Initial Orbit Determination of Third-Generation BeiDou MEO Spacecraft

F. Dilsner, T. Springer, E. Schönemann, W. Enderle

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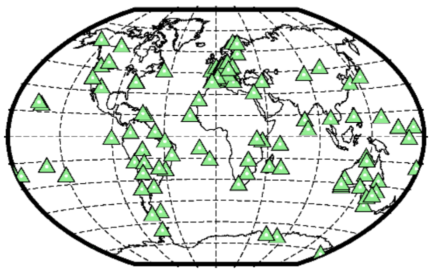
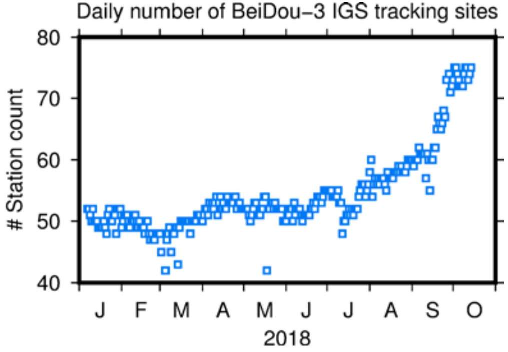
Introduction

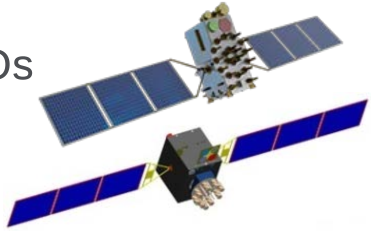
- Built-up of third-generation BeiDou system (BDS-3) started in 2015
  - Launch of five experimental test vehicles (3 MEOs, 2 IGSOs)
  - Goal is to have 27 MEOs, 3 IGSOs, and 5 GEOs by 2020
- Build-up of operational BDS-3 constellation since 2017
- 16 nonexperimental MEO SVs from Nov 2017 to Oct 2018
  - Launched in batches of two from Xichang in southwest China
  - Dispersed in all three orbital planes (A, B, C)
  - Built by two different manufacturers
    - 8 by China Academy of Space Technology (CAST)
    - 8 by Shanghai Engineering Center for Microsatellites (SECM)
  - Still undergoing in-orbit testing and operational evaluation
  - Transmit legacy B1 open service signal at 1561.098 MHz
    - Signal is being tracked by growing number of IGS stations
    - Motivated us to do initial orbit determination





Spacecraft dimensions

- New SVs much lighter and less cuboid as second-generation MEOs
  - Rectangular shape with a ratio of about 2:1 for main body axes
- Estimate effect the varying cross section of the body has on SRP
  - Difference maximum minus minimum radiated area divided by mass
  - Higher for BDS-3 as for BDS-2 MEOs but still moderate compared to other GNSS SVs



Courtesy: SECM (top) & CAST (bottom)

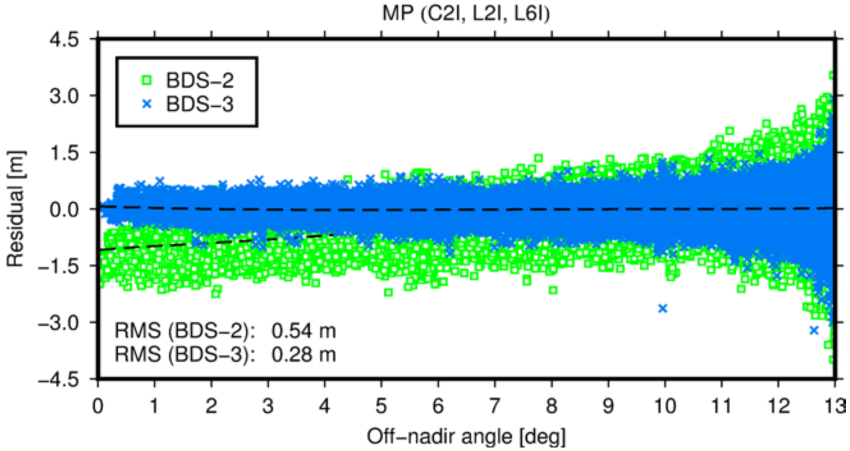
GNSS SV	x-panel [m²]	z-panel [m²]	$A_{max} - A_{min}$ [m²]	m [kg]	Impact
QZSS-1	13.99	5.52	9.52	2000	5.7
Galileo FOC	1.32	3.04	1.99	700	3.4
GLONASS-M	4.20	1.66	2.86	1400	2.4
GPS-IIF	5.72	5.40	2.47	1450	2.0
BDS-3M SECM	1.24	2.58	1.62	1030	1.9
BDS-3M CAST	1.22	2.25	1.34	1014	1.6
BDS-2M	3.44	3.78	1.67	2000	1.0

