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Relative Navigation to Non-cooperative Targets in LEO: Achievable Accuracy from Radar Tracking Measurements

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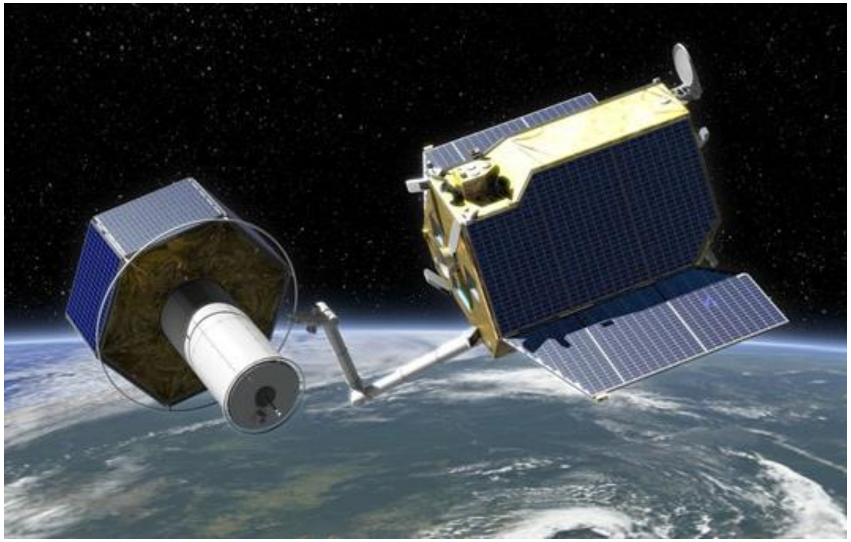
DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

Motivation

Any future ***space debris removal*** or ***on-orbit servicing mission***
to a non-cooperative target
faces the problem of the initial relative orbit determination.

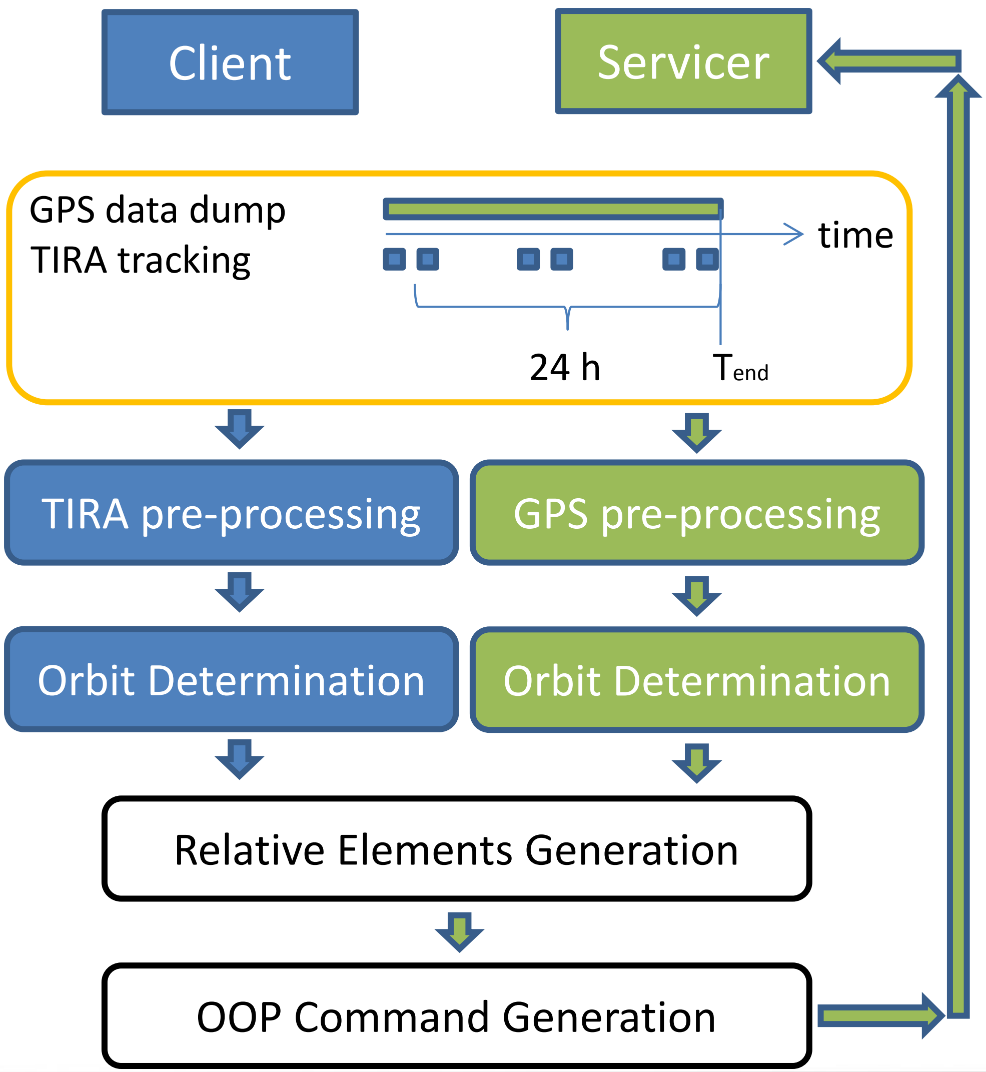
Study objectives:

