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# Validation and assessment of space debris orbits based on two-color and multi-static laser tracking data

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October 14, 2016

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# Outline

1. Available data from tracking campaigns
2. Orbit determination
3. TLE based data filtering and initialization
4. Validation
   a) Kinematic single-pass solutions
   b) Cross-validation
   c) Consistency bi-static ranges with mono-static data
5. Summary and next steps

# 1. Available data

## Tracking campaign 1

### Overview

| NORAD ID | WETTZELL | GRAZ | STUTTGART |
|---|---|---|---|
| 3230 | 2 | 1 | 0 |
| 4327 | 2 | 0 | 0 |
| 14372 | 2 | 0 | 1 |
| 14699 | 1 | 0 | 0 |
| 14820 | 1 | 0 | 0 |
| 15772 | 3 | 1 | 0 |
| 16182 | 3 | 0 | 1 |
| 16496 | 2 | 0 | 0 |
| 16792 | 0 | 1 | 0 |
| 17291 | 0 | 1 | 0 |
| 17589 | 1 | 0 | 0 |
| 19120 | 0 | 1 | 0 |
| 19573 | 3 | 0 | 1 |
| 19650 | 1 | 0 | 0 |
| 20466 | 1 | 0 | 0 |
| 21574 | 0 | 2 | 0 |
| 22285 | 1 | 0 | 0 |
| 23087 | 1 | 0 | 1 |
| 23405 | 1 | 0 | 0 |
| 23560 | 0 | 1 | 0 |
| 24953 | 1 | 0 | 0 |
| 25163 | 0 | 1 | 0 |
| 25263 | 0 | 1 | 0 |
| 25621 | 0 | 1 | 0 |
| 27386 | 1 | 2 | 2 |
| 28059 | 1 | 1 | 0 |
| 28931 | 0 | 1 | 0 |
| 36417 | 0 | 1 | 0 |
| 37390 | 0 | 1 | 0 |
| 37731 | 0 | 1 | 0 |
| 37789 | 0 | 1 | 0 |
| 38043 | 0 | 1 | 0 |

**August 13-27**

**32 objects** successfully tracked

**54 passes**

Mostly typical space debris objects
(~80% spent rocket bodies)

# 1. Available data

## Tracking campaign 2

### Overview (1)

| NORAD ID | WETTZELL | GRAZ | GRAZ(BI) | STUTTGART(BI) |
|---|---|---|---|---|
| 733 | 1 | 0 | 0 | 0 |
| 5560 | 7 | 1 | 0 | 4 |
| 8459 | 1 | 0 | 0 | 2 |
| 10967 | 1 | 1 | 0 | 0 |
| 14699 | 1 | 0 | 0 | 1 |
| 15483 | 2 | 1 | 0 | 2 |
| 16615 | 0 | 2 | 0 | 0 |
| 16792 | 1 | 0 | 0 | 0 |
| 16882 | 4 | 2 | 1 | 1 |
| 17129 | 0 | 1 | 0 | 0 |
| 17590 | 1 | 0 | 0 | 2 |
| 17973 | 4 | 1 | 0 | 3 |
| 18187 | 2 | 1 | 1 | 2 |
| 19650 | 1 | 0 | 0 | 1 |
| 20466 | 0 | 0 | 0 | 1 |
| 21088 | 1 | 0 | 0 | 0 |
| 21610 | 4 | 1 | 2 | 0 |
| 22220 | 5 | 3 | 2 | 1 |
| 22286 | 1 | 0 | 0 | 2 |
| 22566 | 4 | 4 | 2 | 3 |
| 22803 | 1 | 0 | 0 | 1 |
| 23088 | 6 | 2 | 2 | 3 |
| 23548 | 1 | 0 | 0 | 0 |
| 23705 | 1 | 0 | 0 | 3 |
| 24298 | 4 | 2 | 1 | 0 |
| 24946 | 1 | 0 | 0 | 1 |
| 24953 | 0 | 1 | 0 | 0 |
| 25407 | 2 | 1 | 0 | 5 |
| 25860 | 1 | 0 | 0 | 1 |
| 27386 | 1 | 2 | 1 | 4 |
| 28521 | 1 | 0 | 0 | 0 |
| 31793 | 2 | 0 | 0 | 4 |
| 36417 | 0 | 1 | 0 | 0 |
| 37731 | 0 | 1 | 0 | 0 |
| 39271 | 4 | 1 | 1 | 2 |

**September 7-14**

**35 objects** successfully tracked

(More than) **162 passes**

Mostly typical space debris objects
(~80% spent rocket bodies)

# 1. Available data

## Tracking campaign 2

### Overview (2)

7 objects , 67 passes

| NORAD ID | WETTZELL | GRAZ | GRAZ (BI) | STUTTGART (BI) |
|---|---|---|---|---|
| 16882 | 4 | 2 | 1 | 1 |
| 18187 | 2 | 1 | 1 | 2 |
| 22220 | 5 | 3 | 2 | 1 |
| 22566 | 4 | 4 | 2 | 3 |
| 23088 | 6 | 2 | 2 | 3 |
| 27386 | 1 | 2 | 1 | 4 |
| 39271 | 4 | 1 | 1 | 2 |

- Objects for which all “types“ of observations are available

- Black background indicates favourable temporal distribution of data

- All objects are rocket bodies except 27386 = Envisat (some pre-processing issues to be solved)