Processing strategy

- Processing carried out in daily batches with latest version of NAPEOS (4.2)
- 11-month period from January 1 to October 25, 2018
- Precise orbit determination (POD) solution for GPS constellation
  - Same set-up we use for our operational IGS Final processing
- Follow-up BeiDou solution to estimate satellite orbits and clocks while holding all other parameters fixed
  - Station positions, receiver clocks, troposphere, and EOPs fixed to GPS solution
  - Very simple orbit model – constant acceleration D0 in spacecraft-Sun direction plus constant tightly-constrained along-track CPR
  - First-order ionospheric delays removed by averaging the B1 phase and pseudorange observables (“GRAPHIC” method)
- Combination of daily NEQs to estimate BeiDou satellite antenna offsets

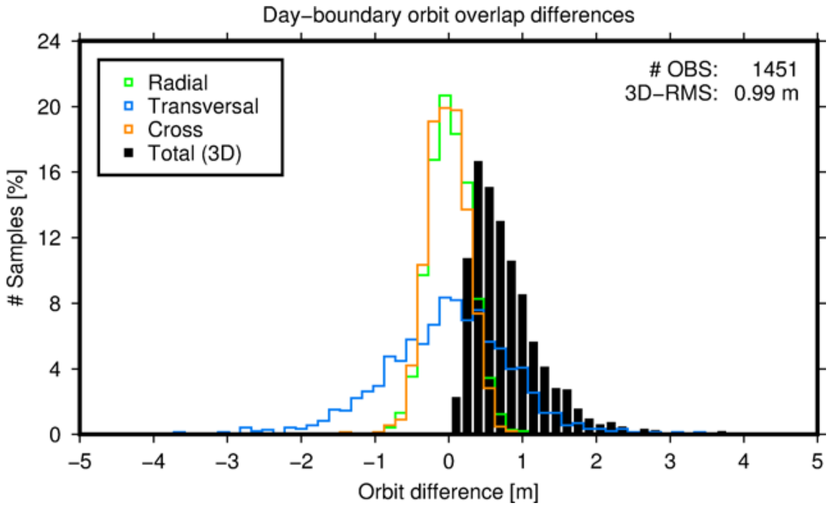
Pseudorange data quality

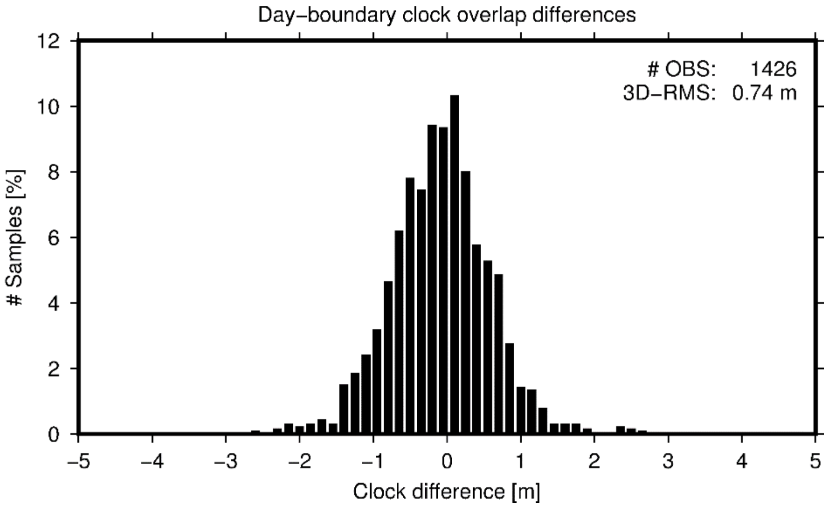
- Data post-fit residual RMS of less than 0.2 m
  - 40% smaller than for BDS-2 MEOs
- Compute TEQC multipath metrics MP1 & MP2
  - Use dual-frequency data from 10 IGS PolaRx5 station receivers over 10 days
  - 48% (MP1) and 26% (MP2) lower RMS values compared to BDS-2
  - No evidence for existence of elevation-dependent group delay biases



Satellite orbit and clock overlaps

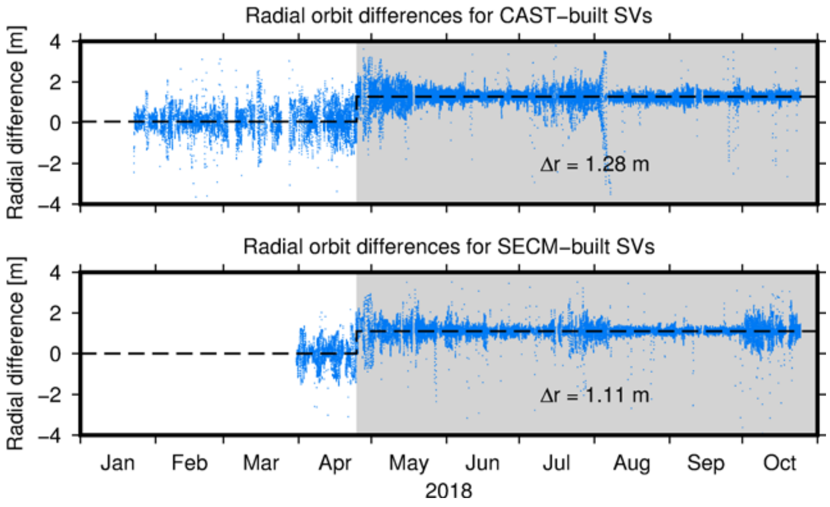
- Compute day-boundary orbit and clock differences as measure for consistency
- Total RMS of 1.0 m for orbit overlaps and 0.7 m for clock overlaps
  - 0.3 m in radial, 0.9 m in transversal, and 0.3 m in cross direction
- No substantial differences in overlap statistics between CAST and SECM SVs

