No signal in the last four X-band channels at Ft, Mt and Ny	16-h obs. period
	RFI at S band (Ft, Mt, Zc)	
	Manual phase calibration (Kk)	
	Ho and Ur - not correlated	

The italic font indicates sessions used in this study. Two-letter telescope codes: BADARY (Bd), FORTLEZA (Ft), HARTRAO (Hh), HART15M (Ht), HOBART26 (Ho), KOKEE (Kk), KUNMING (Km), MATERA (Mt), MEDICINA (Mc), NYALES20 (Ny), ONSALA60 (On), SESHAN25 (Sh), URUMQI (Ur), WETTZELL (Wz), ZELENCHK (Zc)

Tab. 1 from Klopotek et al. (2019)

Processing strategy (1)

Quasar and lunar data handling



I Correlation of quasar and lunar observations

II Extraction of geodetic VLBI observables from the correlation results

III Resolve ambiguities and determine ionosphere delays

IV

a Solve for station clocks and Zenith Wet Delays (ZWDs) using only quasar data

- Apply station clocks and ZWDs from the quasar-only solution

b
- Resolve ambiguities
- Apply IONEX-derived ionosphere delays
- Estimate lunar-based parameters

Fig.2 from Klopotek et al. (2019)

Processing strategy (2)

Geodetic VLBI analysis in c5++

Modelling:

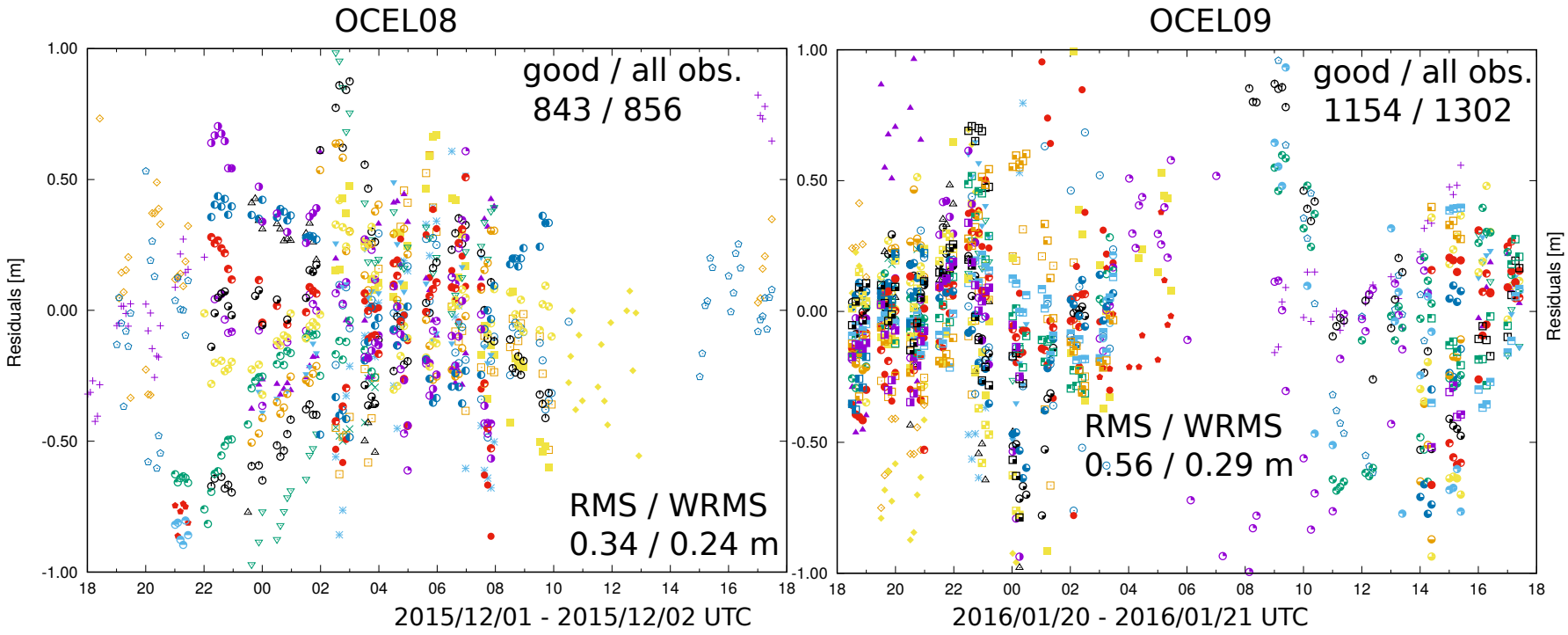
- Quasar observations (Q-only):
  - In accordance with IERS Conventions (2010) (Petit & Luzum 2010)
- Lunar observations (L-only):
  - VLBI delay: objects in the 'near field' (Duev et al. 2012)
  - Ephemeris: JPL DE421
  - A priori lander's position ($\phi_{lan}[^\circ]/\lambda_{lan}[^\circ]/H_{lan}[m]$): 0° /0° /-2637.6 m (H_{lan} from Cao et al. (2016))

