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SATELLITE GEODESY

1.1 DEPARTMENT OF GEODESY AND GEODETIC ASTRONOMY, WARSAW UNIVERSITY OF TECHNOLOGY

The Department of Geodesy and Geodetic Astronomy at the Faculty of Geodesy and Cartography, Warsaw University of Technology (WUT), conducts research in satellite geodesy, geodynamics, gravimetry, GNSS-based remote sensing, and ionospheric studies.

Research in GNSS-based remote sensing focused on the application of GNSS Interferometric Reflectometry (GNSS-IR) to snow-cover monitoring in polar regions. For the first time, GNSS-IR was applied to snow-depth monitoring in the Svalbard region using data from three monitoring stations of the CRIOS network. The study presented the data-processing methodology, snow-depth estimation procedures, and validation against in situ measurements. During the one-year study period from September 2023 to August 2024, the average snow-depth estimation error remained at the level of several centimeters. Median daily standard deviations ranged from 2.4 to 5.4 cm, while correlation coefficients with manual and automatic reference measurements ranged from 0.83 to 0.93.

Continuous GNSS observations at the Polish Polar Station in Hornsund have supported geodetic and geodynamic research for more than two decades. In 2020, in cooperation with the Institute of Geophysics of the Polish Academy of Sciences (PAS), two new receivers were installed and incorporated into global and regional networks, including IGS and EUREF. Using all available satellite observations, researchers determined vertical uplift rates and their temporal variability related to Glacial Isostatic Adjustment (GIA) and contemporary ice-mass loss. In recent years, uplift rates increased from approximately 10 mm yr^{-1} to about 12 mm yr^{-1}. This change was attributed to intensified melting of Svalbard glaciers.

Since 2020, the Department has conducted continuous monitoring of high-latitude ionospheric parameters using the WUTH GISM station located at the Polish Polar Station in Hornsund, Svalbard. The station contributes to international GNSS networks, including IGS, EPN, and EPOS. The collected data support studies of ionospheric disturbances, climatological characterization of ionospheric scintillation, and assessment of GNSS-system susceptibility to ionospheric disturbances.

Research was also conducted on quad-frequency GNSS observation combinations for the BeiDou system (BDS), with particular emphasis on the meta-signal concept. The study investigated the reconstruction of meta-signal observations from signals transmitted on multiple frequencies and their representation using narrow-lane, wide-lane, and Hatch–Melbourne–Wübbena combinations. The findings indicate that quad-frequency combinations have significant potential to support single-epoch ambiguity resolution.

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1.2 NATIONAL INSTITUTE OF TELECOMMUNICATIONS: TIME METROLOGY AND GNSS SYSTEMS MONITORING

The National Institute of Telecommunications (NIT) conducts activities in space technologies, including time metrology, GNSS systems, and positioning, navigation, and timing (PNT) services. The Institute develops and maintains advanced methods for comparing atomic time standards using satellite techniques and fiber-optic links. These activities ensure the high stability of the Polish Atomic Time Scale TA(PL) and support the alignment of UTC(PL) with international UTC.

A stationary monitoring station has been established at the NIT premises in Gdańsk. The station continuously collects GNSS raw data and network streams for analyses of GNSS availability and positioning-service quality. The GNSS Galileo Mobile Measurement System (MSP2G), developed using a professionally adapted VW Crafter van, enables laboratory-grade field measurements, including monitoring of GNSS signal availability and detection of interference across all GNSS frequency bands.

Experience gained within the Polish Galileo Monitoring System led to the concept of a nationwide Real-Time GNSS Monitoring System for Poland (RTGMS), developed under the ESA NAVISP Element 3 programme. RTGMS is intended to serve as a national early-warning system for GNSS interference. NIT is also the initiator of the Polish PNT Shield programme, aimed at strengthening national resilience to disruptions affecting positioning, navigation, and timing systems.

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1.3 PLANETARY GEODESY DEPARTMENT, SPACE RESEARCH CENTRE OF THE POLISH ACADEMY OF SCIENCES (CBK PAN)

Research at the Planetary Geodesy Department of the Space Research Centre of the Polish Academy of Sciences (CBK PAN) focused on satellite gravimetry, hydrological and cryospheric angular momentum, polar motion excitation, Earth Orientation Parameters (EOP) prediction evaluation, and selected geodynamic and ionospheric studies.

Research on terrestrial water storage (TWS) variations in the Bug River transboundary catchment used data from the Gravity Recovery and Climate Experiment (GRACE) and Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) missions, together with water-balance (WB) components, including precipitation, evapotranspiration, and runoff. GRACE-derived TWS anomalies and monthly TWS changes were compared with WB-based estimates. The analyses demonstrated good agreement between both approaches, with an average coefficient of determination of 0.77, slightly higher in lowland areas and lower in upland regions, and reduced consistency during dry months. In addition, GRACE and hydrometeorological data were assimilated using a regression-based model to reduce uncertainties associated with the coarse spatial and temporal resolution of GRACE/GRACE-FO observations and to minimize the impact of the data gap between the GRACE and GRACE-FO missions.

Another study assessed the effectiveness of GRACE/GRACE-FO observations for monitoring groundwater storage (GWS) in Poland and proposed a hydrodynamic-zoning-based method for estimating satellite-derived GWS. Satellite-based GWS estimates were evaluated against in situ

groundwater measurements, considering the effects of monitoring-point location, physiographic region, and hydrodynamic zone. The results revealed long-term negative GWS trends across Poland, reaching up to −2.45 mm yr^{-1} in south-eastern Poland.

A new method for estimating GWS changes was developed by integrating GRACE/GRACE-FO data, meteorological inputs (precipitation, evapotranspiration, and runoff), and hydrogeological observations. The proposed approach increased the spatial resolution of GRACE/GRACE-FO data using machine-learning techniques and high-resolution predictors. GWS was subsequently estimated by modifying the difference between TWS derived from GRACE/GRACE-FO observations and modeled water content in the vadose zone, conditioned by groundwater-table depth. Satellite-based GWS estimates were calibrated with in situ groundwater measurements using a combined machine-learning and kriging approach. This methodology supports continuous groundwater monitoring and forecasting, particularly in regions with sparse in situ observations and in transboundary areas where data exchange is limited.

Hydrological angular momentum (HAM) and cryospheric angular momentum (CAM) represent the contribution of mass redistribution within the hydrosphere and cryosphere to variations in polar motion (PM). The applied methodology was based on comparing the sum of GRACE/GRACE-FO-derived hydrological and cryospheric signals (HAM/CAM) with the corresponding signal contained in the geodetic PM excitation function (GAO), obtained after removing atmospheric and oceanic effects from geodetic observations of PM excitation. HAM/CAM was reassessed using variations in the Earth's gravity field quantified by changes in the C21 and S21 geopotential coefficients derived from GRACE/GRACE-FO, Satellite Laser Ranging (SLR), hybrid SLR, and combined GRACE/GRACE-FO plus SLR solutions. Most HAM series derived from hybrid solutions closely matched the hydrological signal in geodetically observed PM excitation. Hybrid SLR-based HAM performed similarly to, or better than, HAM derived from individual GRACE/GRACE-FO solutions, demonstrating strong agreement between geodetic measurements of PM excitation and observations of gravity-field variations.

The study also continued earlier investigations using soil-moisture and snow-water-equivalent data from climate models disseminated within the Coupled Model Intercomparison Project Phase 6 (CMIP6) to examine the impact of climate variability and continental hydrosphere changes on PM. A novel aspect of the research was the estimation of HAM using both individual climate models and combined solutions, including simple averages, weighted averages, and a combined model developed using the three-cornered hat (TCH) method. These estimates were compared with HAM derived from GRACE/GRACE-FO observations and the Land Surface Discharge Model (LSDM). All HAM series were analyzed across different spectral ranges and compared with GAO. The results indicated that although climate models do not allow accurate assessment of non-seasonal HAM variability, they are useful for interpreting seasonal variations. For annual and semi-annual oscillations, CMIP6-based HAM estimates showed better agreement with GAO than GRACE/GRACE-FO-derived solutions. The choice of the model-combination method had only a minor influence on the consistency of the obtained HAM series with GAO.

The objectives of the 2nd EOP Prediction Comparison Campaign (2nd EOP PCC), conducted between September 2021 and December 2022, included the continuous collection and analysis of EOP predictions provided by institutes worldwide, assessment of prediction accuracy, and identification of

the most accurate prediction approaches. Following the official completion of the campaign, the EOP PCC Office continued collecting forecasts submitted by registered participants and expanded the database by registering new participants and prediction methods. Submitted forecasts were routinely verified and evaluated against EOP observations as soon as the observations became available. In November 2024, a sub-campaign dedicated to machine-learning-based prediction approaches, EOP PML, was launched within the framework of the 2nd EOP PCC.

