HRWS – An Ambitious 4+ Satellite Formation Flying Mission

Sofya Spiridonova [1], Ralph Kahle [1]

[1] *German Aerospace Center (DLR), German Space Operation Center (GSOC), Muenchener Strasse 20, 82234 Wessling, Germany, sofya.spiridonova@dlr.de*

Abstract

High Resolution Wide Swath (HRWS) is an ambitious Synthetic Aperture Radar (SAR) mission proposed by Airbus Defence and Space, which will potentially exploit formation flight and the novel MirrorSAR concept to achieve unprecedented imaging characteristics by means of fractionated radar architecture, Ref. [1] and [2]. Originally planned as a follow-on of the extremely successful TerraSAR-X project, the HRWS mission and the satellite itself gradually took on a very different form, as the scientific goals grew more and more challenging. Now to be possibly equipped with electric propulsion and more than 3 times heavier than TerraSAR-X, the HRWS satellite is to be maintained within the control tube of merely 100 m (desired minimum) to maximum 250 m radius around the repeat ground-track reference orbit. On top of that, it is planned to augment the mission by 3 to 4 low-cost companion satellites flying in close proximity (down to ~100 m) to one another. Altogether, these challenges call for a very careful consideration of the absolute and relative orbit control concepts in order to develop a safe and precise maneuver strategy.

Keywords: High Resolution Wide Swath, formation flight, passive formation safety

Introduction

As TerraSAR-X, the HRWS satellite is to be flown in a sun-synchronous dusk-dawn orbit in 505 km altitude with a repeat ground-track cycle of 11 days. The launch is currently planned for year 2024. While with TerraSAR-X it is possible to obtain high resolution images at the cost of relatively small scene sizes, the advanced instruments aboard the HRWS satellite will allow image acquisition with both high resolution and large area coverage at the same time, Ref. [3]. To fulfil the additional scientific objective of improving the existing Digital Elevation Model, the current mission concept foresees 3 to 4 low-cost microsatellite Companions flying in formation ca. 15 km ahead of the main satellite.

Relative orbit control in the augmented mission can be characterized as challenging due to the small relative separations between the neighbouring Companions. Moreover, the large difference in area-to-mass ratios (see Table 1, faster orbital decay of the Companions) leads to the necessity of a very frequent formation control.

	TerraSAR-X	HRWS	Companion
Wet mass, kg	1340	4445	200
Fuel	Hydrazine	Xenon	Xenon
Thrust, N (BOL)	4 x 1	3 x 0.014	0.014
Specific impulse, s	210	>1190	>1190
Area in flight-direction, m²	3.2	6.0	0.9
Area-to-mass ratio at BOL, m²/kg	0.0024	0.0013	0.0045

Table 1: TSX, HRWS and Companion spacecraft characteristics

Based on the decade of TerraSAR-X / TanDEM-X formation flight experience collected at the German Space Operations Center (GSOC) of DLR, Ref. [4] and [5], the feasibility of the proposed formation flight mission was investigated by the flight dynamics group as part of the ground segment Phase A. Special attention was paid to the achievable accuracy of the absolute and relative navigation and control. In the present paper, however, only a few aspects of the formation maintenance strategy will be treated with a focus on passive formation safety in particular.

Throughout this analysis, the relative orbits of the Companions with respect to the HRWS satellite are described in terms of the relative orbital elements (ROEs), introduced in [6] for LEO formation flight:

$$a\delta\vec{\alpha} = \begin{pmatrix} a\delta a \\ a\delta\lambda \\ a\delta e_x \\ a\delta e_y \\ a\delta i_x \\ a\delta i_y \end{pmatrix} = \begin{pmatrix} a^C - a \\ a(u^C - u) + a(\Omega^C - \Omega)\cos i \\ a(e_x^C - e_x) \\ a\left(e_y^C - e_y\right) \\ a(i^C - i) \\ a(\Omega^C - \Omega)\sin i \end{pmatrix}.$$

Here, orbital elements $\left(a, u, e_x, e_y, i, \Omega\right)$ parameterize the absolute orbit of the HRWS spacecraft, where the following definitions apply:

a: semi-major axis
$u = \omega + M$: argument of latitude
$e_x = e\ \cos\omega$: x-component of the ecc. vector
$e_y = e\ \sin\omega$: y-comp. of the ecc. vector
i: inclination
Ω: right asc. of the asc. node

The same denominations with an additional index C refer to the absolute orbital elements of a companion satellite. Additionally, the following notations are used throughout this document:
ω: argument of perigee
M: mean anomaly
n: mean motion.