Parametrization:

- Earth-based parameters: fixed to their a priori values
- ϕ_{lan},λ_{lan}: solve, H_{lan}: constraint $\pm$ 10 m
- Clock offsets w.r.t. Q-only: one per session per station
- Estimate "VTEC biases" as TEC maps were used for τ_{iono} (Hobiger et al. 2006)

OCEL08 & OCEL09 - Postfit RMS - **L-only**

Geodetic VLBI analysis in c5++



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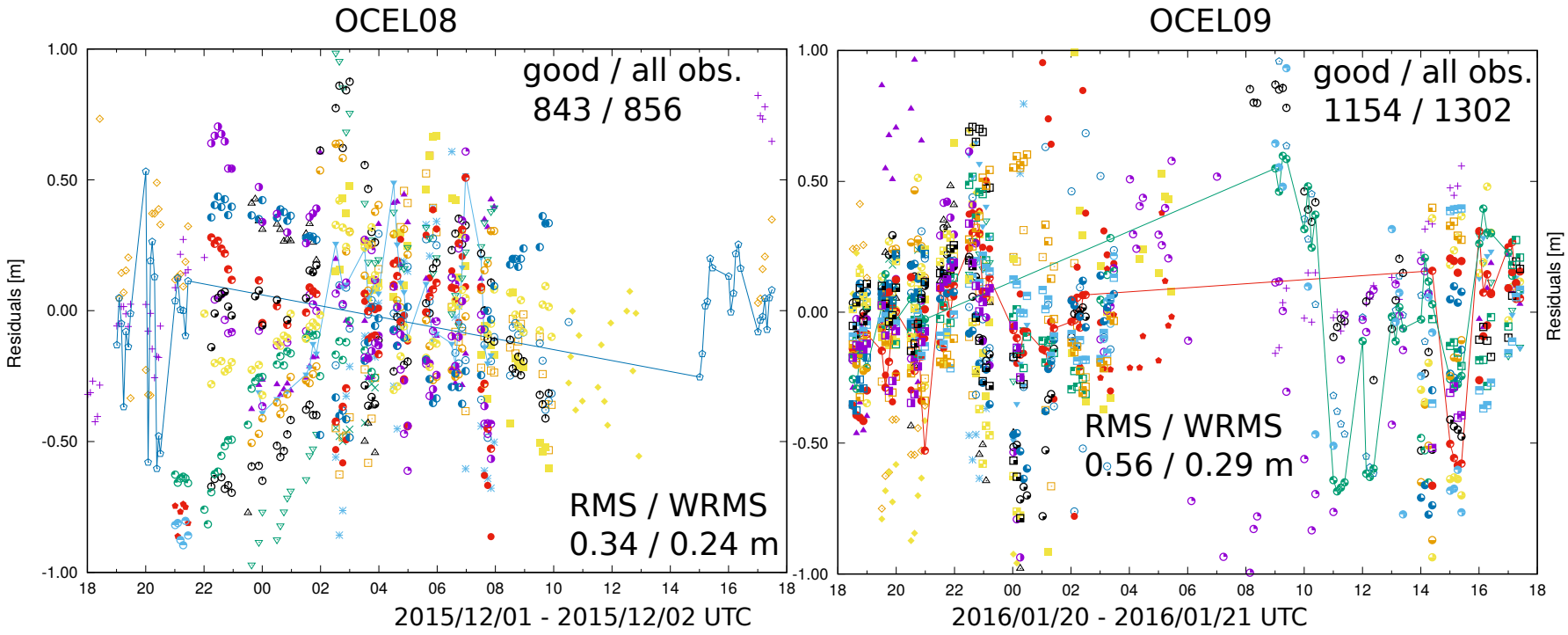
OCEL08 & OCEL09 - Postfit RMS - **L-only**