- How accurately can the relative orbit be determined from the ground by means of Client radar tracking?
- What are the requirements on the radar tracking campaign?

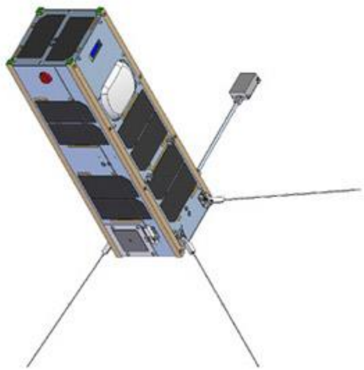


The German on-orbit servicing demonstration mission DEOS

Far Range Navigation Concept



CanX-2 Radar Tracking Campaign



CanX-2 [UTIAS]

CanX-2:

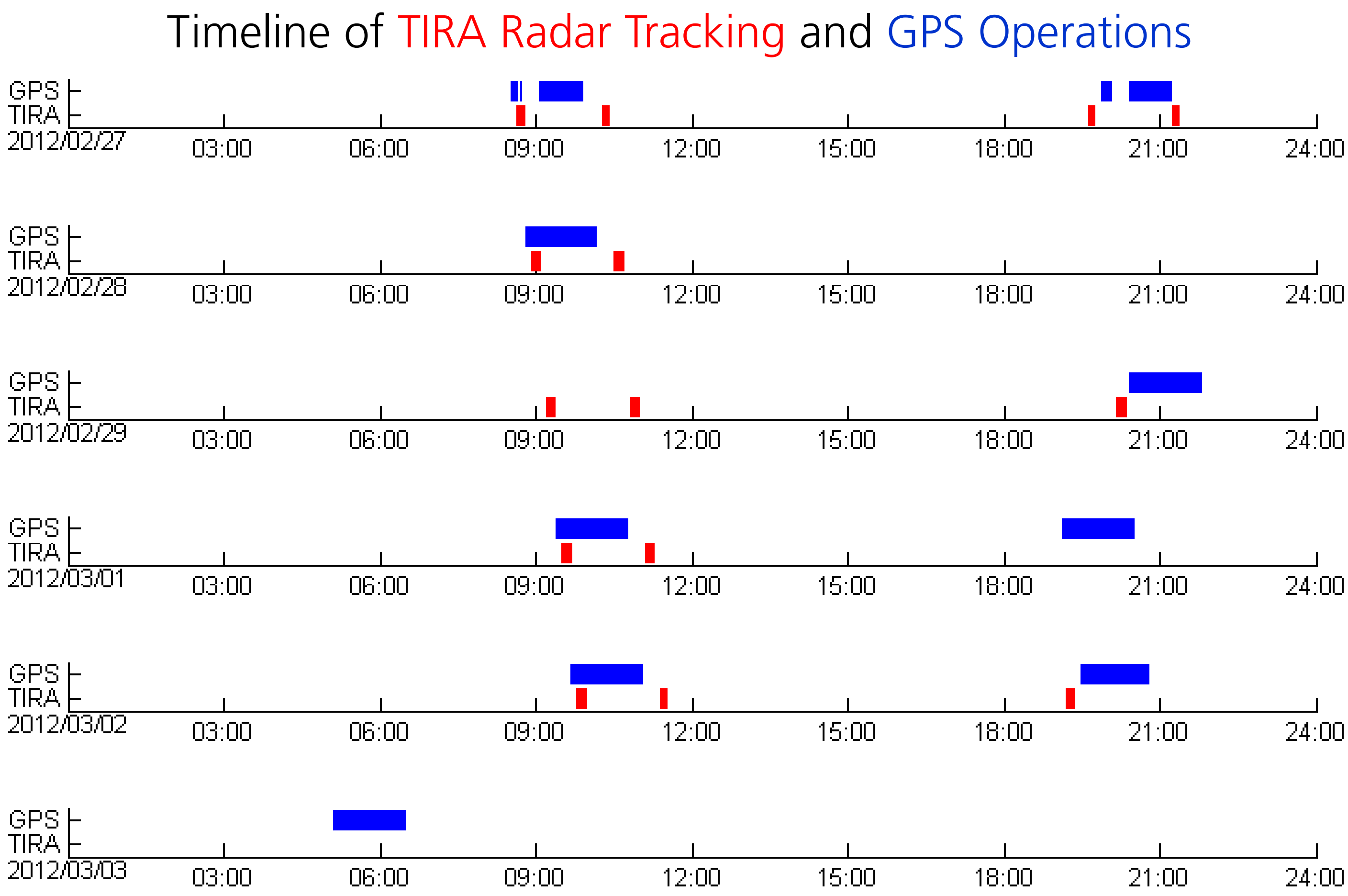
- Triple CubeSat with dimensions 10 x 10 x 34 cm
- Carries a NovAtel OEM4-G2L dual frequency GPS receiver
- Built under the Canadian Advanced Nanospace eXperiment (CanX) program and operated by the University of Toronto