# 1. Available data

## Tracking campaign 2

### Temporal distribution (1)

| 16882 | 07.Sep | 08.Sep | 09.Sep | 10.Sep | 11.Sep | 12.Sep | 13.Sep | 14.Sep |
|---|---|---|---|---|---|---|---|---|
| Wettzell | | | | | X | X | X | X |
| Graz | | | | | | | X | X |
| Grazbi | | | | | | | | X |
| Stuttgartbi | | | | | | X | | |

| 18187 | 07.Sep | 08.Sep | 09.Sep | 10.Sep | 11.Sep | 12.Sep | 13.Sep | 14.Sep |
|---|---|---|---|---|---|---|---|---|
| Wettzell | | | | X | | | | X |
| Graz | | | | | | | | X |
| Grazbi | | | | | | | | X |
| Stuttgartbi | | | X | | | | | X |

| 23088 | 07.Sep | 08.Sep | 09.Sep | 10.Sep | 11.Sep | 12.Sep | 13.Sep | 14.Sep |
|---|---|---|---|---|---|---|---|---|
| Wettzell | XX | X | X | | | | X | X |
| Graz | | | | | | | X | X |
| Grazbi | | | | | | | X | X |
| Stuttgartbi | X | | X | | | | | |

| 39271 | 07.Sep | 08.Sep | 09.Sep | 10.Sep | 11.Sep | 12.Sep | 13.Sep | 14.Sep |
|---|---|---|---|---|---|---|---|---|
| Wettzell | XX | X | X | | | | | X |
| Graz | | | | | | | | X |
| Grazbi | | | | | | | | X |
| Stuttgartbi | | X | X | | | | | |

# 1. Available data

## Tracking campaign 2

### Temporal distribution (2)

| 22220 | 09.Sep | 10.Sep | 11.Sep | 12.Sep | 13.Sep | 14.Sep |
|---|---|---|---|---|---|---|
| Wettzell | X | | X | X | X | X |
| Graz | | | | X | X | X |
| Graz bi | | | | | X | X |
| Stuttgart bi | | | | X | | |

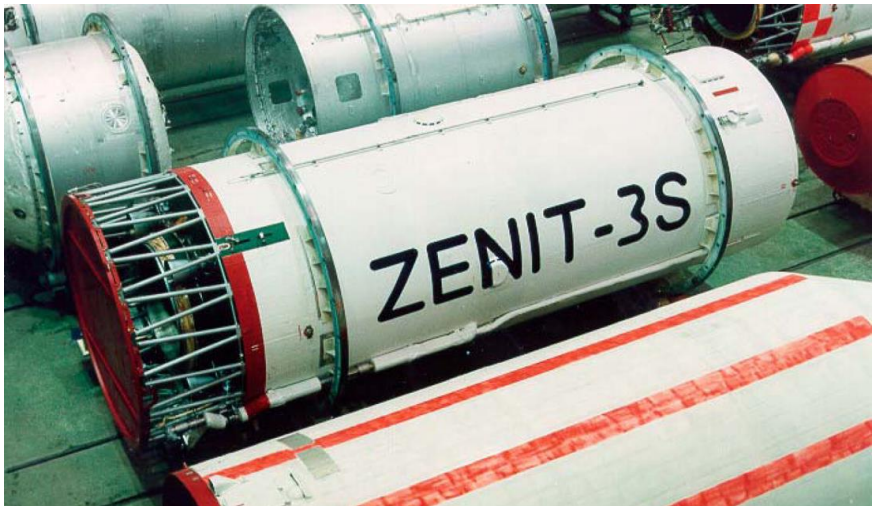
Near-circular ~800 km orbits

| 22566 | 09.Sep | 10.Sep | 11.Sep | 12.Sep | 13.Sep | 14.Sep |
|---|---|---|---|---|---|---|
| Wettzell | | | | X | XX | X |
| Graz | | | | X | X | XX |
| Graz bi | | | | | X | X |
| Stuttgart bi | | | | X | X | X |

Successful multi-static tracking campaign

# 1. Available data

## Object characteristics




SL-16 R/Bs (Zenit second stages)

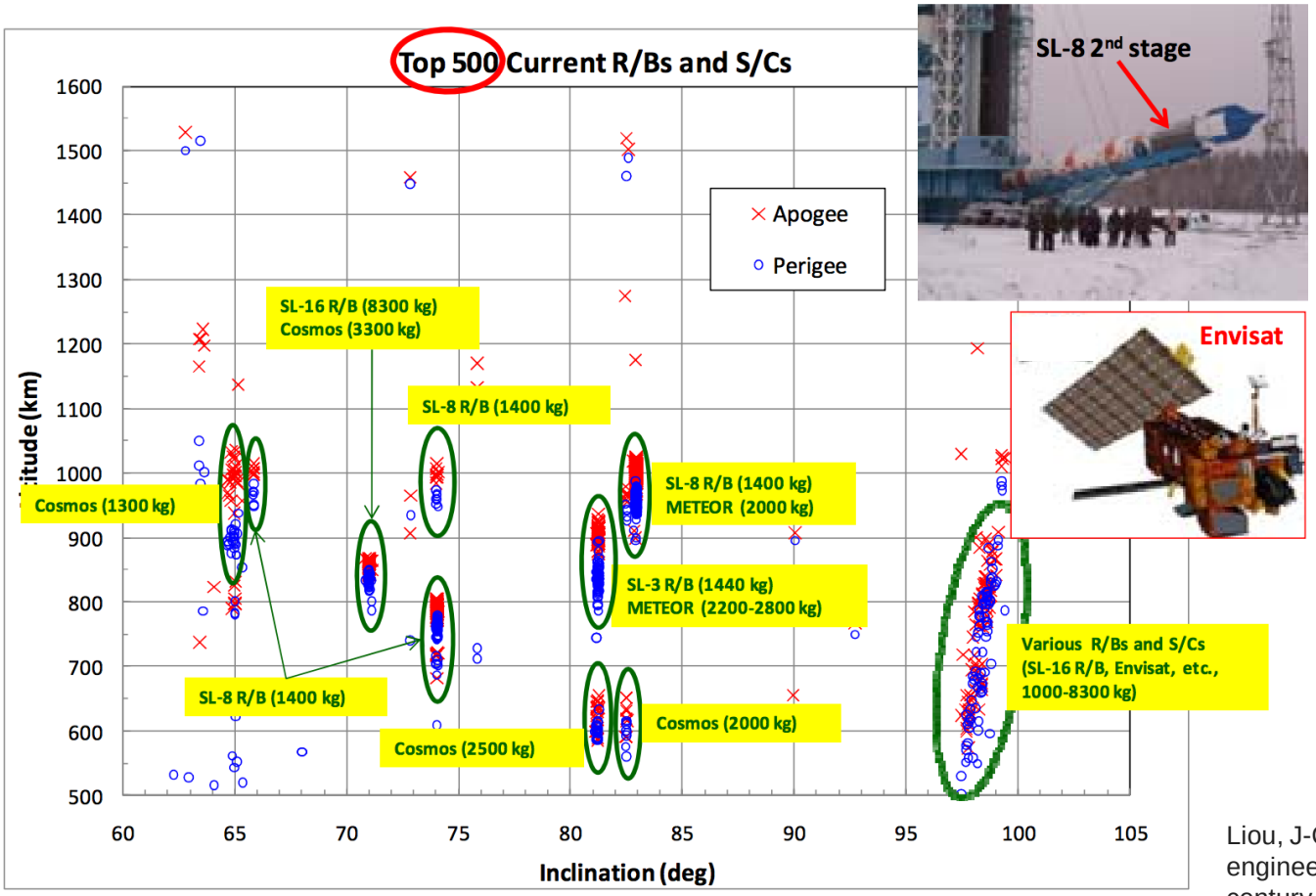
| | |
|---|---|
| Diameter | 3.9 m |
| Length | 10.4 m |
| Dry mass | 8300 kg |