Geodetic VLBI analysis in c5++



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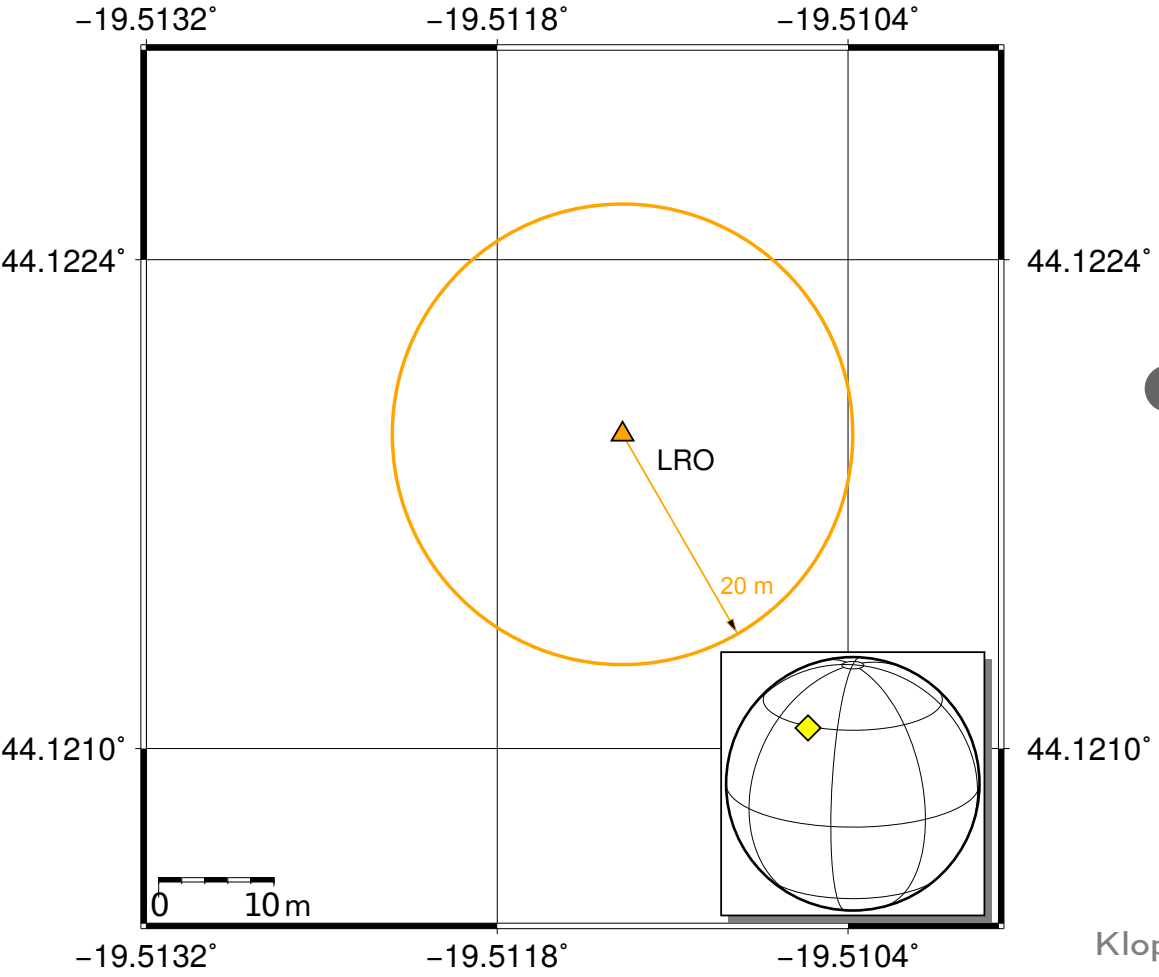