The EOP PCC Office also examined the impact of reference-data selection on the evaluation of EOP predictions. The study compared 11 solutions, including combined products from the International Earth Rotation and Reference Systems Service (IERS), the European Space Agency (ESA), and the Jet Propulsion Laboratory (JPL), as well as single-technique series based on Global Navigation Satellite Systems (GNSS), Satellite Laser Ranging (SLR), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), and Very Long Baseline Interferometry (VLBI). Prediction accuracy was assessed using the Mean Absolute Error (MAE) over a 10-day prediction horizon. The analyses demonstrated that the choice of reference series significantly affects EOP evaluation outcomes. Prediction errors were lowest when GNSS-based series from the International GNSS Service (IGS) and combined solutions were used as reference data in MAE computations.

In collaboration with the Jagiellonian University in Kraków, a unique isotopic-research installation was deployed in the Geodynamic Laboratory in Książ together with precise instrumentation for monitoring radon-concentration changes in underground corridors. Following the implementation of an improved data-processing methodology, the system is expected to provide more reliable identification of correlations between radon-concentration changes and strong non-periodic geodynamic signals recorded by clinometer systems operating in the laboratory, as well as by two GNSS receivers installed on opposite sides of the active tectonic fault located near the underground laboratory. The study investigated interactions between geodynamic activity and radon-concentration changes as potential indicators of seismic events. The analysis included data on ^222Rn activity concentrations and tectonic activity derived from two KH and five SRDN-3 radon probes. Four seismic events with magnitudes greater than 4.0 and hypocentral depths between 1 and 10 km were analyzed. The findings suggest that, at the research site, the radon–tectonic signal was most clearly detectable 1–3 days before seismic events.

Continuation of monitoring and analysis of GNSS and EGNOS satellite navigation systems. The research focused not only on system performance analysis but also on the impact of the ionosphere models used. As a continuation of earlier research, new analyses focused on the NeQuick Total Electron Content Model, ionospheric parameters (Azpar) transmitted in navigation messages, the solar radio flux index (F10.7), and the European Geostationary Navigation Overlay Service (EGNOS) ionospheric model. Comparative analyses were conducted to evaluate the effect of ionospheric models on station position errors, as well as a metric representing the ratio of ionospheric delay error between the Neustrelitz Total Electron Content Model (NTCM) and the Global Ionospheric Map (GIM) relative to a reference value.

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1.4 ASTROGEODYNAMIC OBSERVATORY, SPACE RESEARCH CENTRE OF THE POLISH ACADEMY OF SCIENCES (CBK PAN), BOROWIEC

In 2024–2025, the Astrogeodynamic Observatory of the Space Research Centre of the Polish Academy of Sciences (CBK PAN) in Borowiec conducted research in satellite geodesy, time metrology, and optical observations of satellites and space debris. A key component of the Observatory's activities was satellite laser ranging (SLR), including observations of geodetic satellites and space debris. In 2024, 2,012 successful observations were performed, while in 2025 the number reached 1,032.

The GNSS station BOR1 operated continuously and reliably, providing RINEX data for GPS, GLONASS, Galileo, BeiDou, and SBAS systems. The data were distributed within the IGS-IP and EUREF-IP projects and used by numerous scientific institutions. Hydrogen masers and cesium standards ensured generation of the local UTC(AOS) time scale with an accuracy of ±5 ns relative to UTC. Time-comparison systems based on GNSS, TWSTFT, and optical fiber links supported maintenance of the national UTC(PL) time scale.

Scientific activities included publications in journals such as Remote Sensing and Metrologia, as well as conference presentations in laser tracking and space-debris research.

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1.5 DEPARTMENT OF GEODESY, UNIVERSITY OF WARMIA AND MAZURY IN OLSZTYN

Research conducted at the University of Warmia and Mazury in Olsztyn (UWM) focused on ionospheric modeling, GNSS positioning, earthquake-related ionospheric disturbances, low-cost GNSS technologies, and positioning in challenging environments.

UWM researchers evaluated the quality of the UWMG Global Ionospheric Maps (GIMs) through comparison with six widely used GIM products: CASG, CAS0, IGSG, UQRG, IRTG, and UADG. The evaluation covered two seven-day periods representing extreme solar activity from 9 to 15 May 2024 (DOY 130–136) and nominal solar activity from 8 to 14 July 2024 (DOY 190–196). The accuracy of the GIMs was validated using directly observed ground GNSS data and positioning-domain analyses. In the kinematic single-frequency PPP domain, UWMG maintained decimeter-level stability and effectively mitigated the impact of the severe geomagnetic storm.

UWM also participated in research on ionospheric responses to earthquakes and potential earthquake precursors within the framework of lithosphere–atmosphere–ionosphere coupling (LAIC). Recent work focused on larger-scale local VTEC anomalies. The application of UQRG VTEC maps from the IonSAT group at the Polytechnic University of Catalonia enabled detection of high-resolution VTEC changes. These anomalies revealed transient regional extrema concentrated over tectonic plate boundaries and resembling their shapes, supporting the occurrence of LAIC processes.

Preliminary studies were also conducted on correlations between VTEC time series, solar-wind parameters, and cumulative global seismicity during the second half of solar cycle 24. The team

analyzed eight years of UQRG maps and compared them with global seismic records and solar-wind data averaged over several-day windows. The results indicated discontinuous but frequent correlations between VTEC, solar wind, and cumulative seismic energy.

Further research addressed the applicability of low-cost and non-professional GNSS receivers for precise applications. A comprehensive assessment of smartphone GNSS observations was followed by an evaluation of low-cost GNSS receivers for geodetic surveying. The results showed that such receivers, when augmented with MEMS accelerometers, may meet the requirements of demanding applications such as precise vibration detection. UWM also developed novel multi-layer ionosphere mapping functions to support precise absolute positioning; assessments in PPP-RTK and observation domains showed that the new mapping function outperforms the standard single-layer model, particularly in equatorial regions.

UWM researchers also worked on improving GNSS positioning accuracy in challenging environments, including urban and forested areas. They developed the GNSS MPD tool, which predicts satellite visibility and detects multipath-affected signals using line-of-sight analysis and obstacle models derived from airborne LiDAR data. Validation through comparative visibility analyses and long-duration static positioning experiments showed that incorporating modeled satellite visibility into observation processing improves positioning accuracy and increases the success rate of position determination.

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1.6 INSTITUTE OF GEODESY AND GEOINFORMATICS, WROCŁAW UNIVERSITY OF ENVIRONMENTAL AND LIFE SCIENCES

The Institute of Geodesy and Geoinformatics (IGG) at the Wrocław University of Environmental and Life Sciences (UPWr) is an internationally recognized research centre specializing in satellite geodesy. In 2025, the Institute's activities focused on multi-GNSS processing, lunar navigation, global geodynamics, atmospheric modeling using artificial intelligence, and relativistic orbital physics.

A major research direction at IGG is the development of navigation infrastructure for the Moon, supporting the European Space Agency Moonlight initiative and the Lunar Communication and Navigation Service (LCNS). Researchers introduced a novel architecture for orbit determination and time synchronization (ODTS) based on K-band frequency links and the multiple spacecraft per aperture (MSPA) concept. IGG researchers also investigated broadcast ephemerides for satellites in highly eccentric lunar orbits and demonstrated that Chebyshev polynomials of degree 10 provide sub-decimeter reconstruction accuracy, significantly outperforming traditional Keplerian models in data efficiency and precision.

IGG also contributed to the definition of lunar reference systems, including refined standards for the Principal Axis (PA) and Mean Earth (ME) systems, as well as the establishment of relativistic lunar coordinate time (TCL). These standards are essential for integrated lunar navigation services and accurate lunar cartography.

The Institute developed an enhanced multi-GNSS orbit-combination methodology using a modified Förstner Variance Component Estimation (VCE) scheme. The framework incorporates machine learning, including hierarchical clustering, to identify satellite behavioral groups. It achieved inter-consistency below 3 mm for GPS and Galileo while stabilizing temporal Analysis Center weights. In time transfer, simultaneous estimation of station coordinates and tropospheric delays using VMF3 models provided the highest receiver clock stability, reaching 9.5×10^{-12} for global time synchronization.