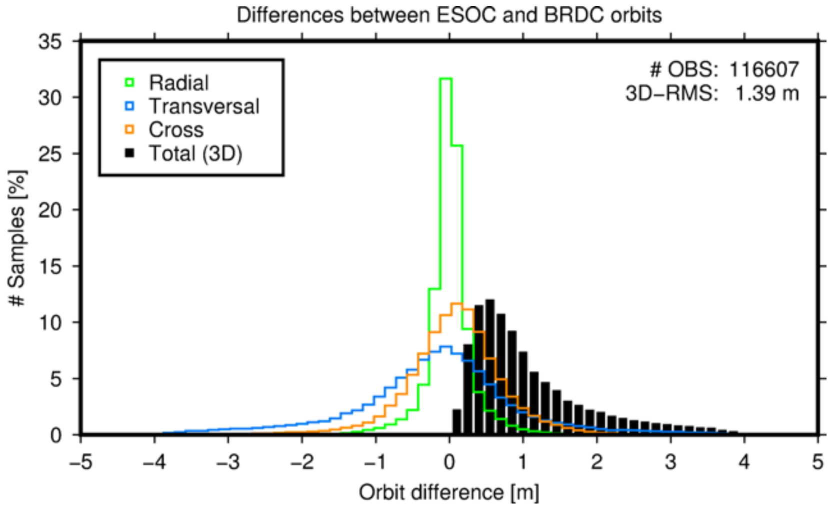




Comparison to broadcast ephemeris

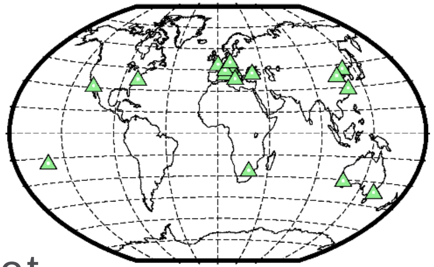
- Different orbit reference points to be taken into account
  - ESOC orbits ⇒ center of mass (COM), BRDC orbits ⇒ antenna phase center (APC)
  - Radial differences reveal broadcast antenna z-offsets ($z_{CAST} \approx 1.3$ m, $z_{SECM} \approx 1.1$ m)
  - Jump on April 25, indicating transition of BRDC orbits from COM to APC coordinates
- Overall 3D-RMS agreement of 1.4 m between ESOC and BRDC orbits

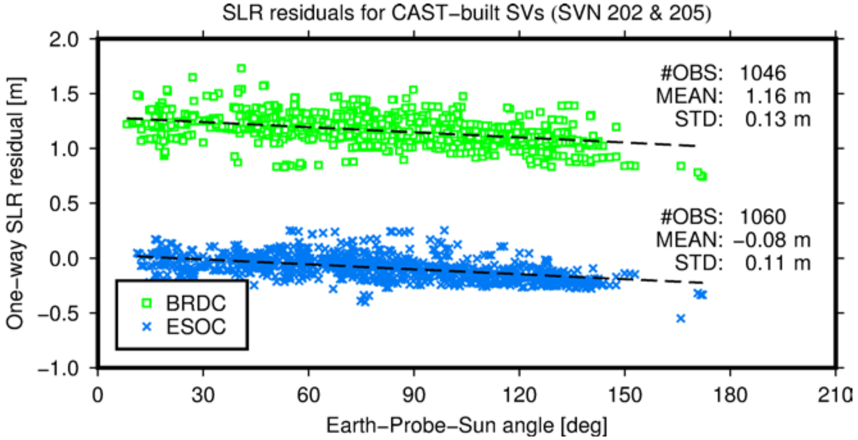


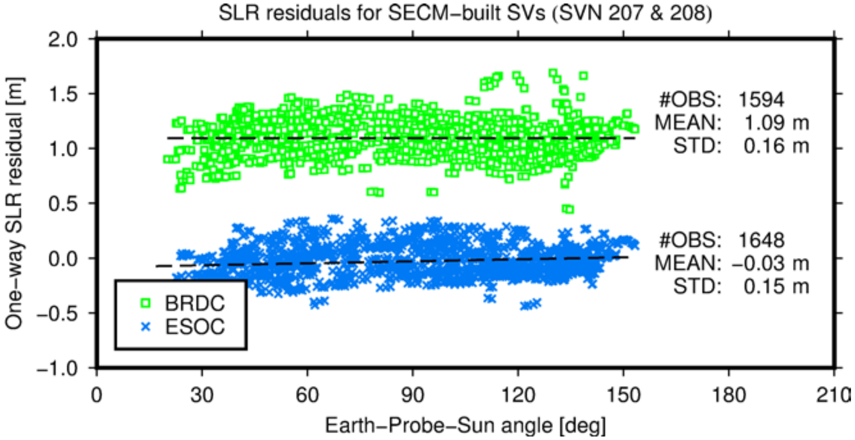


SLR residuals

- SLR normal point data for 4 SVs from 18 ILRS sites
- 1-way SLR residuals as measure for radial orbit accuracy
  - Total RMS over all stations/satellites of 0.14 m
- Linear trend for CAST SVs when plotted over EPS angle
  - Shows up for both ESOC and BRDC orbits
- 1-m SLR bias wrt BRDC orbits, confirming size of APC z-offset