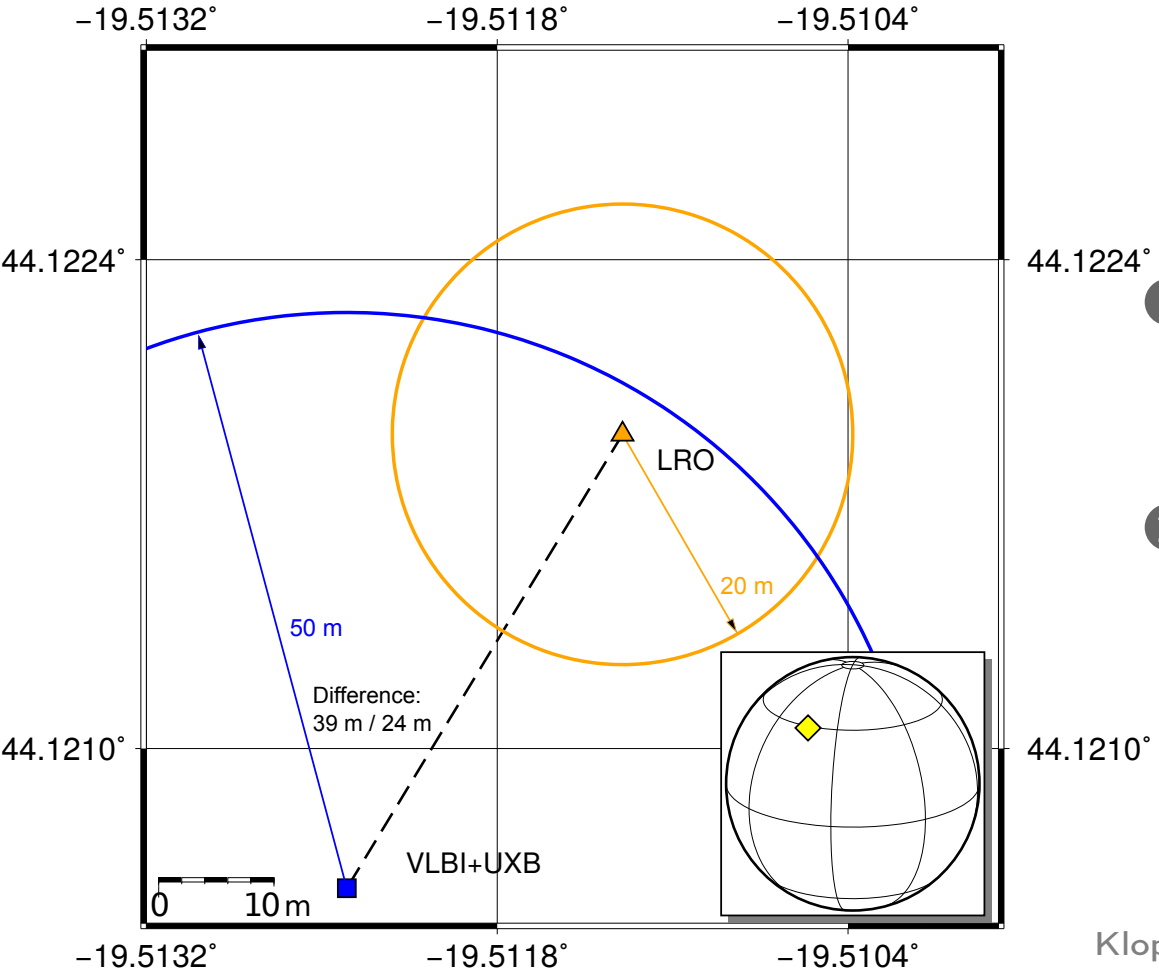
OCEL09 - lander's position - Precision and Accuracy