Several possible formation geometries have been analysed and iterated to meet the scientific demands, with the Companions being distributed over 2 or 3 relative ('inner' and 'outer') orbits of various dimensions. The non-zero components of the eccentricity and the inclination vectors are summarized in Table 2. The rest of the elements is defined as $a\delta a = 0$ m, $a\delta\lambda = 15$ km, $a\delta e_x = 0$ m, $a\delta i_x = 0$ m. Fig. 1 depicts the current baseline scenario (Formation 3).

	Formation 1				**Formation 2**				**Formation 3**		
	Outer 1	**Outer 2**	**Inner 3**	**Inner 4**	**Outer 1**	**Outer 2**	**Inner 3**	**Inner 4**	**Outer 1**	**Inner 2**	**Inner 3**
$\boldsymbol{a\delta e_y}$	-350	+350	-200	+200	-500	+500	-400	+400	1100	350	250
$\boldsymbol{a\delta i_y}$	+350	-350	+200	-200	-500	-500	+400	-400	1650	550	350

Table 2: Relative orbital elements (ROEs) of investigated formations

Relative Orbit Dynamics

A simple relative dynamics model developed in [6] was used for this analysis. The model allows predicting the development of ROEs taking into account average differential drag and planned maneuvers. GSOC flight dynamics formation flight experience (TerraSAR-X / TanDEM-X, PRISMA, etc.) demonstrates that the model is accurate enough to be used for coarse formation keeping maneuver planning.

According to the model, the "free motion" ROEs at time t can be estimated as $a\delta\vec{\alpha}(t) = a\delta\vec{\alpha}_{J_2}(t) + a\delta\delta\vec{\alpha}_{\text{Drag}}(t)$, where denoting $\gamma = \frac{J_2}{2}\left(\frac{R_E}{a}\right)^2$ and $\varphi' = \frac{3}{2}\gamma(5\cos^2 i - 1)$

$$a\delta\vec{\alpha}_{J_2}(t) = \begin{pmatrix} a\delta a(t_0) \\ a\delta\lambda(t_0) - \frac{21}{2}\left(\gamma\ \sin 2i\ a\delta i_x(t_0) + \frac{1}{7}\ a\delta a(t_0)\right)\ (u(t) - u(t_0)) \\ a\delta e(t_0)\cos\left(\varphi + \varphi'(u(t) - u(t_0))\right) \\ a\delta e(t_0)\sin\left(\varphi + \varphi'(u(t) - u(t_0))\right) \\ a\delta i_x(t_0) \\ a\delta i_y(t_0) + 3\gamma\sin^2 i\ a\delta i_x(t_0)\ (u(t) - u(t_0)) \end{pmatrix}.$$