IGG made significant progress in defining and correcting geocenter motion (GCM). Long-term evaluations spanning 1994–2025 showed that seasonal variations account for only 20–35% of total variance, with the remaining variability driven mainly by orbital artifacts. To mitigate these artifacts, IGG proposed combining GNSS microwave data with SLR observations to LAGEOS satellites, effectively reducing spurious draconitic signals in the Z component.

The Institute also plays an important role in validating and optimizing SLR-based geodetic parameters. Research on the LARES-2 mission confirmed that its solid-sphere construction enables precise orbit determination superior to LAGEOS-1/2 and reduces formal errors of the Z-geocenter component by up to 59%. In preparation for the Genesis mission, IGG simulations demonstrated its potential to reduce Z-geocenter motion errors below 1 mm, meeting Global Geodetic Observing System (GGOS) stability goals.

IGG uses inverse GNSS methods to estimate low-degree gravity-field coefficients, including C20 and C30, from global station displacements. This approach provides an independent alternative to SLR for monitoring Antarctic ice-sheet mass balance. In theoretical geodesy, IGG identified a previously neglected orbital relativistic correction associated with the Earth's oblateness term J2. This effect exceeds the geodetic precession currently included in the IERS Conventions and causes secular orbital rates of up to 5 mm/day, indicating that it should be included in future millimeter-accuracy missions.

Within atmospheric remote sensing, IGG developed a LEO satellite simulation package focused on the influence of satellite geometry on tropospheric retrieval for GNSS radio occultation, GNSS reflectometry, and LEO-PNT applications. For ionospheric studies, IGG assessed the quality of Real-Time Global Ionospheric Maps (RT-GIMs) and identified UPC products as the most stable during severe G4-class geomagnetic storms.

The TropoDeep framework was introduced to downscale weather-model outputs and improve InSAR tropospheric corrections. The method achieved an average RMSE improvement of 21%, with improvements of up to 40%, compared with standard correction services, and reduced tropospheric artifacts in subsidence time series by up to 66%. IGG researchers also investigated artificial-intelligence methods for tropospheric modeling in positioning; machine-learning networks used for wet-refractivity prediction during extreme weather reduced the MAE of three-dimensional position components by 8–33% in static mode and improved convergence time by 6–17% in kinematic real-time PPP.

IGG led an interdisciplinary review of artificial-intelligence-based weather models and was active in nowcasting research. A convolutional neural network approach integrating three-dimensional GNSS tropospheric tomography with Weather Research and Forecasting (WRF) data significantly improved regional rainfall prediction, achieving a Probability of Detection of up to 93% and reducing the False

Alarm Rate to 45%. IGG also developed high-resolution GNSS troposphere tomography using SRGAN and explainable AI, reducing RMSE by up to 62%.

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1.7 INSTITUTE OF GEODESY AND CARTOGRAPHY

The Institute of Geodesy and Cartography conducts research in physical geodesy, satellite gravimetry, height-reference systems, hydrological applications of space geodetic data, and the assessment of global geopotential models. Recent studies focused on temporal height variations relevant to the International Height Reference Frame (IHRF), hydrological monitoring in data-sparse regions, and accuracy assessment of satellite-only and combined global geopotential models.

Following the 2015 recommendation of the International Association of Geodesy concerning the establishment of the IHRF, the Institute investigated temporal variations of geoid, ellipsoidal, and orthometric heights at proposed IHRF sites. The study used GRACE and GRACE-FO satellite gravimetry data, GNSS, VLBI, SLR, DORIS, and hydrological data to estimate temporal variations of geoid height (ΔN), ellipsoidal height (Δh), and orthometric height (ΔH). The results showed that space geodetic data and hydrological models provide consistent estimates at proposed IHRF sites.

Peak-to-peak variations ranged from 5 to 30 mm for ΔN, from 10 to 55 mm for Δh, and from 15 to 80 mm for ΔH. Seasonal variations reached approximately 20 mm for ΔN, 33 mm for Δh, and 50 mm for ΔH. At 93% of proposed IHRF sites, secular variations did not exceed ±1 mm/year. However, in Greenland, post-glacial rebound areas, and forebulge-collapse regions, secular variations reached approximately +1 mm/year for ΔN, +11 mm/year for Δh, and +9.5 mm/year for ΔH, with minimum values reaching −3 mm/year. The study also demonstrated that Δh, ΔN, and ΔH can be predicted with an accuracy of 1–4 mm using machine-learning methods.

Another study investigated hydrological changes in Sudan using space geodetic data and their correlation with climate indices, including the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole. Temporal variations of equivalent water thickness (ΔEWT) were determined using GRACE/GRACE-FO data, hydrological models, and the IGiK-TVGMF software. Satellite altimetry was also used to obtain surface-water variations. The results showed good agreement between GRACE/GRACE-FO-derived ΔEWT and hydrological-model estimates, with strong correlations outside the Sahara region.

The Institute also assessed selected satellite-only and combined Global Geopotential Models (GGMs) over Poland and Ethiopia. The analyzed models included DIR_R06, TIM_R06, TIM_R06e, WHU, GOSG02S, SGG-UGM-2, and XGM2019e. High-quality terrestrial gravity anomalies from Poland and airborne gravity disturbances from Ethiopia were used as reference data. The main findings indicate that gravity anomalies in Poland and gravity disturbances in Ethiopia can be determined using SGG-UGM-2 with an accuracy of approximately 2 mGal. Satellite-only GGMs corrected for omitted gravity signals from EIGEN-6C4 and SRTM topography achieved similar accuracy, whereas XGM2019e remained at approximately 5 mGal.

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References

[1] Bury, G., Zajdel, R., & Sośnica (2025)Correcting geocenter motion in GNSS solutions by combining with satellite laser ranging data. GPS Solutions, 29, 158. https://doi.org/10.1007/s10291-025-01920-x

[2] Bury, G., Zajdel, R., & Sośnica, K. (2025). Design of the broadcast ephemerides for the Lunar Communication and Navigation Services system. Progress in Earth and Planetary Science, 12, 20. https://doi.org/10.1186/s40645-024-00676-1

[3] Dawidowicz, K., Paziewski, J.D., Stępniak, K., & Krzan, G. (2025). On the applicability of low-cost GNSS antennas to precise surveying applications. Measurement Science and Technology. https://doi.org/10.1088/1361-6501/ad83e7

[4] Godah, W., Yadeta, S., Szelachowska, M., & Fotopoulos, G. (2026). Assessment of temporal variations of geoid, ellipsoidal and orthometric heights at proposed IHRF sites using space geodetic data. Journal of Applied Geodesy, 20(1), 51–67. https://doi.org/10.1515/jag-2025-0018

[5] Godah, W., Yadeta, S., & Braun, A. (2025). Hydrological change from space geodetic data and correlation with climate indices in Sudan. Journal of African Earth Sciences, 227, 105608. https://doi.org/10.1016/j.jafrearsci.2025.105608

[6] Godah, W., Szelachowska, M., & Gedamu, A.A. (2024). Accuracy assessment of high and ultra-high-resolution combined GGMs, and recent satellite-only GGMs: Case studies of Poland and Ethiopia. Reports on Geodesy and Geoinformatics, 117, 38–44. https://doi.org/10.2478/rgg-2024-0005

[7] Haji-Aghajany, S., Rohm, W., Lipinski, P., & Kryza, M. (2025). Beyond the horizon: A comprehensive analysis of artificial intelligence-based weather forecasting models. Engineering Applications of Artificial Intelligence, 162, 112335.

[8] Haji-Aghajany, S., Izanlou, S., Tasan, M. et al. (2025). High-resolution GNSS troposphere tomography through explainable deep learning-based downscaling framework. Satellite Navigation, 6, 22. https://doi.org/10.1186/s43020-025-00177-6

[9] Haji-Aghajany, S., Rohm, W., Hadas, T., & Bosy, J. (2025). Machine learning-based tropospheric delay prediction for real-time precise point positioning under extreme weather conditions. GPS Solutions, 29, 36.

[10] Haji-Aghajany, S., Tasan, M., Izanlou, S., & Rohm, W. (2025). TropoDeep: A deep learning-based model for InSAR tropospheric correction on large-scale interferograms using GNSS and WRF outputs. Journal of Geodesy, 99, 76.