1. Lunar Reconnaissance Orbiter (LRO): images taken by the narrow-angle camera (NAC) (Liu et al. 2015): $44.1219°\mathrm{N}, -19.5113°\mathrm{E}, -2640.0\,\mathrm{m}$

Klopotek et al. (2019)

OCEL09 - lander's position - Precision and Accuracy



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2. VLBI+UXB (Unified X-band) (Li et al. 2014): $44.1206°\mathrm{N}, -19.5124°\mathrm{E}, -2632.0\,\mathrm{m}$

Klopotek et al. (2019)

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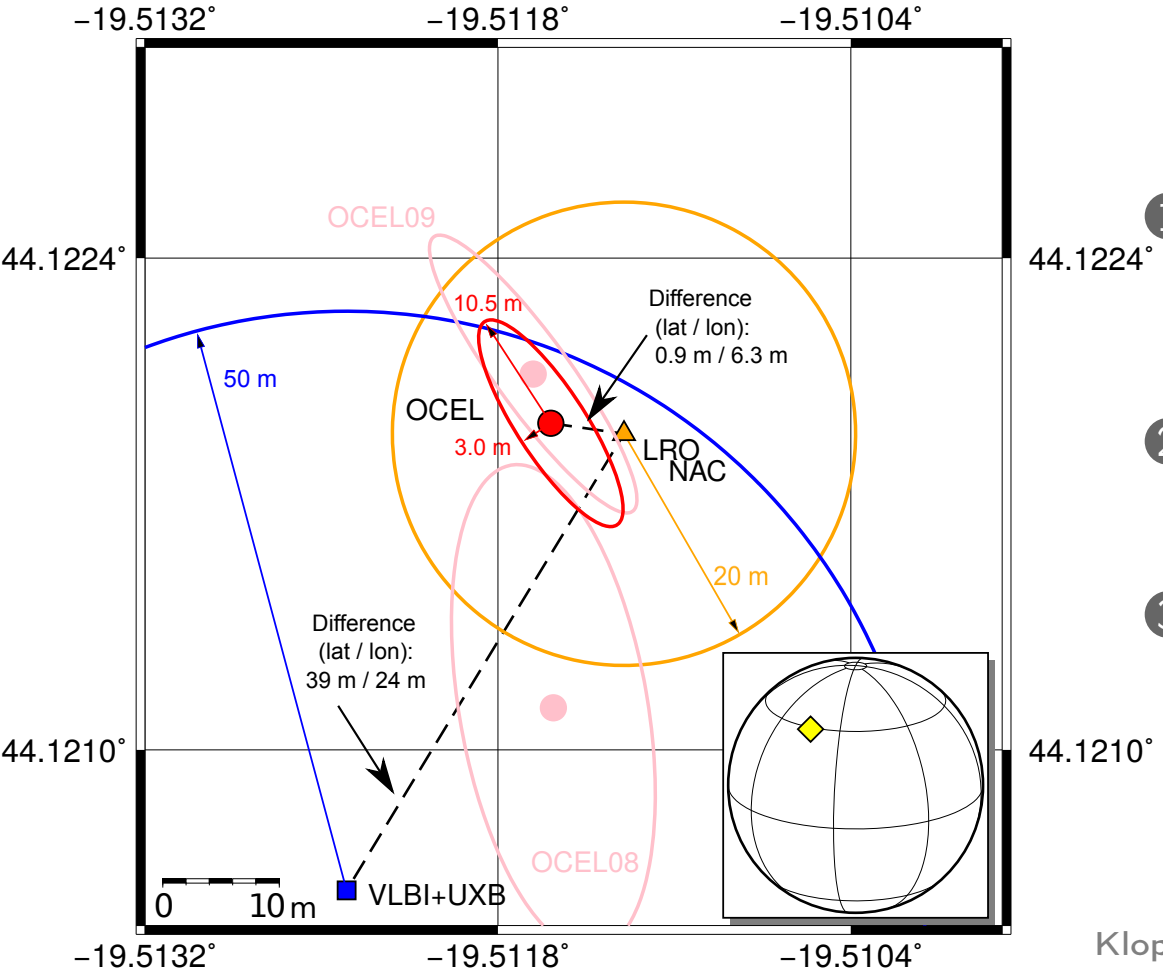
OCEL09 - lander's position - Precision and Accuracy



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3. **VLBI-only (OCEL08+OCEL09)**: $44.12193°\mathrm{N}, -19.51159°\mathrm{E}, -2637.3\,\mathrm{m}$ $\sigma_{lat} = 8.9$ m, $\sigma_{lon} = 4.5$ m

Klopotek et al. (2019)