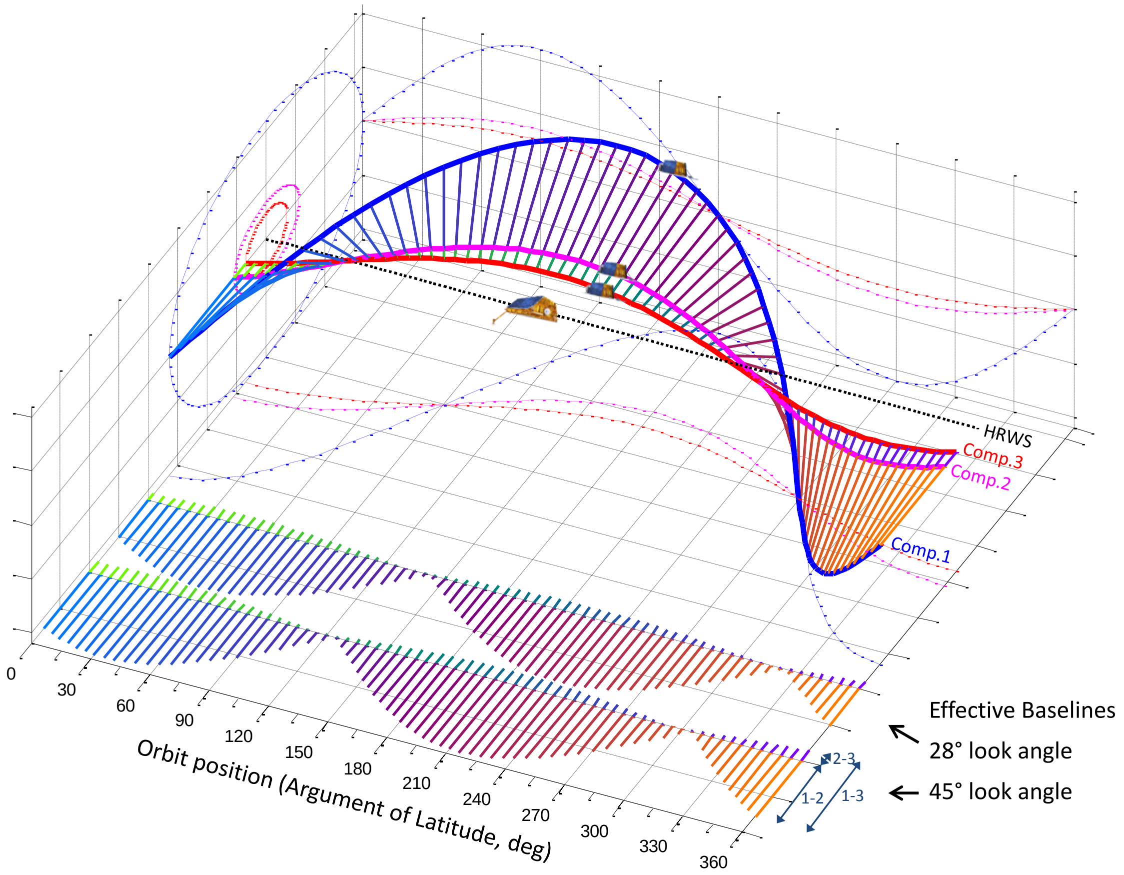

Fig. 1: Formation 3: Companion-HRWS relative motion in the plane orthogonal to flight direction and effective baselines as function of orbital position. Baselines between all three Companions are depicted for 28° and 45° look angles in right-looking attitude.

At the same time, the differential drag manifests itself by a linear trend in the relative semi-major axis and a quadratic trend in the relative mean longitude: $a\delta\delta a_{\mathrm{Drag}}(t) = -\Delta B\rho v(t - t_0)/n$, and $a\delta\delta\lambda_{\mathrm{Drag}}(t) = \frac{3}{4}\Delta B\rho v^2(t - t_0)^2$. The following notations have been used.

$\Delta B = C_D(\frac{A^C}{m^C} - \frac{A^{HRWS}}{m^{HRWS}})$: difference in ballistic coefficients
C_D: aerodynamic drag coefficient
A: satellite cross-section area
m: satellite mass
ρ: atmospheric density
v: spacecraft velocity
J_2: Earth's oblateness parameter
R_E: Earth's equatorial radius

The calculation of the Companion's relative position and velocity vector (with respect to HRWS) in the orbital frame is based on the equivalence of ROEs and the integration constants in Clohessy-Wiltshire equations, [6]:

$$\delta\vec{r} = \begin{pmatrix} \delta r_R \\ \delta r_T \\ \delta r_N \\ \delta v_R \\ \delta v_T \\ \delta v_N \end{pmatrix} = \begin{pmatrix} a\delta a - a\delta e\cos(u-\varphi) \\ a\delta\lambda + 2a\delta e\sin(u-\varphi) \\ a\delta i\sin(u-\vartheta) \\ n\,a\delta e\sin(u-\varphi) \\ -1.5n\,a\delta a + 2n\,a\delta e\cos(u-\varphi) \\ n\,a\delta i\cos(u-\vartheta) \end{pmatrix}, \text{ where } \begin{cases} \delta\vec{e} = \begin{pmatrix} \delta e_x \\ \delta e_y \end{pmatrix} = \delta e\begin{pmatrix} \cos\varphi \\ \sin\varphi \end{pmatrix} \\ \delta\vec{\imath} = \begin{pmatrix} \delta i_x \\ \delta i_y \end{pmatrix} = \delta i\begin{pmatrix} \cos\vartheta \\ \sin\vartheta \end{pmatrix} \end{cases}.$$