[11] Hoque, M.M., Yuan, L., Nykiel, G., Frauenberger, O., Paziewski, J., Sieradzki, R., Wielgosz, P., Dhital, N., & Pérez, R.O. (2025). Multi-layer ionosphere mapping function for ground and LEO GNSS data and its performance analysis. Satellite Navigation, 6, 33. https://doi.org/10.1186/s43020-025-00182-9

[12] Hordyniec, P., Haase, J.S., Murphy, M.J. Jr., Cao, B., Wilson, A.M., & Banos, I.H. (2025). Forward modeling of bending angles with a two-dimensional operator for GNSS airborne radio occultations in atmospheric rivers. Journal of Advances in Modeling Earth Systems, 17, e2024MS004324. https://doi.org/10.1029/2024MS004324

[13] Iess, L., Di Benedetto, M., Boscagli, G. et al. (2025). A novel orbit determination and time synchronization architecture for a radio navigation satellite constellation in the cislunar environment. Navigation, 72(3), 1–38. https://doi.org/10.33012/navi.713

[14] Jarmołowski, W., Wielgosz, P., Krypiak-Gregorczyk, A., & Milanowska, B. (2026). An eight-year global look at correlations between total electron content, earthquakes and solar wind. Advances in Space Research, 77(2), 2508–2521. https://doi.org/10.1016/j.asr.2025.10.064

[15] Kur, T., Najder, J., & Sośnica, K. (2025). Genesis contribution to SLR-based geodetic parameters. Journal of Geodesy, 99, 87. https://doi.org/10.1007/s00190-025-02007-8

[16] Kur, T., Śliwińska-Bronowicz, J., Wińska, M., Dobslaw, H., Nastula, J., Partyka, A., Belda, S., Bizouard, C., Boggs, D., Bruni, S., Chen, L., Dhar, S., Dill, R., Duan, P.S., Ferrándiz, J.M., Gou, J., Gross, R., Guessoum, S., Han, S., et al. (2024). Prospects of predicting polar motion based on the results of the Second Earth Orientation Parameters Prediction Comparison Campaign. Earth and Space Science, 11, e2023EA003278. https://doi.org/10.1029/2023EA003278

[17] Lejba, P., Michałek, P., Suchodolski, T., Smagło, A., Matyszewski, M., & Zapaśnik, S. (2024). Laser observations of GALILEO satellites at the CBK PAN Astrogeodynamic Observatory in Borowiec. Remote Sensing. https://doi.org/10.3390/rs16152862

[18] Makuch, S., & Rohm, W. (2025). LEO satellites simulation for GNSS tomography. Advances in Space Research. https://doi.org/10.1016/j.asr.2025.11.008

[19] Margolis, H.S., Godun, R.M., Huntemann, N., Le Targat, R., Dunst, P., Lemański, D., Nawrocki, J., Nogaś, P., et al. (2024). Robust Optical Clocks for International Timescales (ROCIT). Journal of Physics: Conference Series. https://doi.org/10.1088/1742-6596/2889/1/012022

[20] Michalczak, M., Śliwińska-Bronowicz, J., Wińska, M., Partyka, A., Ligas, M., & Nastula, J. Exploring various approaches to combine selected Earth Rotation Parameter predictions gathered during the Second Earth Orientation Parameters Prediction Comparison Campaign (2nd EOP PCC). Journal of Geodesy.

[21] Mikoś, M., Kaźmierski, K., & Sośnica, K. (2025). Multi-GNSS time transfer with different modeling of station coordinates and troposphere delays. GPS Solutions, 29, 192. https://doi.org/10.1007/s10291-025-01950-5

[22] Morzyński, P., Bilicki, S., Bober, M., Kovačić, D., Ciuryło, R., Zawada, M., Nawrocki, J., Dunst, P., Kobayashi, T., Hosaka, K., & Akamatsu, D. (2024). Intercontinental frequency ratio measurement of Yb and Sr optical lattice clocks. Metrologia. https://doi.org/10.1088/1681-7575/ad6a1e

[23] Nastula, J., Śliwińska-Bronowicz, J., Wińska, M., & Kur, T. (2024). Analysis of combined series of hydrological angular momentum developed based on climate models. Frontiers in Earth Science, 12, 1369106, 1–20. https://doi.org/10.3389/feart.2024.1369106

[24] Nowak, A., Zajdel, R., Gałdyn, F. et al. (2025). Low-degree gravity-field coefficients based on inverse GNSS method: Insights into hydrological and ice-mass change studies. GPS Solutions, 29, 5. https://doi.org/10.1007/s10291-024-01760-1

[25] Partyka, A., Nastula, J., Śliwińska-Bronowicz, J., Wińska, M., & Michalczak, M. (2024). Comparison of short-periodic polar motion and UT1-UTC variations obtained from various EOP solutions. Proceedings of the 9th International Colloquium on Scientific and Fundamental Aspects of GNSS, 25–27 September 2024, Wrocław. https://doi.org/10.57780/esa-0yq5l8b

[26] Partyka, A., Śliwińska-Bronowicz, J., Nastula, J., Wińska, M., & Michalczak, M. The impact of reference series selection when evaluating celestial pole offset predictions. Earth, Planets and Space. https://doi.org/10.1186/s40623-026-02443-6

[27] Paziewski, J., Hoque, M.M., Sieradzki, R., Frauenberger, O., Wielgosz, P., Dhital, N., Nykiel, G., & Perez, R.O. (2026). Validation of a multi-layer approach-based ionospheric mapping function supporting PPP-AR. Satellite Navigation, 7, 7. https://doi.org/10.1186/s43020-026-00193-0

[28] Paziewski, J., Sieradzki, R., Rapiński, J., Tomaszewski, D., Stępniak, K., Geng, J., & Li, G. (2025). Integrating low-cost GNSS and MEMS accelerometer for precise dynamic displacement monitoring. Measurement, 242, 115798. https://doi.org/10.1016/j.measurement.2024.115798

[29] Rapiński, J., & Tomaszewski, D. (2026). On the geometry of GBAT and its implications on positioning accuracy. GPS Solutions, 30, 2. https://doi.org/10.1007/s10291-026-02062-4

[30] Rambaux, N., Fienga, A., Seyffert, Y., Sośnica, K. et al. (2026). Lunar reference systems and their realisations using INPOP ephemerides. Astronomy & Astrophysics, 705, A88. https://doi.org/10.1051/0004-6361/202555962

[31] Sieradzki, R., & Paziewski, J. (2025). Analyzing the stochastic properties of code observations using various low-cost GNSS receivers. GPS Solutions, 29, 168. https://doi.org/10.1007/s10291-025-01926-5

[32] Sośnica, K., & Gałdyn, F. (2025). Orbital relativistic correction resulting from the Earth's oblateness term. Journal of Geodesy, 99, 52. https://doi.org/10.1007/s00190-025-01973-3

[33] Sośnica, K., Gałdyn, F., Zajdel, R. et al. (2025). LARES-2 contribution to global geodetic parameters from the combined LAGEOS-LARES solutions. Journal of Geodesy, 99, 1. https://doi.org/10.1007/s00190-024-01925-3

[34] Solovey, T., Śliwińska-Bronowicz, J., Janica, R., & Brzezińska, A. (2024). Terrestrial water storage changes in the Bug River transboundary catchment observed by GRACE and water balance analysis. Meteorology, Hydrology and Environmental Monitoring, 2(6), 4–16. https://doi.org/10.15407/Meteorology2024.06

[35] Solovey, T., Śliwińska-Bronowicz, J., Janica, R., & Brzezińska, A. (2025). Assessment of the Effectiveness of GRACE Observations in Monitoring Groundwater Storage in Poland. Water Resources Research, 61(8). https://doi.org/10.1029/2024WR038888

36] Solovey, T., Śliwińska-Bronowicz, J., Janica, R., Brzezińska, A., & Stradczuk, A. (2025). Fusing GRACE data into terrestrial water budgets to improve their predictive performance: a case study of the Bug River Transboundary Catchment, Polish-Ukrainian-Belarusian borderland. Geological Quarterly, 69(2), 1–23. https://doi.org/10.7306/gq.1789

[37] Solovey, T., Śliwińska-Bronowicz, J., Janica, R., Stradczuk, A., & Brzezińska, A. (2025). Temporal and spatial variability of groundwater storage derived from downscaled GRACE data in the transboundary Bug River Basin (Poland–Ukraine–Belarus border region). Science of the Total Environment, 1009. https://doi.org/10.1016/j.scitotenv.2025.181023

[38] Strugarek, D., & Sośnica, K. (2025). Modeling range biases from SLR residuals to GNSS-based orbits of active Low Earth Orbiters: Insights from a study based on a dozen satellites and 21 years of data. GPS Solutions, 29, 154. https://doi.org/10.1007/s10291-025-01916-7