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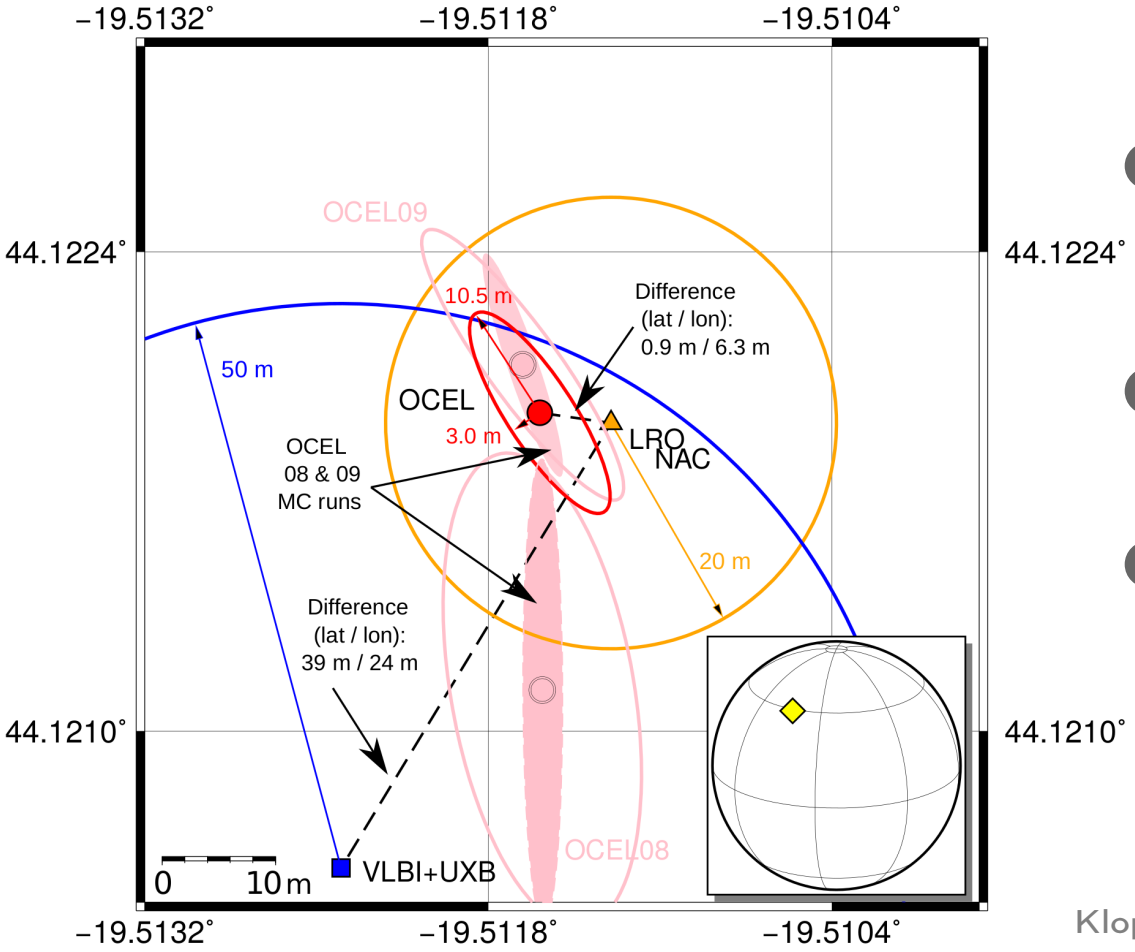
OCEL09 - lander's position - Precision and Accuracy



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Klopotek et al. (2019)

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What next ?