- Sun-synchronous polar orbit with a 635km altitude

Tracking and Imaging Radar (TIRA):

- Fraunhofer Institute for High Frequency Physics and Radar Techniques (FHR), Wachtberg, Germany
- 34-meter parabolic antenna system
- Narrowband, fully coherent mono-pulse tracking radar at L-band (1.333 GHz)
- Wideband Ku-band imaging radar

TIRA [FHR]

CanX-2 Radar Tracking Campaign



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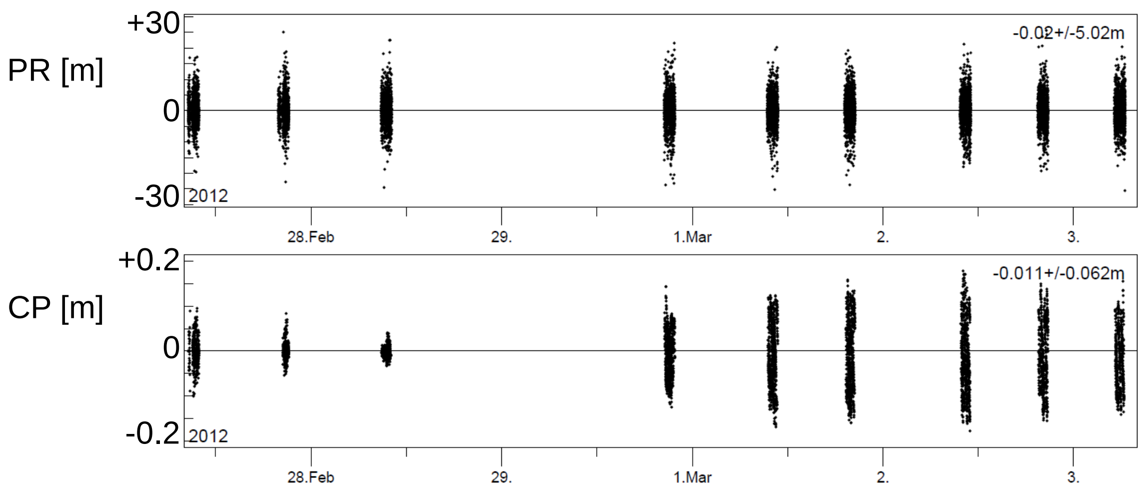
Precise Reference Orbit from CanX-2 GPS measurement