SL-8 R/Bs (Kosmos 3M second stages)

| | |
|---|---|
| Diameter | 2.4 m |
| Length | 6.0 m |
| Dry mass | 1400 kg |

# 1. Available data

## Object relevance










Liou, J-C. "Active debris removal-a grand engineering challenge for the twenty-first century." (2011).

# 2. Orbit determination

**Estimated parameters in orbit determination process:**

1. 6-elements state vector
2. Atmospheric drag coefficient (Cd)
3. Solar radiation pressure coefficient (Cr)
4. Station range biases
5. Station clock offsets for bi-static ranging data

Depending on amount and distribution of data

**Not estimated:**

1. Empirical accelerations → reliance on dynamics model
2. Time dependent station range biases (assumed constant)

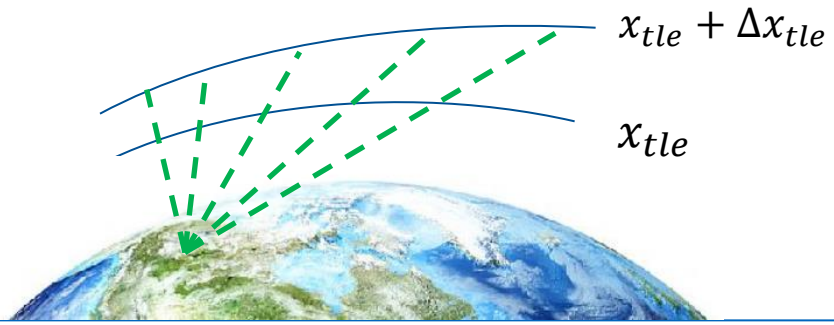
**Force models:** Higher-order gravity, aerodynamic drag (DTM-2000), solar radiation pressure, luni-solar perturbations (DE-430), solid Earth tides, Albedo

# 3. TLE based data filtering and initialization (1)

1. Noisy bi-static ranging data
2. Very inaccurate TLE data (sometimes too far from true orbit to initialize orbit determination → local minima)
3. TLE data improvement based on single-pass tracking data → kinematic single-pass solutions

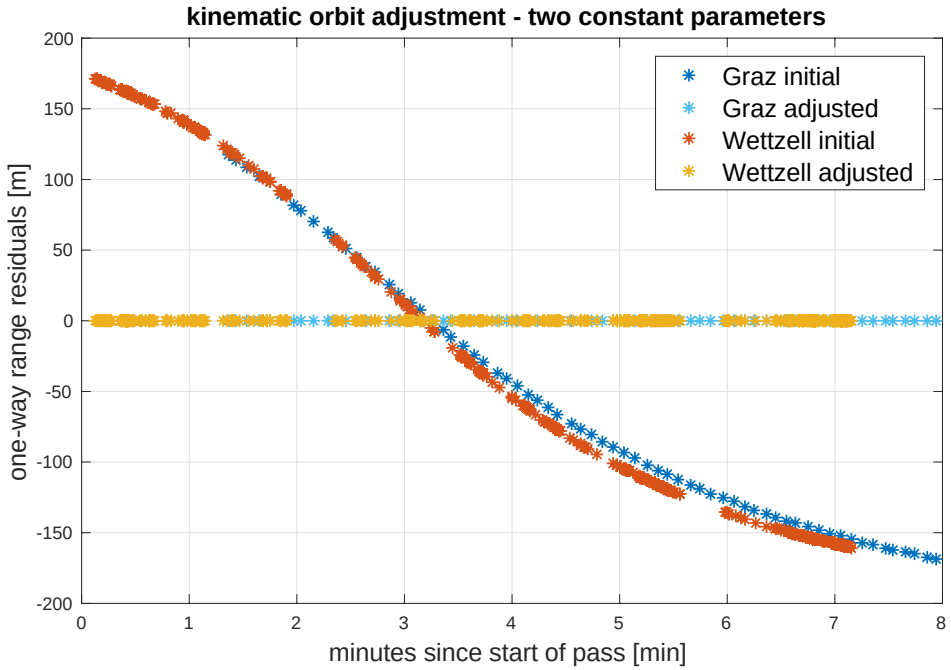
$$\Delta x_{tle}(t) = \vec{R}(t) \cdot p_R(t - t_0) + \vec{I}(t) \cdot p_I(t - t_0) + \vec{C}(t) \cdot p_C(t - t_0)$$

$$p_R(t - t_0) = a_{R,0} + a_{R,1}(t - t_0) + a_{R,2}(t - t_0)^2 + \ldots$$



# 3. TLE based data filtering and initialization (2)

→ Basis for noise filtering (2.x-sigma clipping)
→ Used to initialize orbit determination
→ Validation of high frequency components (jitter, noise, object shape,...)