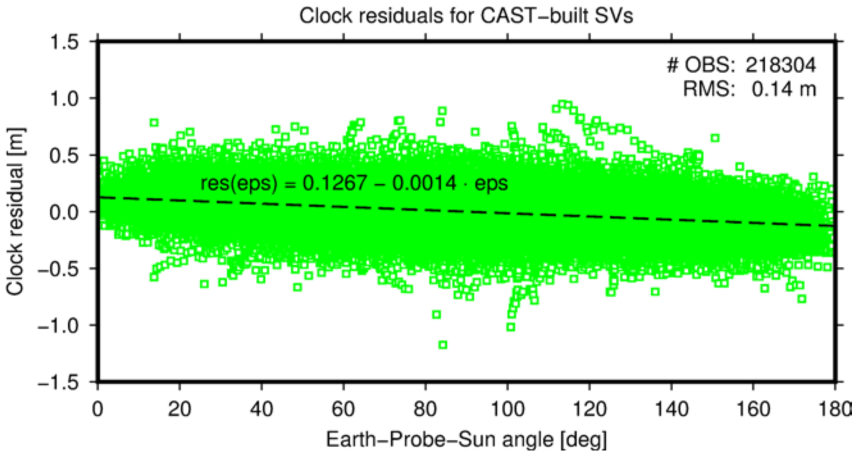


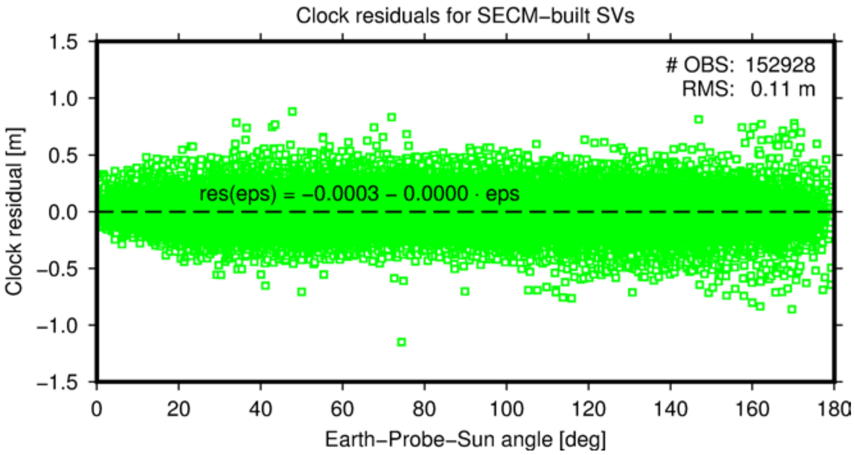




Satellite clock residuals

- Clock estimates after second-order fit as indicator for orbit modeling issues
- Once-per-rev signature in clock residuals of CAST SVs
  - Amplitude of up to ±0.1 m, depending on Sun elevation angle
  - Linear trend again when plotted over EPS angle, matching well with SLR residuals
  - Identifies the need for a “real” radiation model