- NovAtel OEM4-G2L dual frequency GPS receiver provides pseudo range (PR) and carrier phase (CP) raw measurements
- Use of DLR/GSOC's Reduced Dynamics Orbit Determination Software
- Estimated reference orbit accuracy: 1 m (RMS) in the radial and cross-track components and 5 m in the along-track component



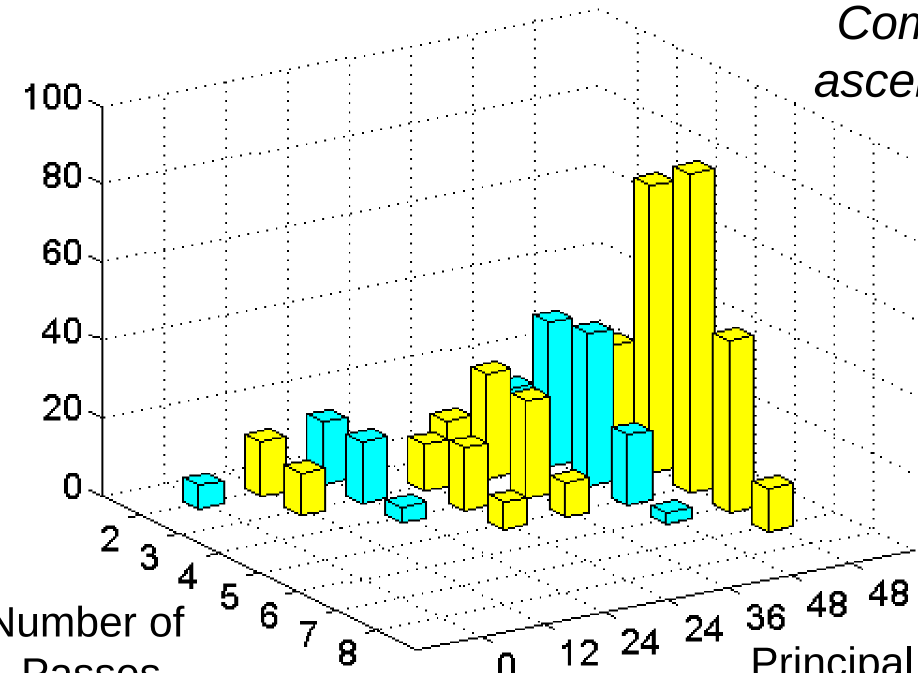
Least squares GPS observation residuals

[Kirschner, M., et al, "Orbit Precision Analysis of Small Man-made Space Objects in LEO Based on Radar Tracking Measurements", 23rd ISSFD, 29 Oct - 2 Nov 2012, Pasadena, CA, USA.]

Statistical Orbit Determination Analysis Methodology

1) Systematic combination of 2-8 radar tracking passes within 48 hours
2) Orbit determination for 529 cases
3) Orbital element errors w.r.t. GPS reference orbit at end of tracking interval
4) Mean and standard deviation for identical tracking scenarios