OCEL - simulations

Monte Carlo simulations based on OCEL sessions

dual-frequency lunar data & no additional (lunar) clock offsets

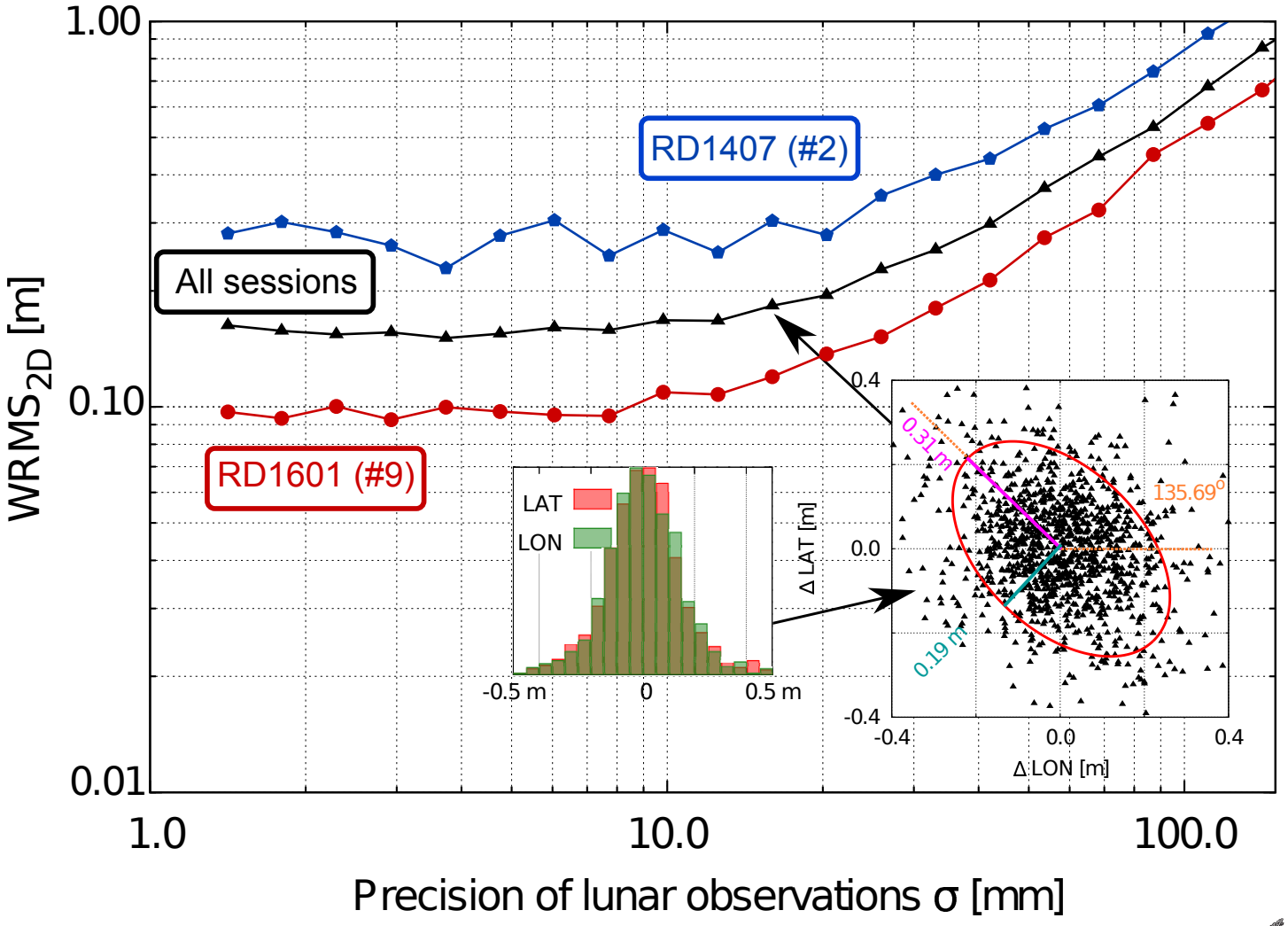

Fig.2 from Klopotek et al. (2017)

OCEL - simulations

IVS-R1-type session: lander's position accuracy vs precision of lunar observations