→ Derivation of force model coefficients from historical TLEs (if not estimated)

# 4. Validation

Assessment of post-fit residuals

1. Kinematic single-pass solutions

   → noise and high-frequency signal components

2. Cross validation (consistency of omitted data with orbit)

   → range prediction accuracy

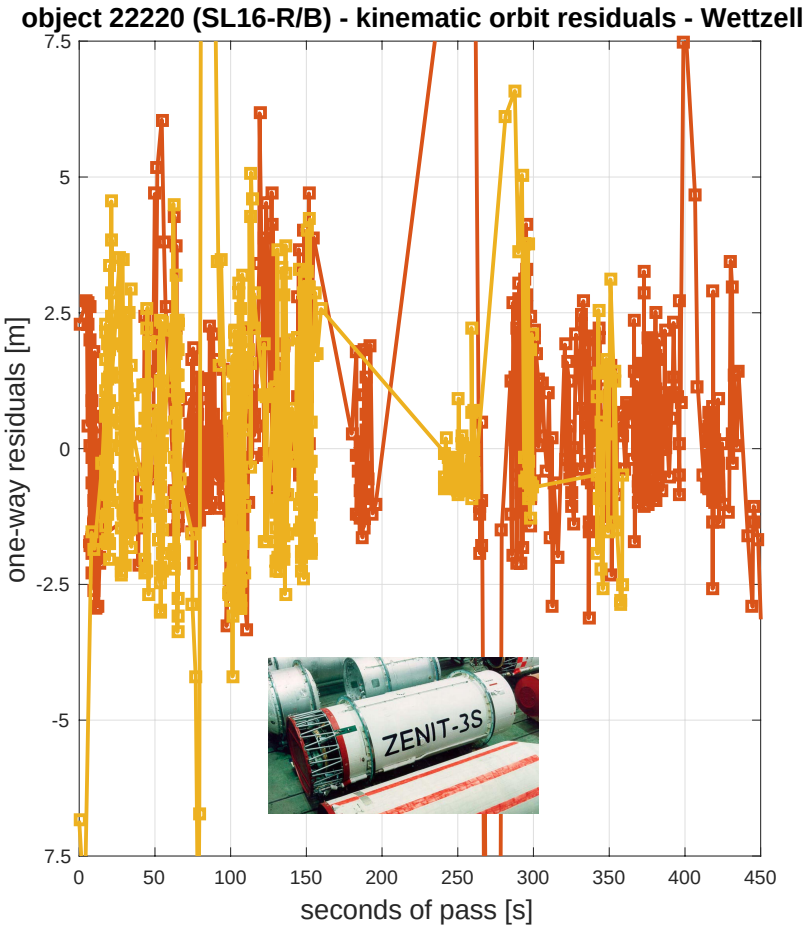
3. Bi-static range residuals (incl. station clock offset estimation)

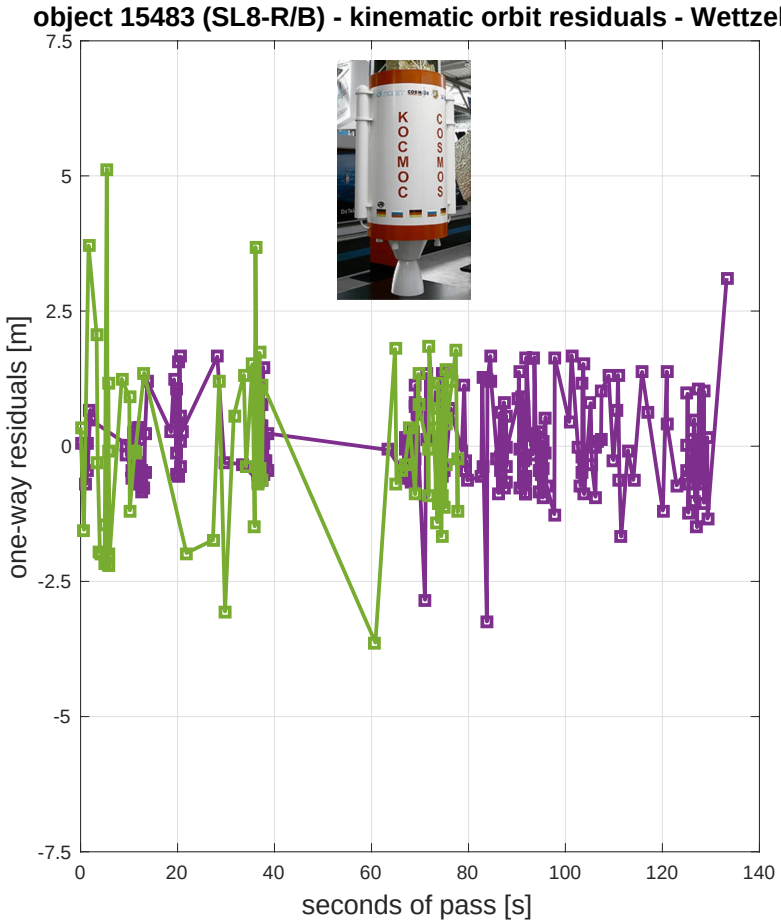
   → consistency with mono-static ranging data