[39] Śliwińska-Bronowicz, J., Kur, T., Wińska, M., Dobslaw, H., Nastula, J., Partyka, A., Belda, S., Bizouard, C., Boggs, D., Bruni, S., Chen, L., Chin, M., Dhar, S., Dill, R., Manuel, J., Junyang, F., Richard, G., Sonia, G., Han, S., et al. (2024). Assessment of length-of-day and universal time predictions based on the results of the Second Earth Orientation Parameters Prediction. Journal of Geodesy, 98(22). https://doi.org/10.1007/s00190-024-01824-7

[40] Wielgosz, P., Jarmołowski, W., Mazur, S., Milanowska, B., & Krypiak-Gregorczyk, A. (2025). Vertical total electron content enhancements and their global distribution in relation to tectonic plate boundaries. Remote Sensing, 17, 614. https://doi.org/10.3390/rs17040614

[41] Wińska, M., Kur, T., Śliwińska-Bronowicz, J., Nastula, J., Dobslaw, H., Partyka, A., Belda, S., Bizouard, C., Boggs, D., Chin, M., Dhar, S., Ferrandiz, J.M., Gou, J., Gross, R., Guessoum, S., Heinkelmann, R., Modiri, S., Ratcliff, T., Raut, S., et al. (2024). Findings on celestial pole offsets predictions in the second Earth Orientation Parameters Prediction Comparison Campaign (2nd EOP PCC). Earth, Planets and Space, 76(1). https://doi.org/10.1186/s40623-024-02042-3

[42] Wińska, M., Staniszewska, D., Śliwińska-Bronowicz, J., & Nastula, J. Interannual linkage between LOD and ENSO: Insights from geodetic observations, geophysical models, and climate indices. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing. https://doi.org/10.1109/JSTARS.2026.3690967

[43] Yu, H., Liu, W., Zhang, L., Sośnica, K., & Wang, J. (2025). A novel scaling factor correction for GRACE terrestrial water storage anomalies in the Yellow River Basin. Journal of Hydrology: Regional Studies, 59, 102466. https://doi.org/10.1016/j.ejrh.2025.102466

[44] Yu, H., Zhang, Y., Sun, Y., Sośnica, K., & Shen, Y. (2025). Analysis of fingerprint-derived geocentre motion time series using multichannel singular spectrum analysis. Geophysical Journal International, 243(1), ggaf310. https://doi.org/10.1093/gji/ggaf310

[45] Yu, K., Li, Z., Nilsson, T., Wang, X., Nurul Huda, I., Śliwińska-Bronowicz, J., Wu, Z., & Jiang, W. High-frequency Earth rotation parameters estimated from VLBI observations during CONT campaigns. Surveys in Geophysics.

[46] Zajdel, R., Balidakis, K., Nowak, A., Kur, T., Sośnica, K., & Douša, J. (2026). Three decades of GNSS-derived geocenter motion: Disentangling geophysical signal from systematic errors. Advances in Space Research, 77(1), 74–100. https://doi.org/10.1016/j.asr.2025.11.053

[47] Zajdel, R., Mansur, G., Sakic, P. et al. (2025). Advancing multi-GNSS orbit combination in the variance component estimation framework. Journal of Geodesy, 99, 90. https://doi.org/10.1007/s00190-025-02005-w

2

REMOTE SENSING

2.1 EARTH OBSERVATION DEPARTMENT SPACE RESEARCH CENTRE PAS

The Earth Observation Department (ZOZ) at the Space Research Centre of the Polish Academy of Sciences (CBK PAN) conducts scientific and applied research focused on the processing and analysis of optical and radar satellite data. The department's expertise covers land cover classification, biodiversity monitoring, climatology, and the integration of satellite observations with socio-economic phenomena. The Crisis Information Centre (CIK) operates as an dedicated unit within the Department.

Earth Observation Department develops new satellite data processing methods for the identification, monitoring, and modelling of processes occurring on the Earth's surface within an interdisciplinary framework. It also carries out applied research and develops products tailored to the needs of stakeholders.
ZOZ actively participates in European projects funded under Horizon Europe, EEA, and Norway Grants, European Space Agency (ESA), Polish Space Agency (POLSA), as well as national research initiatives. In response to the current geopolitical situation, the department is also increasingly engaged in security- and defence-related activities.

The department's work extends beyond Poland and Europe to Africa, Asia, and North America. Advanced satellite data processing methods are employed, with a strong emphasis on automation across all stages of analysis. This is supported by the department's capacity to develop dedicated software solutions. Competencies in machine learning (ML), deep learning (DL), and artificial intelligence (AI) applications are continuously expanding.

ZOZ researchers publish their works in renowned scientific journals, regularly participate in international conferences and contribute to EuroGEO Action Groups. Through involvement in advisory bodies and expert panels, the department plays an important role in shaping the development of Earth Observation in Poland and on a European level.

Further information on selected projects and publications is available at: https://zoz.cbk.waw.pl/
Among the recent major achievements and activities there are:

- Production of an annual land cover map of Poland for the Polish Space Agency (since 2019). The project uses multitemporal Sentinel-2 imagery acquired during the vegetation season and classified using the S2GLC algorithm developed within an ESA project: https://s2glc.cbk.waw.pl/. The method is fully automated and based on a Random Forest classifier. Its distinctive feature is the use of existing low-resolution databases as reference data sources.

- A multi-directional analysis of refugee/IDP camp areas based on HR/VHR satellite data (within the ARICA project, leadered by ZOZ ans co-ordinated with entities from in Tanzania and Bangladesh). The project analysed land cover and land-use changes around refugee settlements using Earth Observation data combined with field measurements. It also examined vegetation succession processes in rapidly changing environments (1). The results are applied at the dedicated GeoPlatform https://geoplatform-arica.gridw.pl/.

- EOTiST project, investigating the environmental benefits and ecosystem services provided to society. ZOZ collaborated with leading European Earth Observation centres on research covering three main

categories of ecosystem services: provisioning services (e.g. food and energy production), regulating services (e.g. CO_2 sequestration, soil erosion prevention, and soil purification), and cultural services (e.g. tourism, recreation, education, and aesthetic value).

- Satellite climatology (2) research focused on cloud studies aimed at improving understanding of the Earth's radiation budget. Research activities also assessed the accuracy of CALIPSO transect lidar measurements of key cloud parameters compared with full spatial averaging methods. Additional studies analysed the influence of measurement grid resolution on uncertainty levels and identified areas requiring further uncertainty assessment.

- The light pollution research - a phenomenon clearly visible in nighttime satellite imagery, that initiated a nationwide discussion on this topic, also in resulting in the slogan "Save the Night" that has become an important symbol of awareness regarding the environmental and societal impacts of excessive artificial lighting.

- The European FPCUP – Caroline Herschel Framework Partnership Agreement project, which promoted the use of applications and services based on Copernicus data. In total, ZOZ contributed to nine actions related to environmental monitoring across Europe, South America, and Africa. The department also organised seminars and Earth Observation training sessions.

- "Where is Snow?" - the automated snow monitoring service available at https://snieg.cbkpan.pl/en/. The platform provides daily updated maps of snow cover across Europe and attracts considerable public and scientific interest.

- Strengthening of competencies in AI-based methods for satellite data analysis. These competencies are applied both to environmental monitoring and to security and defence applications. In this area, ZOZ collaborates closely with the Institute of Theoretical and Applied Informatics of the Polish Academy of Sciences in Gliwice.

- Editorial, scientific and expertise contribution to the Hovering Horizon Magazine (since 2025), produced on a bi-monthly basis for Copernicus SESA Service and SatCen (EU Satellite Centre), designed to keep readers at the forefront of developments in Space and Security.