Combination of radar passes on ascending/descending orbital arcs

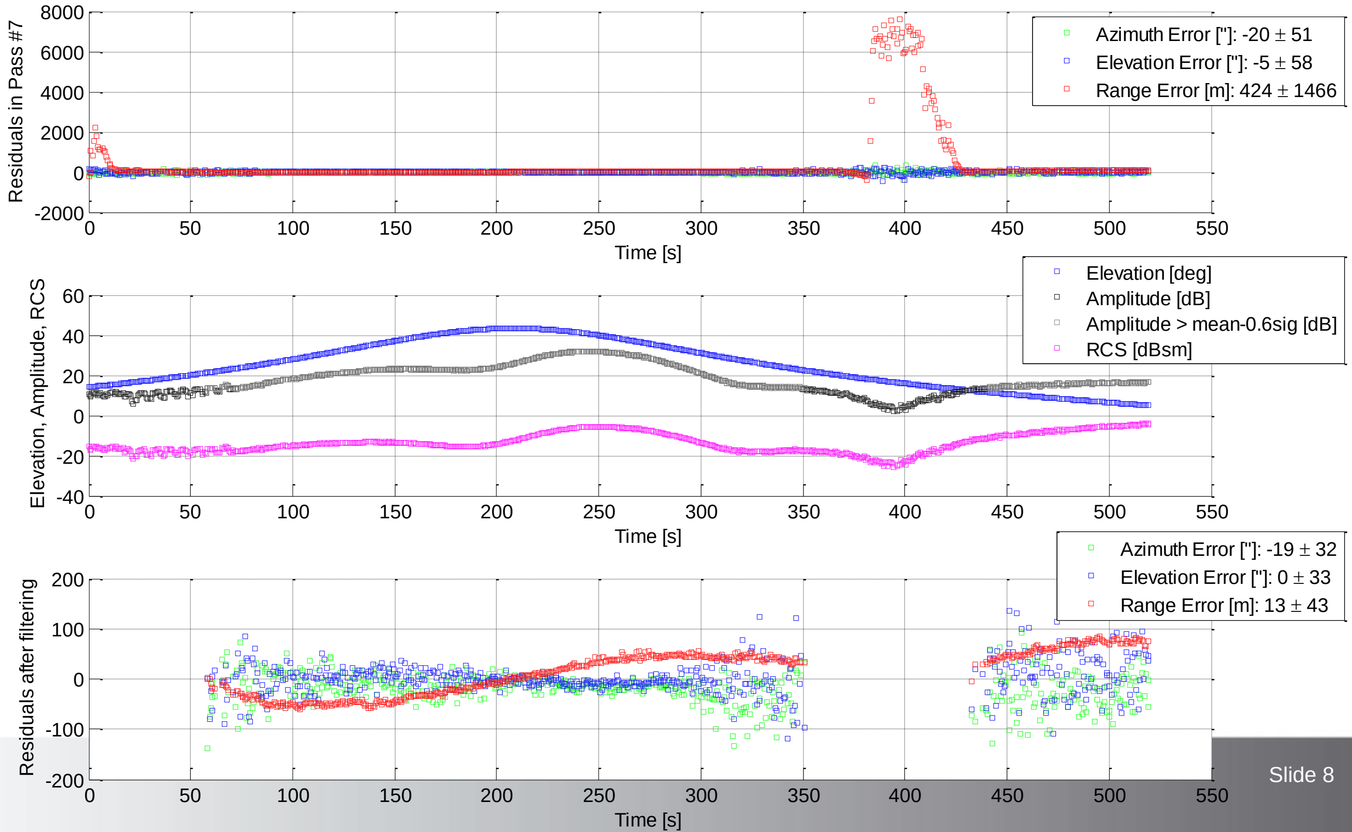


Client Orbit Determination from Radar Tracking Data

Use of DLR/GSOC's ODEM software

- Dynamic modeling: 60 x 60 geo-potential, third bodies sun & moon, solar radiation pressure, atmospheric drag
- Measurements: Range, azimuth and elevation angles
- Additional estimation: Drag coefficient, constant measurement bias

Pre-processing:



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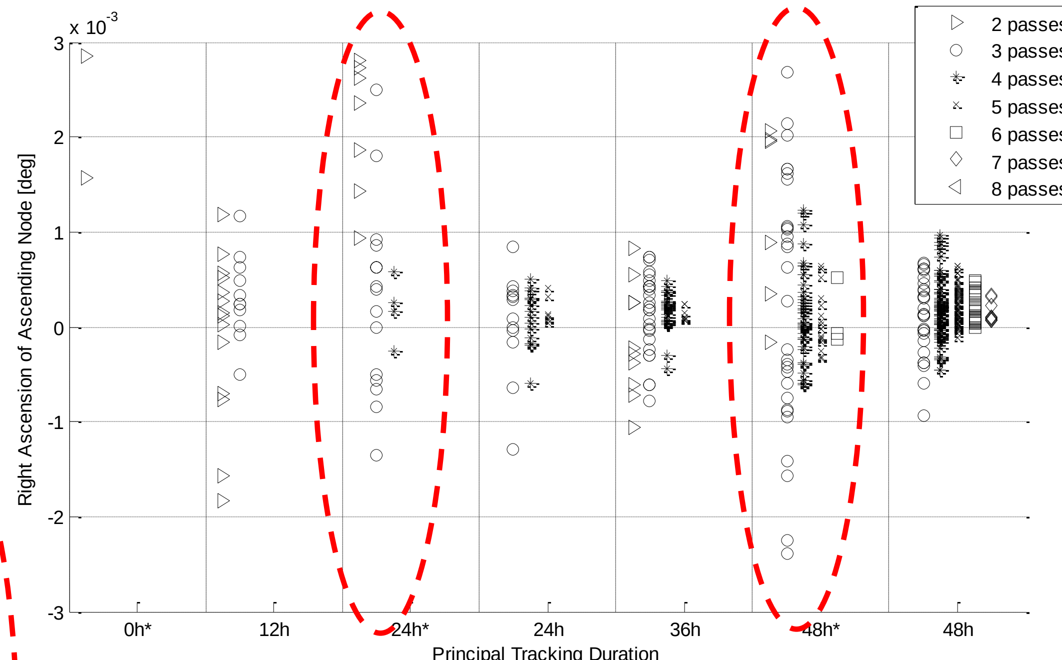
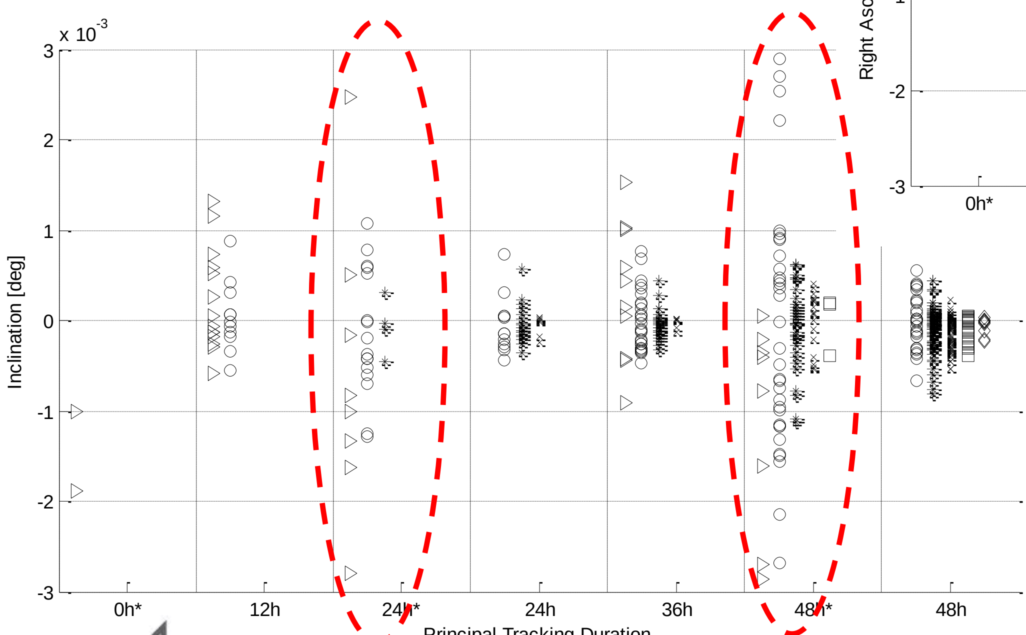
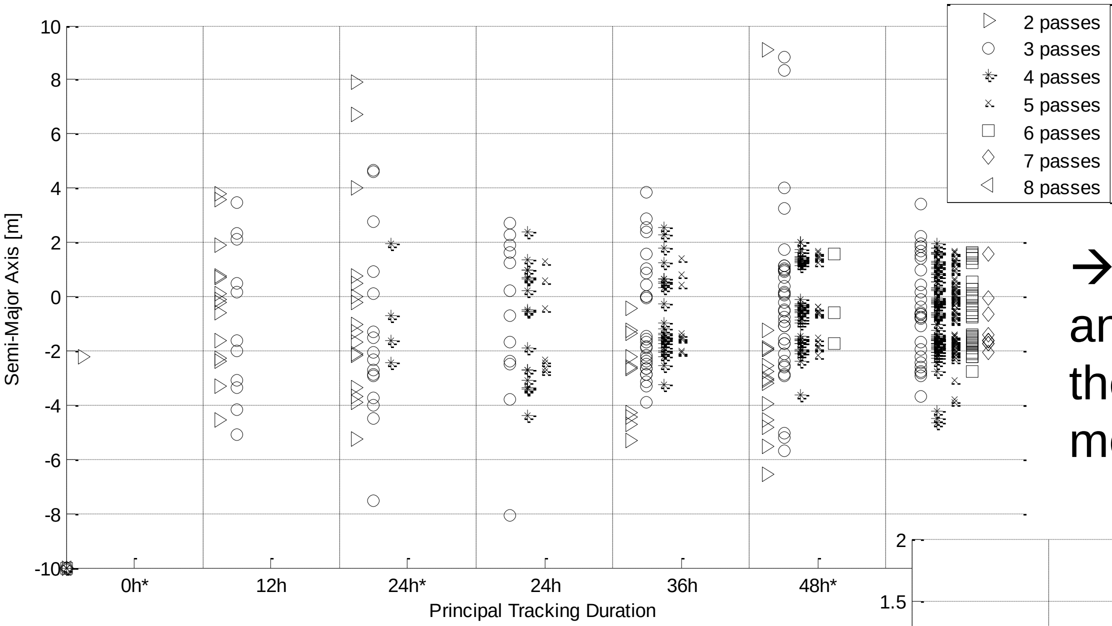
Radar Tracking - Orbit Determination Results