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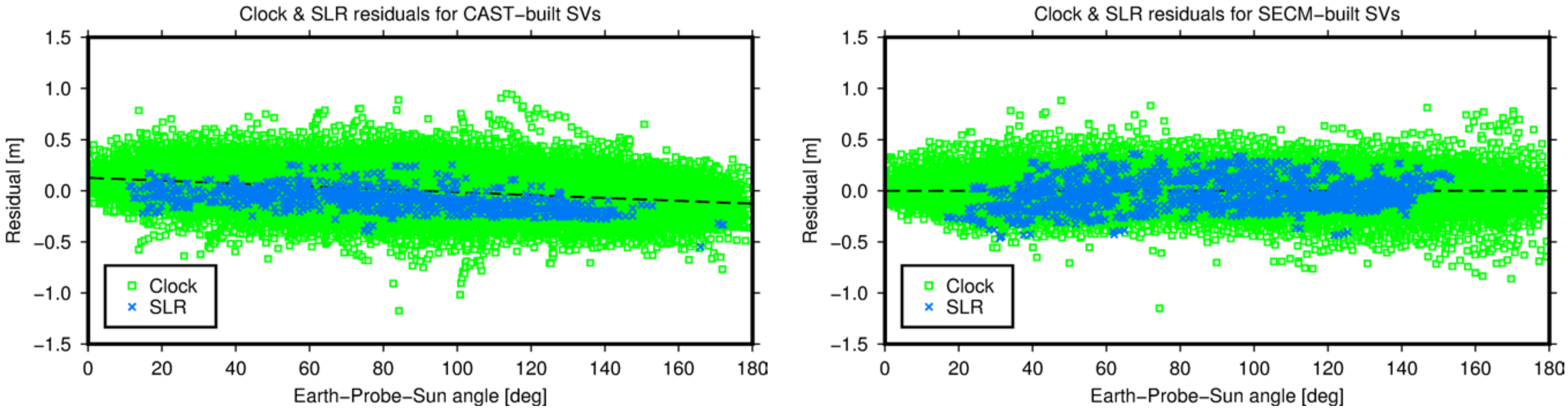
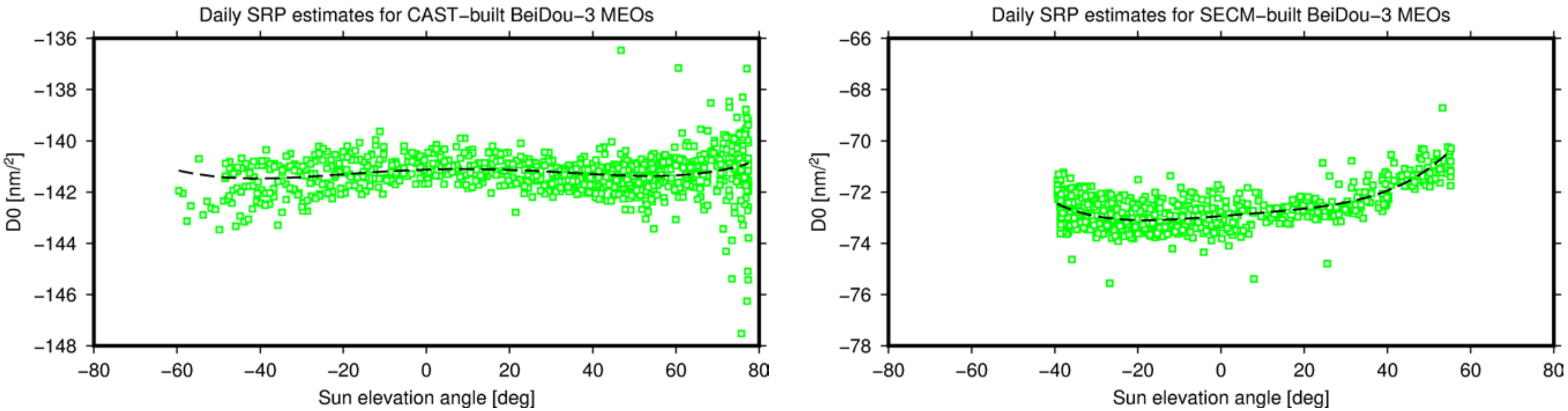