Formation control

Let $\delta v_R, \delta v_T, \delta v_N$ denote the velocity increments in radial, tangential and normal directions, and u_M – the argument of latitude at the epoch of the maneuver. Then the instantaneous changes in ROEs due to an orbit control maneuver can be modelled as

$$a\delta\delta\vec{\alpha}_{\mathrm{Man}} = \frac{1}{n}\begin{pmatrix} +2\delta v_T \\ -2\delta v_R \\ +\delta v_R \sin u_M + 2\delta v_T \cos u_M \\ -\delta v_R \cos u_M + 2\delta v_T \sin u_M \\ +\delta v_N \cos u_M \\ +\delta v_N \sin u_M \end{pmatrix}.$$

Since the relative inclination between Companions and HRWS is zero in all the three formations, vector $\delta\vec{\imath}$ is not drifting along the y-axis. Although third-body gravitational perturbations do result in a slow rotation of the relative inclination vector, this effect is negligible for the current analysis. Therefore, only in-plane relative orbit control will be discussed in the following.

The formation maintenance concept is formulated in terms of control windows for the relative eccentricity vector and the relative mean longitude. The eccentricity vector control window is given by the maximum allowed deviation $\delta\varphi_{\max}$ of the relative perigee from its nominal value. The length of the control cycle can be estimated as $\Delta t = 2\delta\varphi_{\max}/(\varphi' n)$.

For the simultaneous control of the relative eccentricity vector and the relative semi-major axis, a pair of in-plane maneuvers is required. The following formulations define the Δv's and the optimal maneuver locations along the orbit.

$$\Delta v_{T1} = na/4((\delta a^{man} - \delta a) + \|\delta\vec{e}^{man} - \delta\vec{e}\|), \quad u_{M1} = \arctan\left(\frac{\delta e_y^{man} - \delta e_y}{\delta e_x^{man} - \delta e_x}\right)$$
$$\Delta v_{T2} = na/4((\delta a^{man} - \delta a) - \|\delta\vec{e}^{man} - \delta\vec{e}\|), \quad u_{M2} = u_{M1} + \pi$$

Here, $\delta a^{man}, \delta\vec{e}^{man}, \delta e_x^{man}$ and δe_y^{man} denote the target post-maneuver values, while $\delta a, \delta\vec{e}, \delta e_x$ and δe_y denote the values immediately before the maneuvers. The parameters u_{M1} and u_{M2} define the optimal arguments of latitude for the two maneuvers. The relative eccentricity vector desired after the execution of the in-plane maneuvers is given by

$$\delta\vec{e}^{man} = \begin{pmatrix} +\delta e_x^{nom}\cos(\delta\varphi_{\max}) + \delta e_y^{nom}\sin(\delta\varphi_{\max}) \\ -\delta e_x^{nom}\sin(\delta\varphi_{\max}) + \delta e_y^{nom}\cos(\delta\varphi_{\max}) \end{pmatrix}.$$

		Atmospheric density [kg/m3]		
Formation	Companion	1-2.5 × 10-13 (low/medium)	5 × 10-13 (high)	1 × 10-12 (max)
1	Inner (200 m)	0.7 cm/s/day	0.9 cm/s/day	1.8 cm/s/day
	Outer (350 m)	1.2 cm/s/day	1.2 cm/s/day	1.8 cm/s/day
2	Inner (400 m)	1.4 cm/s/day	1.4 cm/s/day	1.8 cm/s/day
	Outer (500 m)	1.7 cm/s/day	1.7 cm/s/day	1.8 cm/s/day
3	Inner (250 m)	0.8 cm/s/day	0.9 cm/s/day	1.8 cm/s/day
	Inner (350 m)	1.2 cm/s/day	1.2 cm/s/day	1.8 cm/s/day
	Outer (1100 m)	3.7 cm/s/day	3.7 cm/s/day	3.7 cm/s/day

Table 3: Formation control Δv budget per Companion as a function of atmospheric density and vertical separation (in brackets).

The relative semi-major axis after the maneuver pair determines the variation of the relative mean argument of latitude and can be calculated as $\delta a^{man} \approx \frac{\pi}{2n\Delta t - \pi}\left[3\delta e_{max} + \delta a - \frac{4}{3\pi}\left(\delta u - \delta u^{nom} + \delta u_{J_2} + \delta u_{Drag}\right)\right]$, where $\delta e_{max} \approx 2\delta e^{nom}\sin(\delta\varphi_{\max}/2)$, Δt is the control cycle length, δu^{nom} is the nominal mean relative argument of latitude, $\delta u_{J_2} + \delta u_{Drag}$ is the total variation of the relative mean argument of latitude over the control cycle due to the combined effect of the Earth's oblateness and the differential air drag.