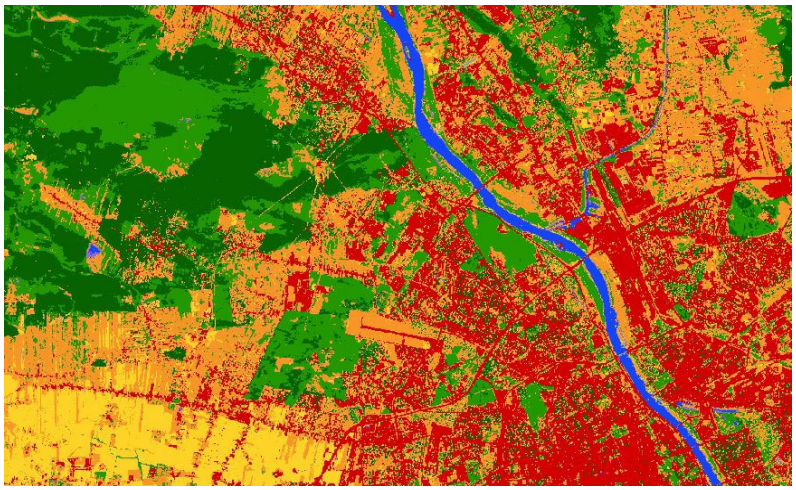

Figure 2.1.1. S2GLC land cover classification, north-western part of Warsaw

Authors and Afiliation: Stanisław Lewiński, Anna Pacholak Centrum Badań Kosmicznych PAN

Selected References:

[1] Domingo-Marimon, C., Jenerowicz-Sanikowska, M., Pesquer, L., Ruciński, M., Krupiński, M., Woźniak, E., Foks-Ryznar, A., Quader, M.A., Developing an early warning land degradation indicator

based on geostatistical analysis of Ecosystem Functional Types dynamics, Ecological Indicators, 169 112815, 2024, https://doi.org/10.1016/j.ecolind.2024.112815

[2]Kotarba, A. Z., Wojciechowska, I., Satellite-based detection of deep-convective clouds: the sensitivity of infrared methods and implications for cloud climatology, Atmos. Meas. Tech., 18, 2721–2738, 2025, https://doi.org/10.5194/amt-18-2721-2025

2.2 CRISIS INFORMATION CENTRE OF THE POLISH ACADEMY OF SCIENCES

In line with its motto, “The right information to the right people at the right time,” the mission of the Crisis Information Centre (CIK) at CBK PAN is to enhance the effective use of geospatial data in civil protection, with a particular focus on the rapid delivery of information derived from satellite and drone-based remote sensing.

Accordingly, CIK:

- provides operational support aimed at improving situational awareness through the use of satellite and UAV data, including on-demand delivery of geoinformation products such as maps and analyses for civil security entities;
- develops innovative solutions, procedures, and operational know-how for the use of GIS, satellite observation, and UAV technologies;
- organises trials, demonstrations, and training activities in these fields.

In 2025, CIK launched the Civil Security Hub Poland initiative, designed to connect technology providers with end users. The Hub supports the development, testing, and operational deployment of solutions based on satellite technologies and drone data, tailored to user requirements. Its overall objective is to maximise the effective use of innovation in crisis management and rescue operations. Civil Security Hub Poland forms part of the European Space Agency’s Space Resilience Nodes initiative.

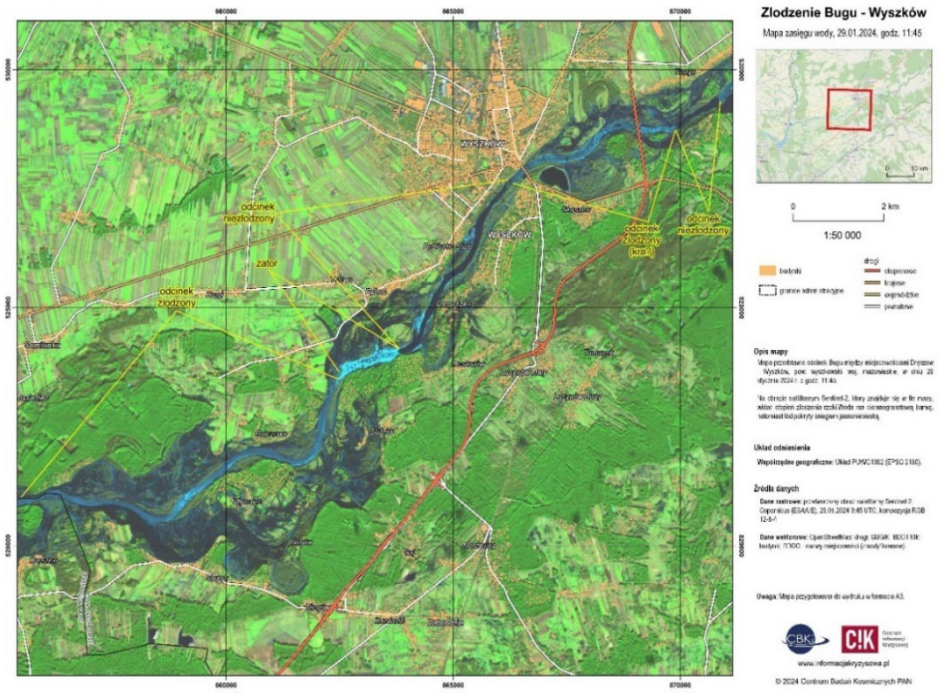

Figure 1.2.1. Map prepared by CIK showing the ice situation on the Bug River near Wyszków, January 29, 2024.

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2.3. INSTITUTE OF GEODESY AND CARTOGRAPHY

The Remote Sensing Center was established in 1976. as the Satellite Image Processing Center (OPOLiS). Currently, the Remote Sensing Center carries out various research topics using optical and radar data, from the COPERNICUS Program. The Center has been active in the international Projects of EC, ESA and Norwegian Fund as well as cooperation between Poland and SA and National Projects. The Center develops innovative applications models which are used by Polish Space Agency, National Statistics, Communes, farmers and National Forests.

BIOMASS & DROUGHT EFFECTS

GrasSAT - Tools for information to farmers on grasslands yields under stressed conditions to support management practices under Norwegian Fund

The main objective of the project was to develop a comprehensive system for managing green forage production and tools for information to farmers in Poland and Norway. A desktop and mobile platform was developed to support farming practices through the application of satellite imagery. The study integrated radar and optical imagery and field observations for spatiotemporal biomass estimation. The model predicted wet biomass, evaluated the drought conditions and the differences in growth between the years .

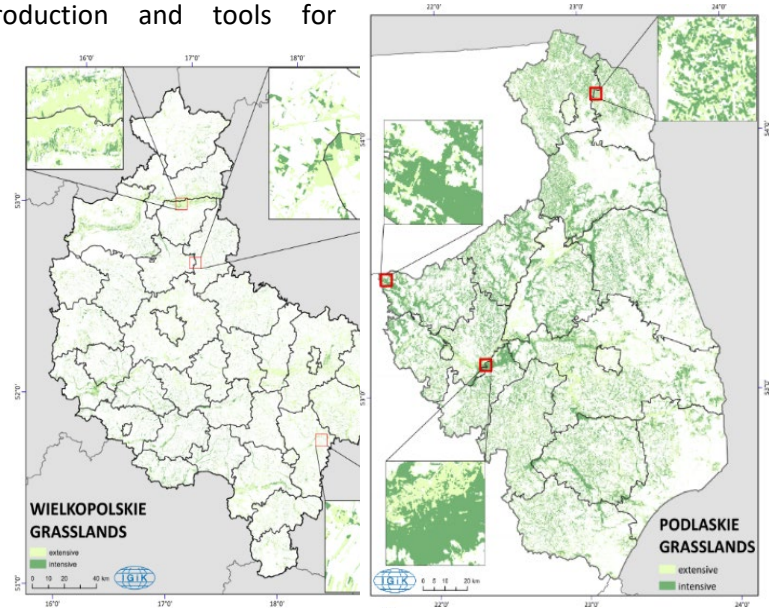


Figure 2.3.1. Maps of grassland management intensity classification for Wielkopolskie and Podlaskie Voivodeships.

The National Centre for Research and Development - NCBiR

South Africa ARC(Agriculture Research Council) Pretoria - Polish collaborative crop growth monitoring and yield assessment -SAPOL4Crop

The main goal of the project was to develop a common operational system for crop growth monitoring in South Africa and Poland. The system was based on the integration of Copernicus satellite data, low resolution satellite imagery, meteorological data, and in situ observations.

FPCUP Agriculture - Common System and Platform, Based on Copernicus Data and Services, for Agricultural Agencies in Poland European Commission

The project focused on the implementation of Copernicus data and services in the agricultural and environmental sectors in Poland. The main objective was to support end users in the application of Earth Observation data for monitoring climate change-related threats such as droughts and frost damage.