→ Large errors for exclusive combinations of ascending or descending tracking passes (0h*, 24h*, 48h*)

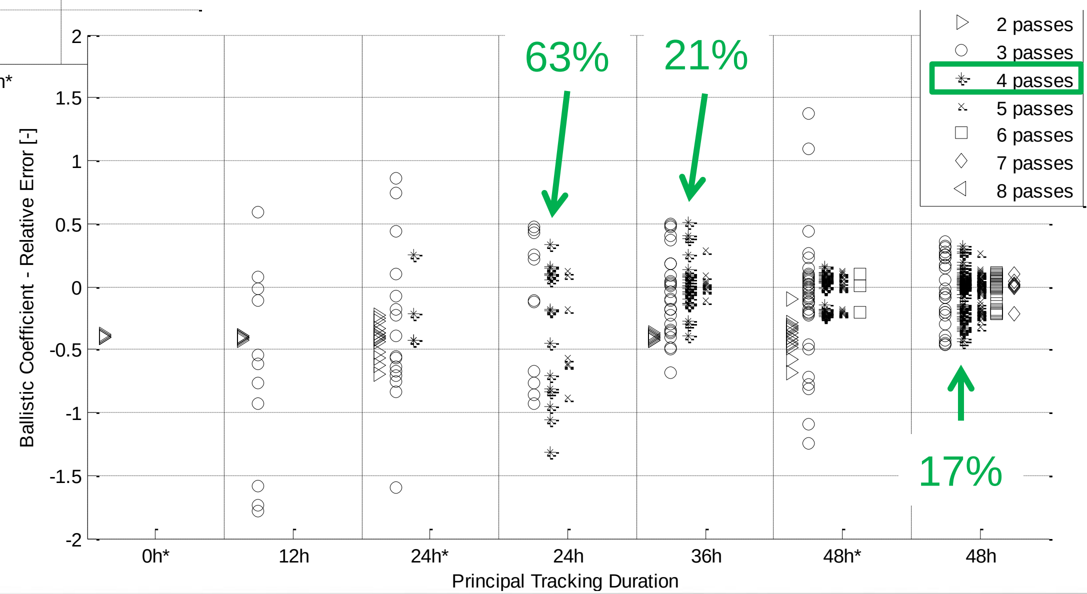




Radar Tracking - Orbit Determination Results (cont.)