In general, the frequency of the in-plane relative orbit control will depend on the launch/operations timing within the 11-years of solar activity cycle. Table 3 gives an overview of the Δv/day budget as a function of relative orbit size and the atmospheric density.

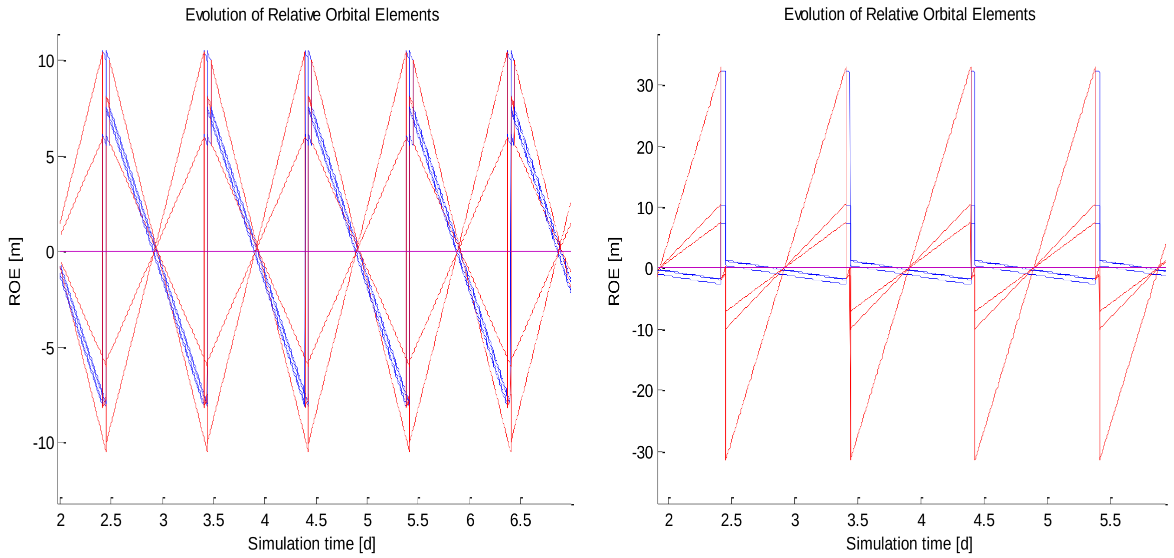

Fig. 2: Formation 1 (left) and 3 (right): $a\delta a$ (blue) and $a\delta e_x$ (red) controlled by means of an along-track maneuver pair, maneuver cycle length: 1 day.

Fig. 2 depicts the controlled relative semi-major axes and scaled x-components of the relative eccentricity vectors for Formation 1 (4 Companions) and Formation 3 (3 Companions). Maneuver times are seen as paired red vertical lines in $a\delta e_x$. It can be seen that the control occurs once a day at approximately the same time. The in-plane maneuver pair is triggered when the angular deviation from the nominal relative eccentricity vector exceeds $\delta\varphi_{\max}$ and brings the relative eccentricity vector to the other “side” of the control window.

Formation Safety

HRWS orbit control maneuvers shall be replicated by the companion satellites; otherwise the Companions will exit the communication cone. In case of any maneuver failure, passive formation safety must be ensured. Thus, HRWS maneuver sizes and timings have to be treated carefully. A minimum threshold for the radial/normal separation between the Companions shall be defined, e.g. 40 m, which shall not be violated.