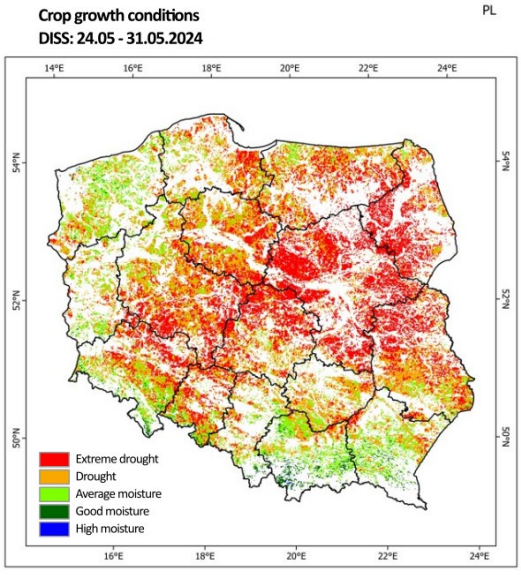
Smart System for Monitoring and Estimating Carbon Storage and Leakage in Agriculture Using Satellite Data (PRIME)

The PRIME project aimed to develop a concept and demonstrator of an Earth Observation (EO)-based system for monitoring carbon sequestration and greenhouse gas emissions in agriculture, supporting future carbon accounting and regulatory frameworks. Extensive consultations with stakeholders from key sectors (agriculture, agri-tech, certification bodies, insurance, finance, and public administration) confirmed strong demand for transparent, auditable, and scalable solutions aligned with emerging EU climate policies.

Polish Space Agency (POLSA)

Satellite Monitoring of Agricultural Drought in Poland

As part of the project, databases and map products are developed, providing analyses of drought conditions for individual growing seasons. The core products include crop growth condition maps based on the Drought Identification Satellite System (DISS). The crop yield reduction assessment maps are produced for major crop groups, including winter cereals, spring cereals, root crops, maize, and winter rapeseed.



European Space Agency ESA

Generating Advanced Usage of Earth Observation for Smart Statistics

The GAUSS project aimed to demonstrate the potential of satellite data for official statistics in the field of monitoring air quality, water resources, snow cover, and the extent and

The GAUSS project demonstrated the potential for operational implementation of satellite data to enrich the databases of European statistical units (Eurostat) with indicators supporting monitoring of the state of the natural environment. The Institute of Geodesy and Cartography was responsible for developing a procedure to assess the quality and extent of green areas at the level of local administrative units, based on Sentinel-2 data, Copernicus Land Monitoring Service products, and ERA5 reanalysis. This constituted an important element in assessing well-being conditions at the commune level.

Copernicus Programme / European Commission

Copernicus Border Surveillance Service Evolution / Digital Twin for Border Management - FRONTEX

The main objective of the project is the development of a concept and demonstrator of a Digital Twin for border management based on Copernicus Earth Observation data. The project focuses on the integration of satellite-derived information with geospatial models to support operational monitoring and decision-making processes in border areas. The Digital Twin concept is implemented as a continuously updated spatial model, integrating satellite observations with analytical tools to support near real-time decision-making processes.

Figure.2.3.2. Operational image – situational awareness reconnaissance (photo by Sebastian Banaszek).

Figure. 2.3.3. System screenshots – analysis and scoring results / operational module.

Figure. 2.3.4. Award ceremony: 10 Years of Copernicus at Frontex: Anniversary Event and Prize Award in Warsaw.

The National Centre for Research and Development / POLNOR Programme (Norway Grants)

InCoNaDa – Enhancing the user uptake of Land Cover / Land Use data from Copernicus

Project duration: 2020–2024

The main objective of the InCoNaDa project is to increase the usability and operational uptake of Copernicus Land Monitoring Service (CLMS) products, particularly in the domain of land cover and land use (LULC), through integration with national geospatial datasets and user-oriented applications.

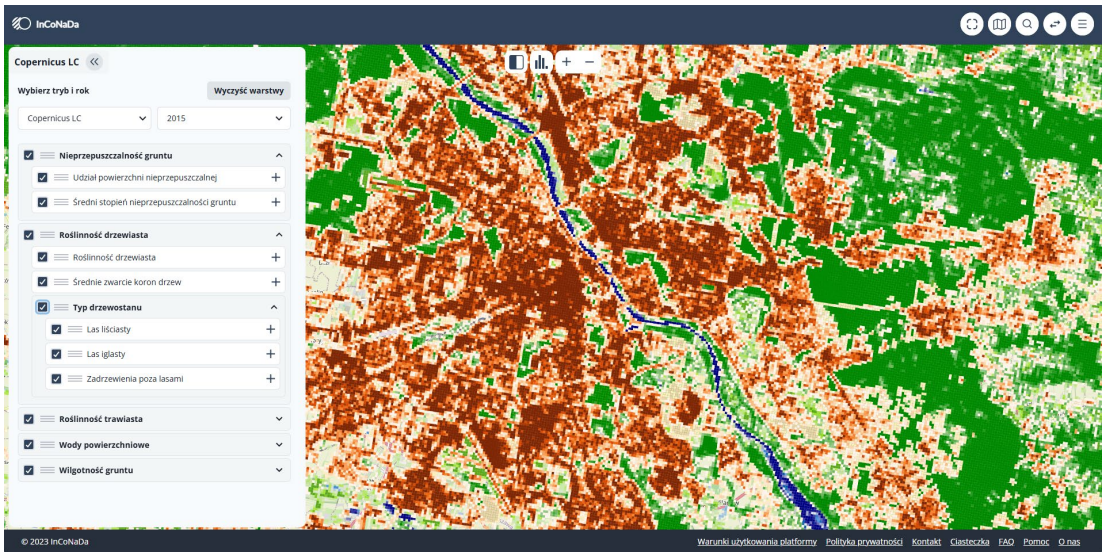
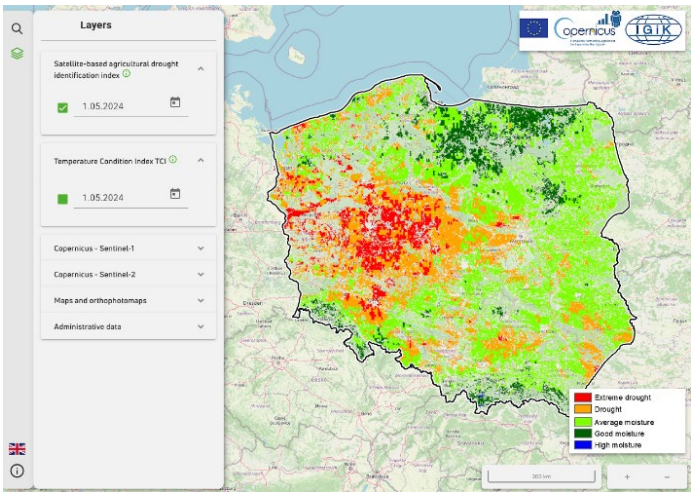


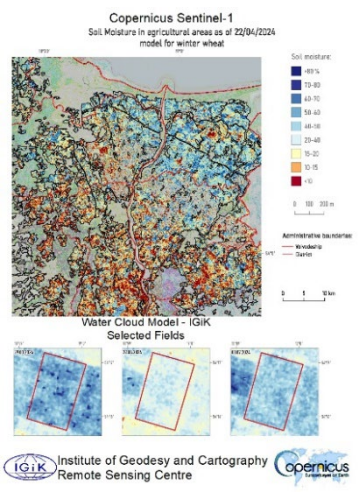
Figure. 2.3.5. Interface of the InCoNaDa web application.

Project financed by the General Directorate of State Forests (DGLP)

Identification of forests occurring on former agricultural land based on archival satellite imagery from the CORONA mission and contemporary imagery from the Sentinel-2 mission, as well as the development of a method for detecting and monitoring weakened forest stands using satellite spectral indices.

The project covered the identification of forests that have been developed on former agricultural land since the 1960s. The research addressed the need to detect stands that are becoming weakened due to various biotic and abiotic factors.





European Commission

FPCUP Baltic – Open Data Framework for the Baltic Sea Drainage Basin

The objective of FPCUP projects was to provide additional services that expanded the portfolio of products and services based on Copernicus data for sectoral information systems and agricultural agencies.

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3

SPACE PHYSICS

3.1 SPACE PHYSICS

3.1.1. LOFAR PL610 station in Borówiec

Figure 3.1.1. LOFAR PL610 station in Borówiec – aerial view

In the past few years, the LOFAR PL610 station in Borowiec, operated by Space Research Centre PAS, continued to strengthen its role within the European low-frequency radio astronomy and space weather research infrastructure. The station supported both regular LOFAR network observations and independent stand-alone campaigns, contributing to studies of the ionosphere, solar wind, heliosphere, and radio astronomy phenomena. Alongside scientific observations, extensive technical work was carried out to improve reliability, data processing, and operational efficiency, reinforcing PL610's position as an important component of the international LOFAR system.