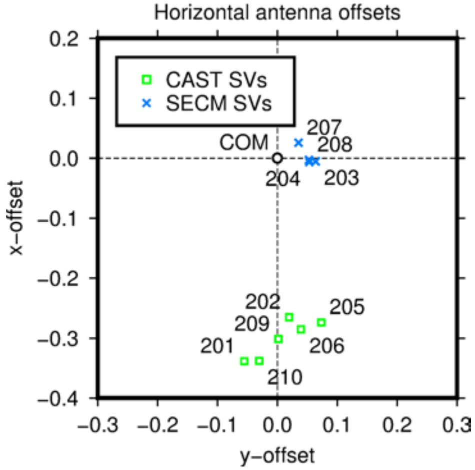
Solar radiation pressure estimates

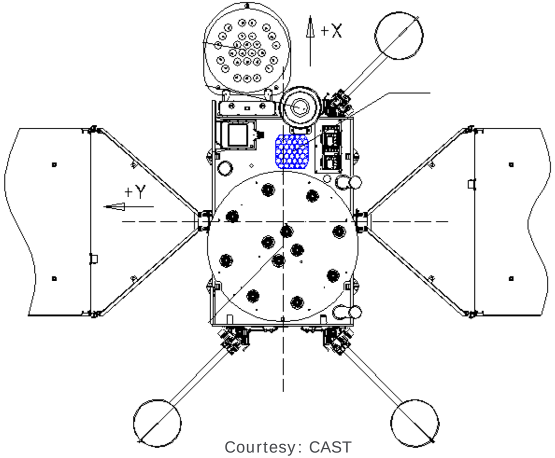
- SRP acceleration on CAST spacecraft twice as large as on SECM spacecraft
  - Mean D0 estimate for CAST and SECM SV of -141 nm/s² and -73 nm/s², respectively
  - Indicates approximately factor two larger solar array on CAST satellite (~ 27 m²)
  - Size of $D0_{SECM}$ fits well to weight and solar array size of SECM SV (Xia et al. 2018)
- Variation in D0 of only 1-2 nm/s² between low and high beta angles
  - Matches quite well the expectations (see "impact" factors on slide 4)



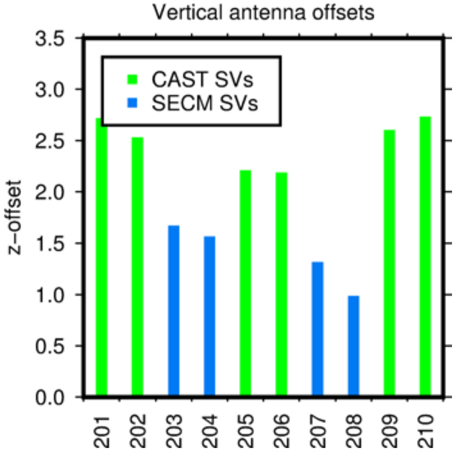
Satellite antenna offset estimates

- Estimated mean offset for CAST SV of (-0.3 m, 0.0 m, 2.5 m)
  - Transmit antenna array is clearly offset in x (see mechanical drawing)
  - z-offset doubtful as it places APC almost 2 m outside the physical bounds of the SV
- Estimated mean offset for SECM SV of (0.0 m, 0.0 m, 1.3 m)
  - z-offset matches well with broadcast z-offset but less well with manufacturer value (z = 0.73 m; Xia et al. 2018)





Courtesy: CAST



Summary and conclusions

- First orbits and clocks for “operational” BeiDou-3 series of SVs generated
  - Very preliminary solution – single frequency data, small network, simple orbit model, no integer ambiguity fixing
  - Systematics seen in SV clock & SLR residuals are indicative of expected orbit modeling issues
- Overlaps indicate 3D orbit accuracies better than 1 m (1-sigma)
  - Radial component accurate to better than 0.2 m according to SLR
- Differences between CAST- and SECM-built spacecraft identified
  - Solar array size
  - Antenna phase center location
- Pseudoranges less noisy and w/o elevation-dependent biases
  - No need for additional group delay corrections to resolve integer ambiguities

References

- Xia L, Baojun L, Yingchun L, Sujie X, Tao B (2018): Satellite Geometry and Attitude Mode of MEO Satellites of BDS-3 Developed by SECM. ION GNSS+, Miami, USA.
- http://spaceflight101.com/spacecraft/beidou-3
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