# 4. Validation

## Kinematic orbits

### Post-fit residuals (Wettzell)

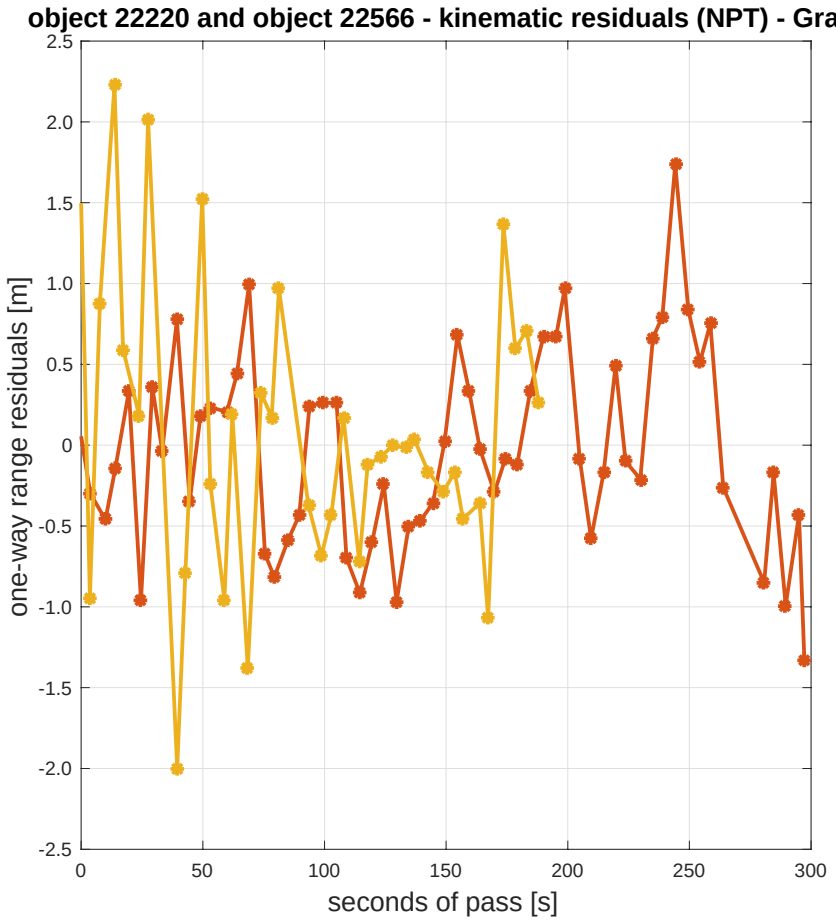


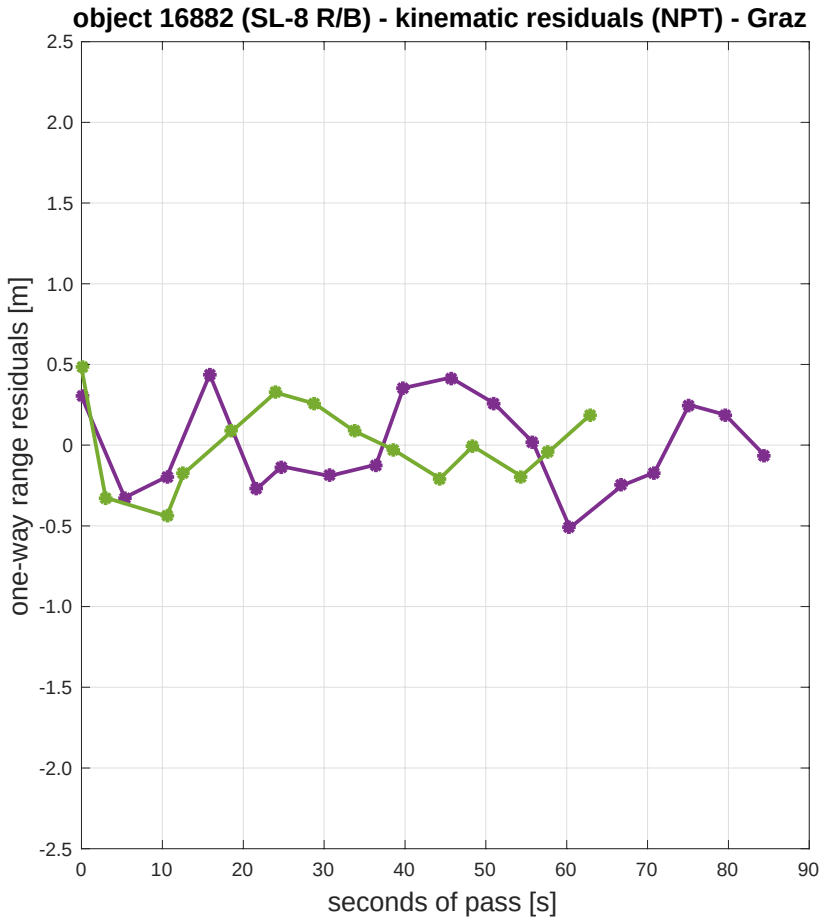



# 4. Validation

## Kinematic orbits

### Post-fit residuals (Graz)



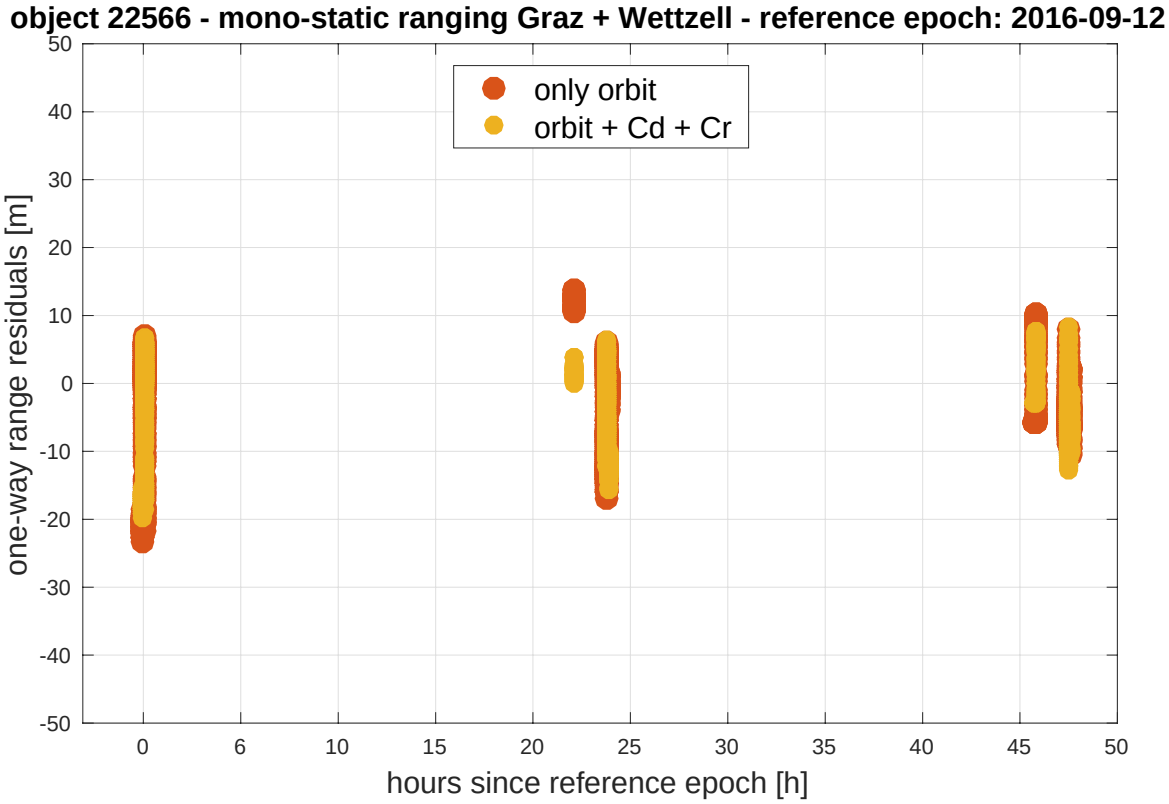



# 4. Validation

## Reference solution (mono-static data)

### Post-fit residuals (1)

| 22566 | 12.Sep | 13.Sep | 14.Sep |