dual-frequency lunar data & no additional (lunar) clock offsets

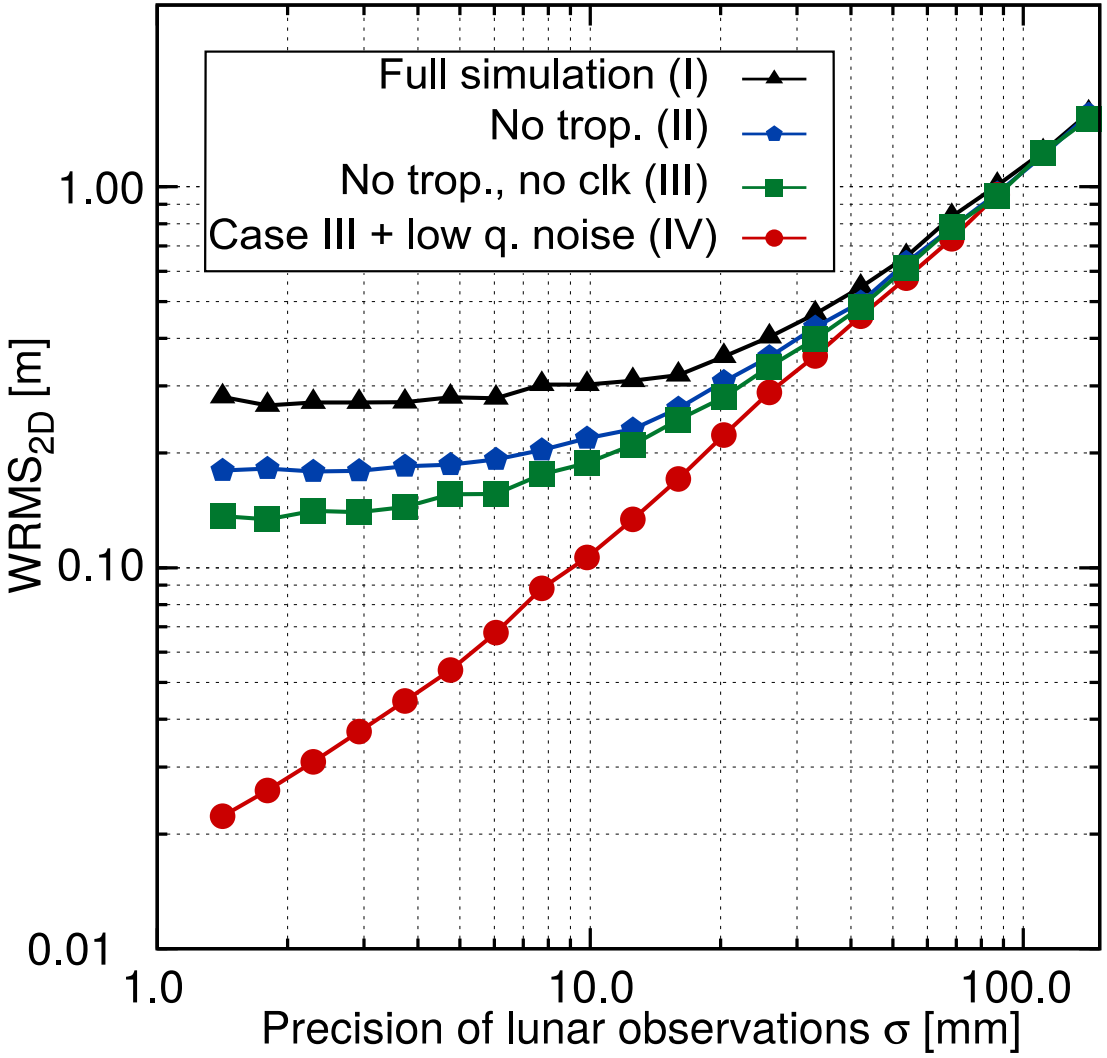

Fig.8 from Klopotek et al. (2018)

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Summary / Conclusions

- OCEL project:
  - Common processing chain applicable to lunar observations
  - Information on the current precision of such new data
  - Reliable position of the CE-3 lander was derived
- Limiting factors:
  - Troposphere, ionosphere, measurement noise
- Major improvements expected from:
  - Dual-frequency lunar data
  - Observations in the VGOS era
- Studies on optimized/dedicated observing networks:
  - Consideration of multiple lunar radio sources
  - Automatic scheduling of both quasar and lunar observations
  - Sensitivity of geodetic VLBI for lunar-based parameters (lunar rotation, selenocentric coordinates)

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Summary / Conclusions

Lunar observations with geodetic VLBI:

- Possibility of including such targets in the (standard) IVS (geodetic) schedules
- No additional/dedicated equipment on Earth
- Low-cost dual-frequency lunar DOR transmitters
- Support lunar navigation ?
- Complement Lunar Laser Ranging ?

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Thank you for your attention!

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