→ With increasing tracking arc length and increasing number of passes the ballistic coefficient is determined more accurately



Expected Relative Orbital Element Accuracy

Example mission characteristics:

- Altitude = 550 km, eccentricity = 0.002, inclination = 87.0 deg
- Client ballistic coefficient: 0.0069 m²/kg (e.g. C_D = 2.3, A = 3 m², m = 1000 kg)

Client radar tracking errors are assumed to be the same as those for CanX-2.

Servicer GPS-based navigation accuracy (RMS):

	a [m]	e [-]	i [deg]	Ω [deg]	ω [deg]	u [deg]
RMS	0.37	4.5E-8	1.2E-5	3.1E-6	1.8E-3	3.1E-5

Relative Orbital Elements:

$$\begin{pmatrix} \delta a \\ a\delta\lambda \\ a\delta e_x \\ a\delta e_y \\ a\delta i_x \\ a\delta i_y \end{pmatrix} = \begin{pmatrix} a - a_c \\ a(u-u_c) + a(\Omega-\Omega_c)\cos i \\ a(e_x - e_x^c) \\ a(e_y - e_y^c) \\ a(i - i_c) \\ a(\Omega-\Omega_c)\sin i \end{pmatrix} \qquad \begin{pmatrix} \delta\delta a \\ a\delta\delta\lambda \\ a\delta\delta e_x \\ a\delta\delta e_y \\ a\delta\delta i_x \\ a\delta\delta i_y \end{pmatrix}_{Drag} = \begin{pmatrix} -\frac{1}{n}\Delta B\rho v^2 (t - T_{End}) \\ +\frac{3}{4}\Delta B\rho v^2 (t - T_{End})^2 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Achievable Relative Orbit Accuracy (RMS) in 550 km Orbit

Tracking scenario	δa [m]		$a\delta\lambda$ [m]		$a\delta e$ [m]	$a\delta i$ [m]
	T_{End}	T_{End}+24h	T_{End}	T_{End}+24h		
24h, 3 passes	3.3	9.2	106.9	530.5	35.8	85.9
24h, 4 passes	2.3	6.7	79.3	388.5	34.2	45.8
24h, 5 passes	2.1	5.9	72.2	338.9	35.0	30.0
36h, 3 passes	2.4	4.6	92.3	254.4	43.2	67.2
36h, 4 passes	1.7	3.2	59.6	163.0	28.7	39.5
36h, 5 passes	1.6	2.4	37.0	93.5	21.1	18.8
48h, 3 passes	1.9	3.8	95.4	229.7	33.4	63.2
48h, 4 passes	1.7	2.8	63.8	145.6	23.3	53.8
48h, 5 passes	1.6	2.4	53.9	109.9	16.6	40.6
48h, 6 passes	1.5	2.2	46.8	90.8	12.0	31.9
48h, 7 passes	1.6	2.1	42.6	79.5	9.7	24.1

δa: relative semi-major axis
$a\delta\lambda$: relative mean longitude (*equivalent to relative along-track separation*)
$a\delta e$: relative eccentricity vector norm (*equivalent to max. radial separation*)
$a\delta i$: relative inclination vector norm (*equivalent to max. normal separation*)

Conclusions

The achieved results demonstrate the potential of the proposed ground-based relative navigation concept for the far range approach of a debris removal or on-orbit servicing satellite to its target object.

The provided ROE accuracies are important parameters within the mission analysis and design phase.

They are necessary, for example, to derive relative navigation sensor requirements or to design the formation geometry for the approach phase.

From the CanX-2 campaign we derive the following requirements on future radar-tracking campaigns:

- The tracking duration should cover a minimum of 24 hours preferably 36 hours for a precise ballistic coefficient estimate,
- Ascending and descending passes should be tracked to improve the out-of-plane accuracy, and
- The campaign should comprise a minimum of 4 tracking passes.