|---|---|---|---|
| Wettzell | X | XX | X |
| Graz | X | X | XX |



# 4. Validation

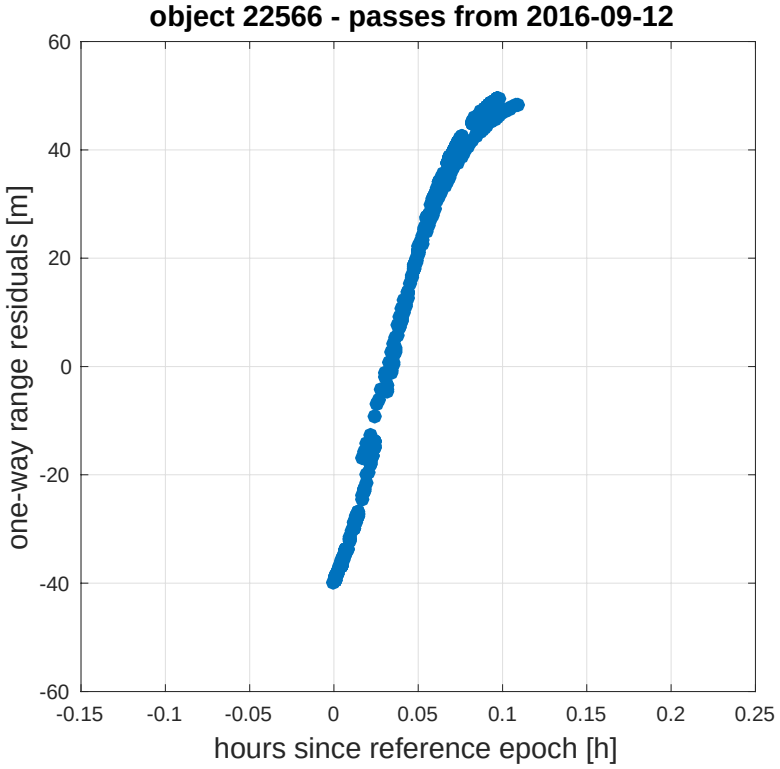
## Cross-validation (mono-static data)

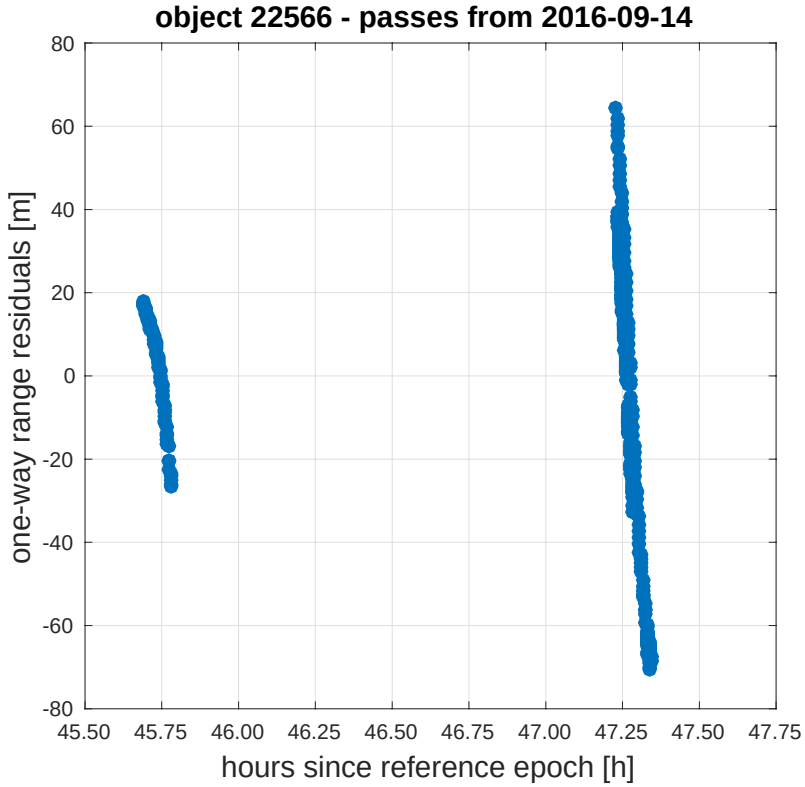
### Post-fit residuals (2)

cross-validation

| 22566 | 12.Sep | 13.Sep | 14.Sep |
|---|---|---|---|
| Wettzell | X | XX | X |
| Graz | X | X | XX |