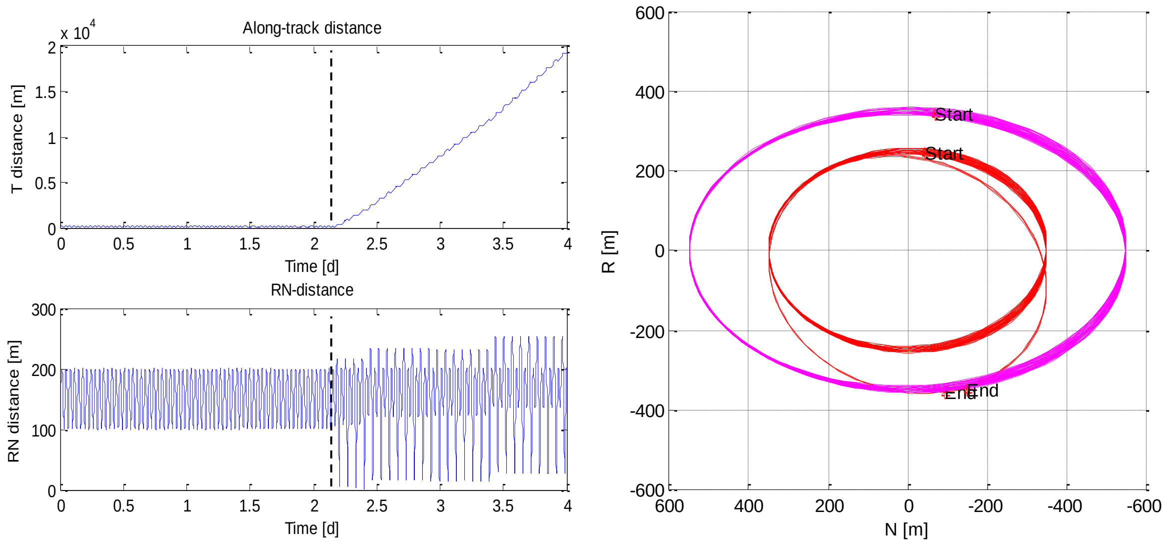

Fig. 3: Formation 3, control cycle length: 1 day. Failed drag make-up maneuver with Δv=3 cm/s on an inner Companion on sim. day 2 (dashed vertical lines) leads to a collision risk. Upper left: along-track distance between the uncontrolled Companion and his closest neighbour. Lower left: distance in the plane normal to flight direction (reduces to zero

without any along-track separation). Right: Inner relative orbits (2.4 days only) projected onto the RN-plane.

Depending on the year within the solar activity cycle, tangential drag make-up maneuvers of ca. 1-3 cm/s every 2-3 days may be required to maintain the orbital height of the HRWS satellite. In case of Formation 1, due to the relatively large radial separation between neighboring Companions (~150 m), a tangential maneuver of up to 3 cm/s may be replicated by the Companions with no collision risk in case of a maneuver failure. In case of Formations 2 and 3 (radial separation ~100 m), a failed maneuver of 3 cm/s would already lead to a high collision probability, Fig. 3. Thus, such a HRWS drag make-up maneuver would have to be split into a maneuver pair separated by half an orbit, Fig. 4.

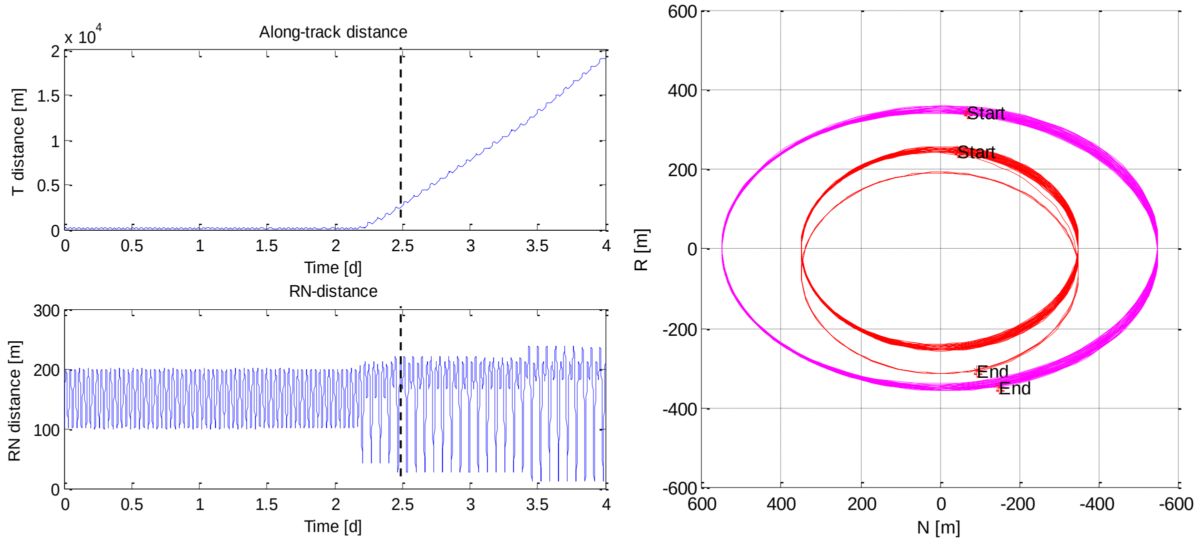

Fig. 4: Formation 3; a failed drag make-up maneuver pair, each Δv=1.5 cm/s, does not lead to a collision risk, post-maneuver minimum RN-distance > 40 m. The uncontrolled Companion drifts rapidly away. Next formation keeping maneuver pair on day 2.5 can be performed on the remaining Companions with no collision risk (sufficient along-track separation).