cross-validation



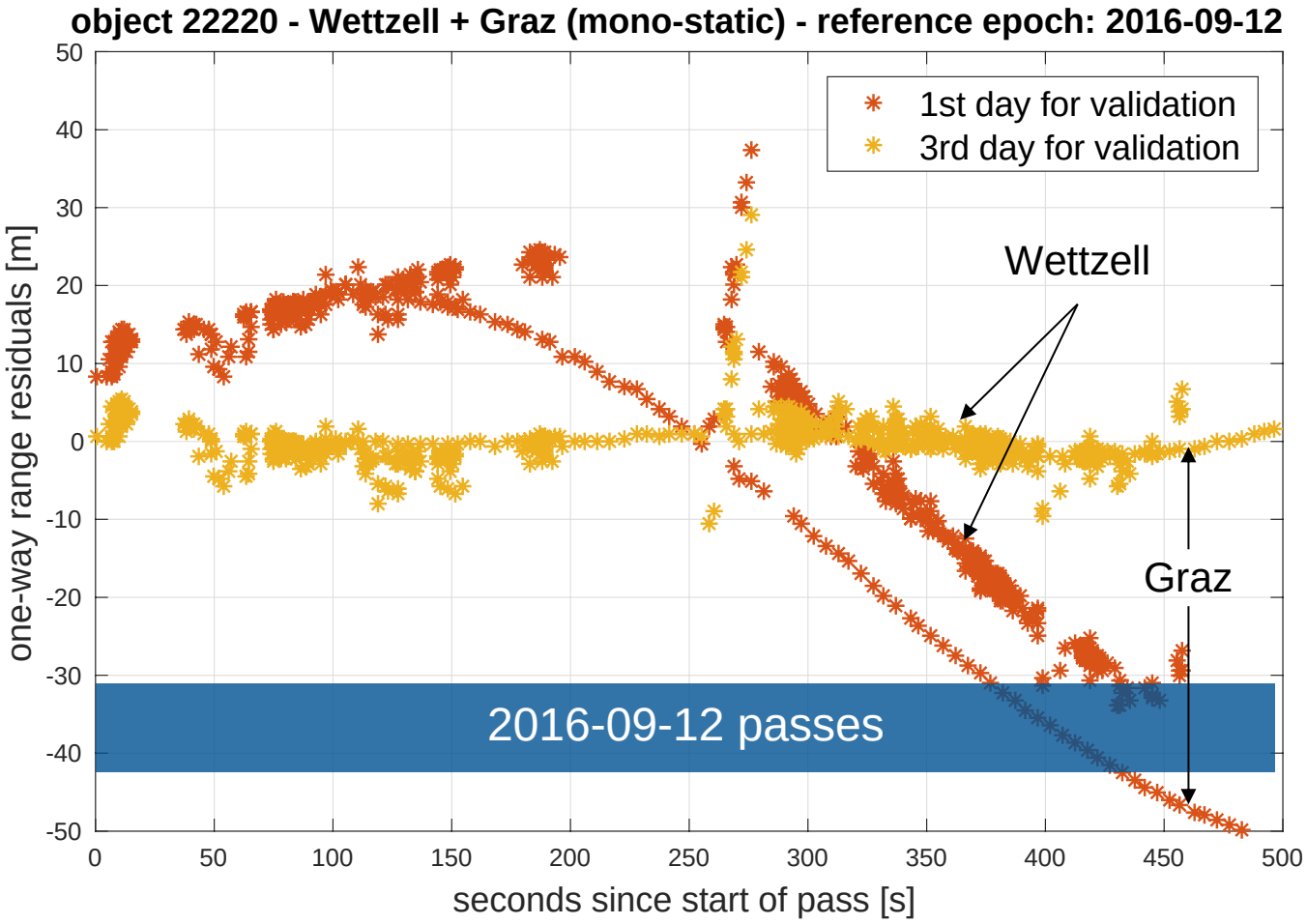
# 4. Validation

## Cross-validation (mono-static data)

### Post-fit residuals (3)

| 22220 | 12.Sep | 13.Sep | 14.Sep |
|---|---|---|---|
| Wettzell | X | X | X |
| Graz | X | X | X |

| 22220 | 12.Sep | 13.Sep | 14.Sep |
|---|---|---|---|
| Wettzell | X | X | X |
| Graz | X | X | X |