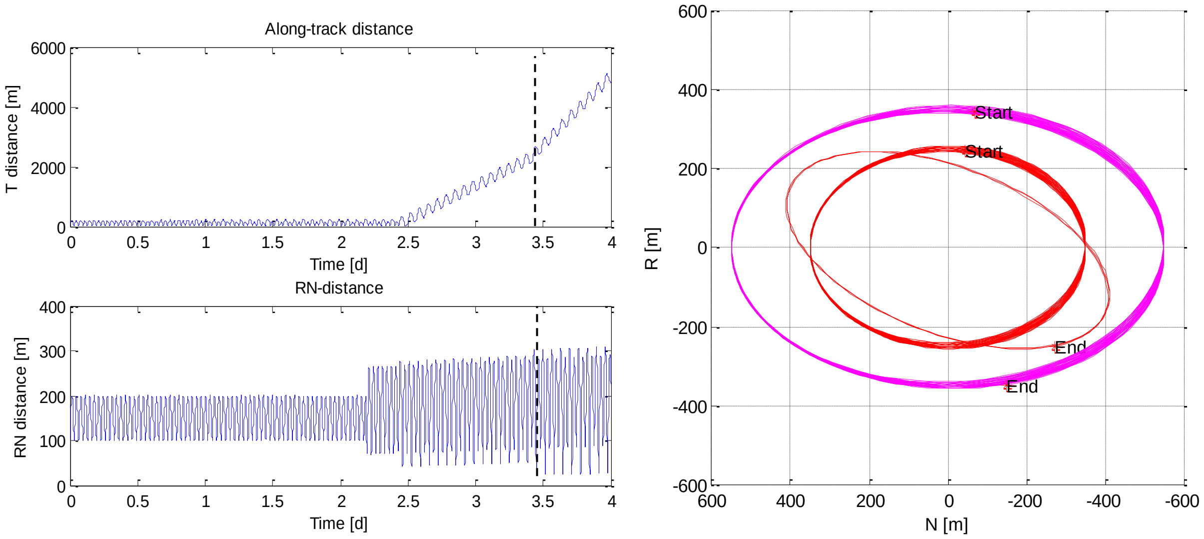

Fig. 5: Formation 3; failed out-of-plane maneuver (inclination correction only), Δv=20 cm/s, no collision risk, post-maneuver minimum RN-distance > 70 m. Next formation keeping maneuver pair on day 2.5 can be performed on the remaining Companions without any collision risk (minimum RN-distance > 40m). After that, the uncontrolled Companion drifts rapidly away. Maneuvers on day 3.5 are performed at along-track separation > 2.0 km.

Placing drag make-up maneuvers ca. 6 hours (~ 4 orbits) before the formation keeping maneuver pair is optimal for the safety of the formation. A failed drag make-up maneuver would make the affected Companion drift rapidly away in flight direction. Thus, after ca. 6 hours it will be already at several kilometers along-track separation and present no danger to the remaining Companions which can continue performing formation keeping maneuvers.

For formations with smaller RN-separation between closest Companions (e.g. of ~100 m as in Formation 2), large inclination corrections of HRWS also have to be split into smaller maneuvers of ca. 5 cm/s. These smaller maneuvers have to be separated by at least one control cycle. In case of Formation 3, inclination maneuvers as large as 20 cm/s can be performed without any collision risk due to the large separation on the N-axis (~200 m), Fig. 5.