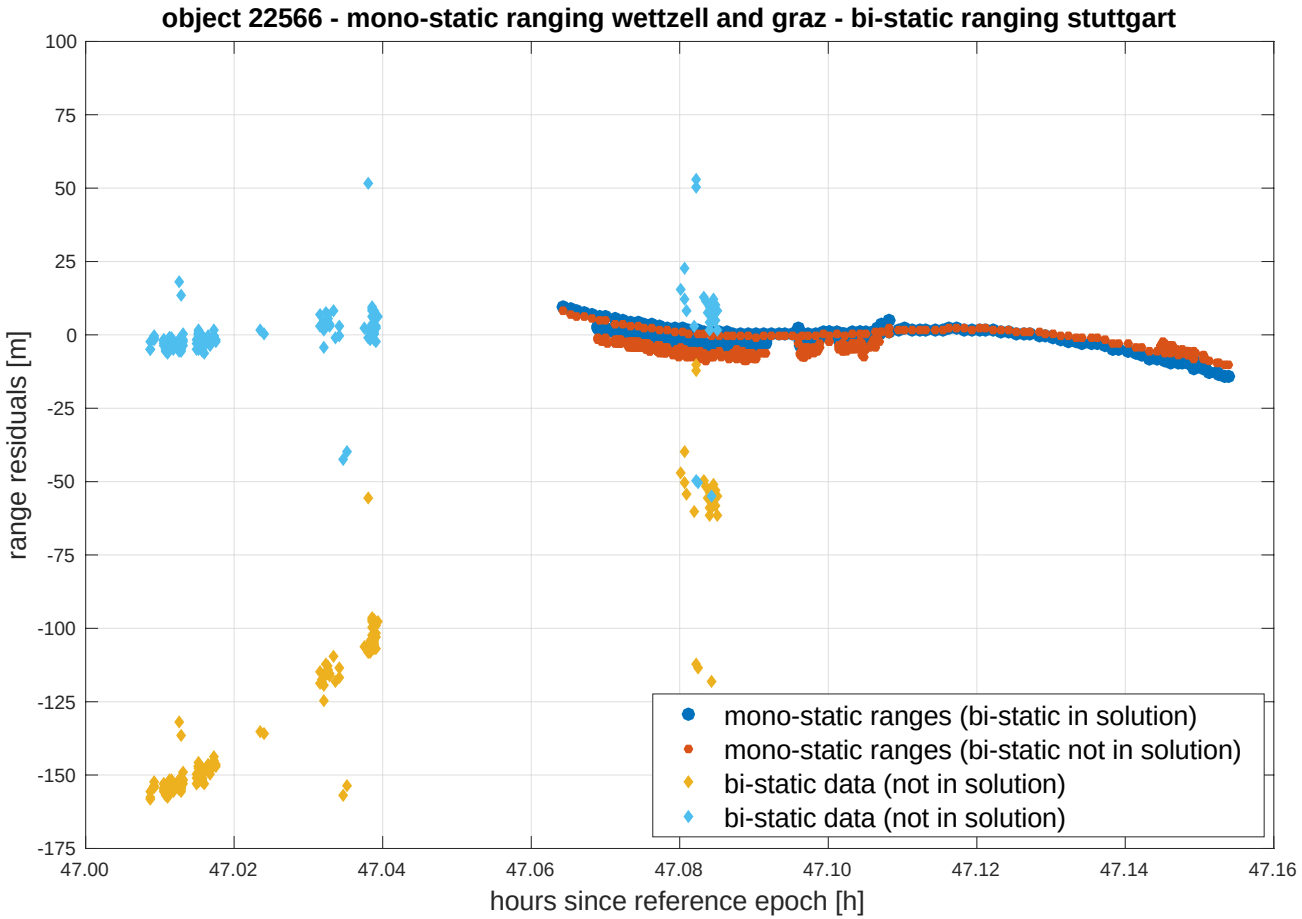


# 4. Validation

## Bi-static data issues

### Bi-static range residuals - Stuttgart (1)

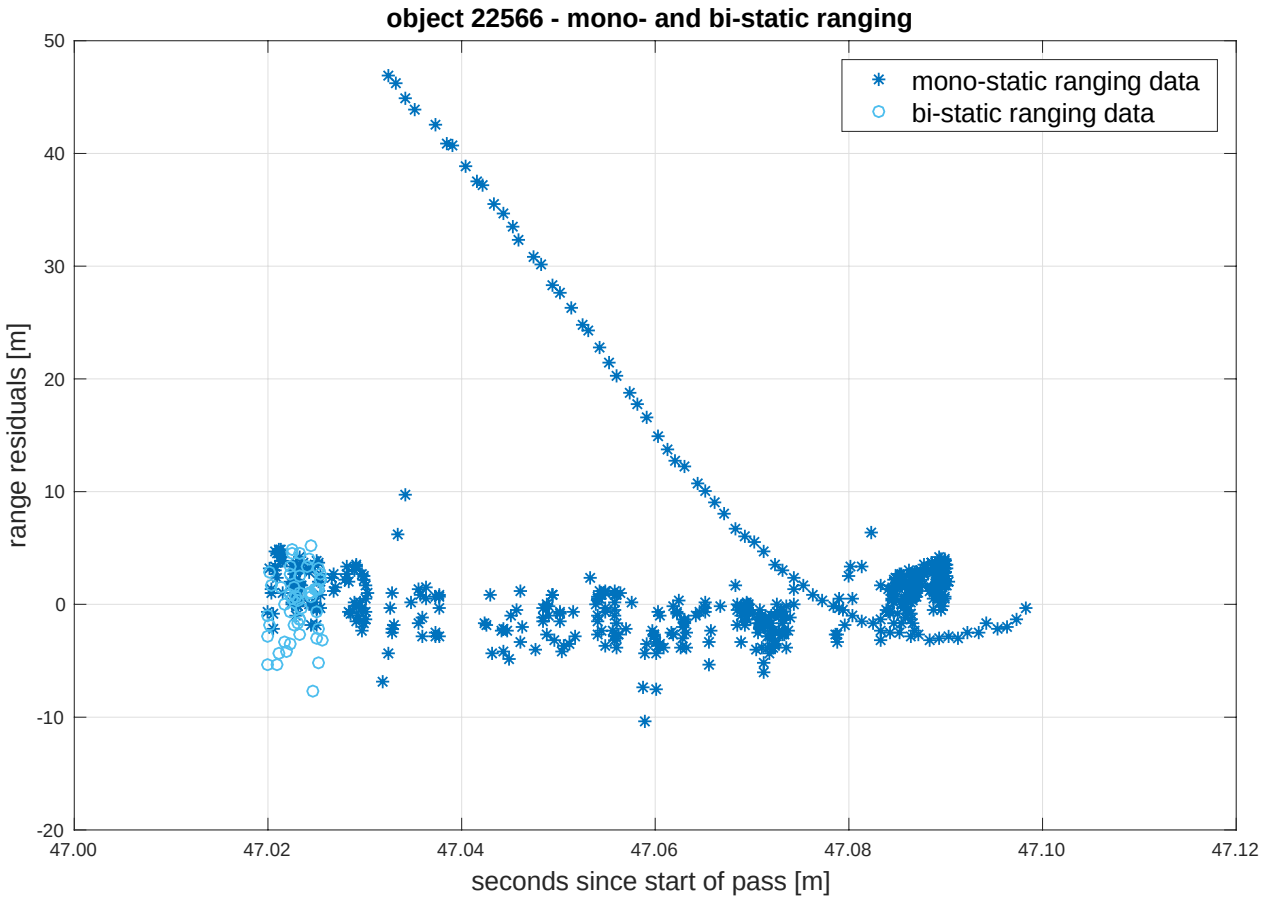
| 22566 | 12.Sep | 13.Sep | 14.Sep |
|---|---|---|---|
| Wettzell | X | XX | X |
| Graz | X | X | XX |
| Stuttgart bi | X | X | X |



# 4. Validation

## Bi-static data issues

### Bi-static range residuals - Stuttgart (2)



# 5. Summary and next steps

**Summary**

1. Useful data available for validation activities from two tracking campaigns
2. One-way ranging “noise“ within expected bounds
3. Data is suitable for orbit determination and prediction as indicated by first validation tests

**Next steps:**

- GNSS-based clock synchronization  and data filtering of bi-static data from Graz
- More tests with bi-static data / understanding the effects seen in first processing
- Assessing the benefits from multi-static tracking
- Further cross-validation tests; also for objects with less data
- Processing Envisat data and validation w.r.t. to external reference orbit