Operations Concept

If the guidelines formulated in the previous section on maneuver timing and size are followed, no confirmation of execution of replicated HRWS maneuvers on companion satellites is required before the next formation control maneuvers can be released. This can be very helpful for operations, as the maneuvers of the next control cycle can be planned all together after the calibration of the entire previous maneuver cycle is accomplished. Therefore, only two ground station contacts per control cycle and per satellite may be enough for safe operations. Fig. 6 depicts a possible operations timeline:

- Replicated HRWS drag make-up maneuvers (black vertical dashed lines) have to be separated from the following formation control maneuvers (red vertical dashed lines) by ca. 6 hours (ca. 4 orbits). For out-of-plane control maneuvers this requirement is not stringent.
- In the dumped telemetry data ("TM"), at least 3 hours (ca. 2 orbits) of GPS measurements have to be available after the last formation control maneuver pair for precise orbit and maneuver determination. Immediately after that, the maneuver planning for the next control cycle is performed (effort of ca. 1.5 hours).
- All the planned maneuvers for the next control cycle are commanded in the next uplink ground station contact ("CMD", e.g. 12 hours after the downlink in case of a control cycle length of 1 day).

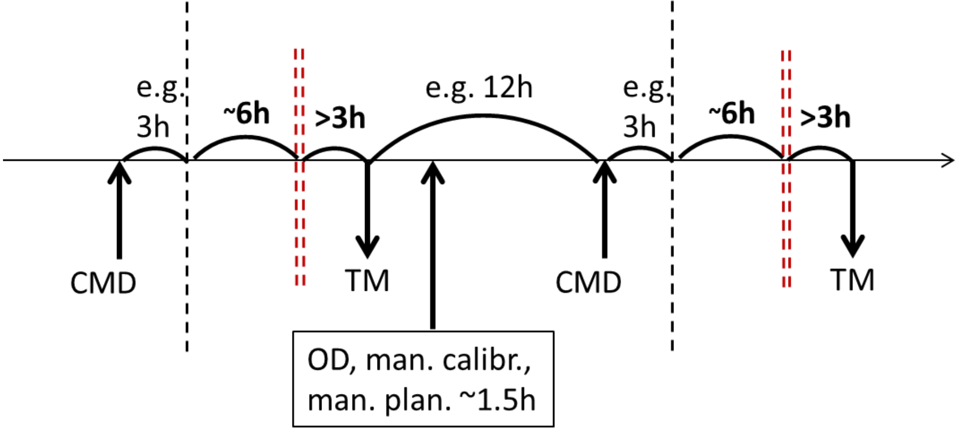

Fig. 6: Possible flight dynamics operations timeline. Black vertical dashed lines: HRWS drag make-up / inclination control maneuvers replicated by the Companions. Red vertical dashed lines: formation control in-plane maneuver pairs on Companions.

Summary and conclusions

In the present paper, the formation control concept for the planned 4+ High Resolution Wide Swath mission was presented. Due to the exceptionally ambitious scientific objectives of the mission, the requirements on the accuracy of the relative orbit control were set very high. However, it was shown that safe formation flight of 3 to 4 microsatellite Companions is, in fact, feasible for a control cycle of 24 hours, even in case of an extremely tight formation with only 100 m of radial/normal separation between the neighbouring Companions. To achieve that, certain recommendations on the maximum maneuver size for in-plane and out-of-plane control for repeat ground-track orbit maintenance have to be followed. On top of that, some rules for proper maneuver timing were established during this analysis. By simulating worst-case maneuver failures for both in-plane and out-of-plane control, it was demonstrated that passive formation safety can be granted at any time. A corresponding timeline for the main flight dynamics activities was elaborated, paving the way for future operations in the service of outstanding science.

References

1. G. Krieger et al., MirrorSAR: “A Fractionated Space Transponder Concept for the Implementation of Low-Cost Multistatic SAR Missions”, *EUSAR* (2018) Aachen, Germany
2. M. Zonno et al., A MirrorSAR-based single-pass dual-baseline SAR interferometer for the generation of very high quality DEMs, *EUSAR* (2018) Aachen, Germany
3. J. Janoth et al., The High Resolution Wide Swath Mission and WorldSAR, *ISRSE*-37 (2017) Tshwane, South Africa
4. O. Montenbruck et al., Navigation and Control of the TanDEM-X Formation, *Journal of the Astronautical Sciences* 56(2009):341-357
5. R. Kahle, S. D’Amico, The TerraSAR-X Precise Orbit Control - Concept and Flight Results, *International Symposium on Space Flight Dynamics*, May 2014
6. S. D’Amico, Autonomous formation flying in Low Earth Orbit, PhD Thesis, Technical University of Delft, 2010.