LOFAR Ionospheric Research Group (LIRG) was established in 2024 to support and coordinate activities across different research groups in ionospheric studies. The coordinated work under the LIRG umbrella resulted in several important studies. Among them, work led by Alan Wood and collaborators and submitted to the JSWSC, analysed over 2,800 hours of LOFAR observations of Cassiopeia A and showed that many mid-latitude ionospheric disturbances are linked to atmospheric gravity waves generated by thunderstorms rather than geomagnetic storms. Another study, led by Rebecca Ghidoni, investigated the extreme ionospheric conditions during the May 2024 "Mother's Day" geomagnetic superstorm, demonstrating LOFAR's high sensitivity to rapid scintillation and electron density changes at low frequencies.

3.1.2. PLASMA DATA AND OBSERVATIONS

Horizon 2020 **PITHIA-NRF project** (Plasmasphere, Ionosphere, Thermosphere Integrated Research Environment and Access Services) was successfully completed in 2025. The initiative aimed to establish a distributed European research environment integrating observational facilities, modelling tools, and data services dedicated to studies of the ionosphere, thermosphere, and plasmasphere. The consortium brought together 22 leading European research institutions. Within the project, PL610 actively supported coordinated observational campaigns, delivered high-quality radio datasets to the PITHIA e-Science Centre, and contributed to the validation and dissemination of scientific and technical results. As part of the PITHIA-NRF activities, the CBK PAS group, using data from the PL610 station,

participated in two Trans-National Access projects: RadioScint, with UKRI STFC RAL Space, focused on interplanetary scintillation studies of the solar wind, and SUNDIAL, with the Institute of Atmospheric Physics of the Czech Academy of Sciences, investigating ionospheric disturbances over Europe related to CIR-driven storms.

BiRaKos project, started in 2025, dedicated to the development of a bistatic passive radar system for monitoring objects in low Earth orbit. The project explores integrating passive radar methods with radio astronomy infrastructure, using commercial radio and television transmitters as illuminators of opportunity. PL610 supplies high-quality observational data from the LOFAR array, enabling the development and validation of advanced signal-processing algorithms designed to detect and track weak reflections from satellites and space debris. Research focuses particularly on noise suppression, improved signal detectability, and accurate trajectory estimation under difficult observational conditions. The project also includes the development of dedicated software and preparatory work on a physical demonstrator of the radar system. Through its contribution to BiRaKos, PL610 supports the advancement of innovative long-range space surveillance technologies and demonstrates the broader applicability of radio astronomy infrastructure in space situational awareness.

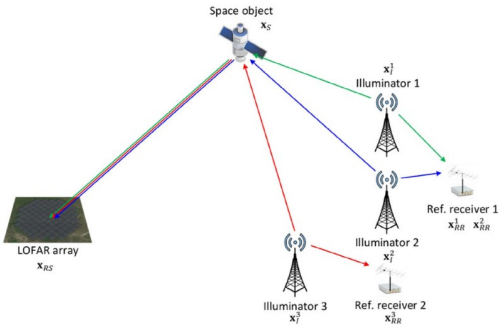


Figure 3.1.2. Configuration of the LOFAR PL610 testing system

In **stand-alone operational mode**, PL610 continued systematic studies of ionospheric irregularities through continuous scintillation monitoring campaigns. Dynamic spectra of strong radio sources were analysed to investigate temporal changes in signal intensity associated with ionospheric disturbances. In parallel, wide-field sky imaging at 32 MHz enabled the estimation of ionospheric gradients by measuring the apparent positional shifts of radio sources due to ionospheric refraction. These combined approaches provided a new perspective on mid-latitude ionospheric dynamics and electron density structures. PL610 also contributed to interplanetary scintillation (IPS) observations within the UK-coordinated RISE-R project, using compact radio source measurements to estimate solar wind velocity and turbulence, thereby demonstrating the capability of a single LOFAR station to support routine heliospheric monitoring

3.1.3. SPACE MISSIONS

JUICE (Jupiter Icy Moons Explorer) is an ESA mission dedicated to the exploration of Jupiter and its three largest icy moons: Ganymede, Europa, and Callisto. The mission aims to investigate their subsurface oceans, geological evolution, and potential habitability, as well as to study Jupiter's atmosphere, magnetosphere, and the dynamics of the Jovian system.

The spacecraft was launched on 14 April 2023 on an Ariane 5 rocket from French Guiana and is currently in its interplanetary cruise phase. It successfully completed a Lunar–Earth gravity assist in

August 2024 and a Venus gravity assist in August 2025. JUICE remains in good health and is on a trajectory for Jupiter arrival in July 2031, after which it will perform a series of flybys within the Jovian system before eventual orbit insertion around Ganymede.

Figure 2.1.3.1. JUICE – artist's impression. ESA.

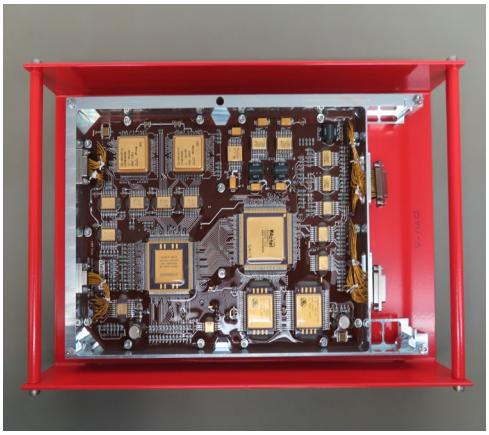


Figure 3.1.3.2. Data Processing Unit developed at the Space Research Centre, Polish Academy of Sciences (CBK PAN)

The Space Research Centre of the Polish Academy of Sciences (CBK PAN) plays a key role in the JUICE mission through its contribution to two onboard scientific instruments: RPWI (Radio & Plasma Wave Investigation) and SWI (Submillimetre Wave Instrument). For RPWI, CBK PAN was responsible for the design and development of the Data Processing Unit (DPU) module and the instrument electronics box, as well as the preliminary design of Langmuir probe booms and RWI antennas. The instrument is used to study plasma processes and radio emissions in the Jovian system. In addition, CBK PAN contributes to SWI data processing and subsystem development, supporting measurements of atmospheric composition, temperature, and dynamics of Jupiter and its icy moons.

Comet Interceptor is an ESA F-class "fast" mission designed to study a pristine long-period comet from the Oort Cloud or a first-time interstellar object entering the Solar System. The mission will consist of a main spacecraft (A) and two probes (B1 and B2). Developed under the leadership of the Space Research Centre of the Polish Academy of Sciences (SRC PAS), the versions of the DFP (Dust, Fields and Plasma) instrument will be placed on A and B2, to enable simultaneous multi-point in situ measurements of dust, plasma, and electric and magnetic fields in the comet environment. These coordinated observations will allow reconstruction of the three-dimensional structure of the coma and improve understanding of cometary evolution and Solar System formation.

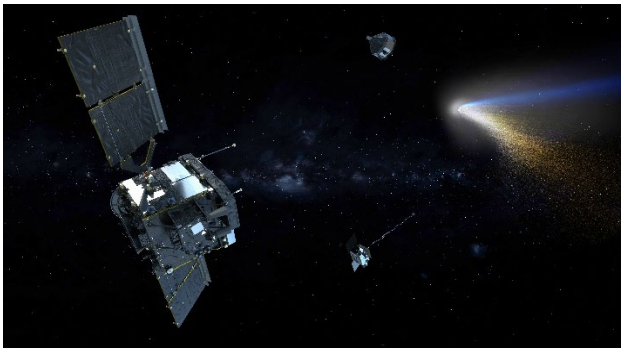


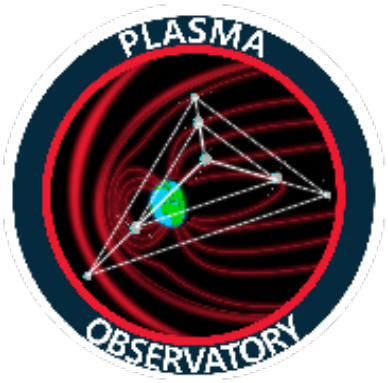
Figure 3.1.3.3. Comet Interception – artist's impression. ESA.

The DFP instrument plays a central role in this effort and is part of a broader international consortium led scientifically by Prof. Hanna Rothkaehl from CBK PAN. The Space Research Centre PAS is responsible for key subsystems, including the power supply unit (PSU) and electronics box (CEBOX), as well as

instrument integration, testing, operations coordination, and data management. In 2025, the Comet Interceptor mission's DFP-B2 instrument underwent integration and testing, including magnetic calibration, thermal-vacuum (TVAC) testing, and vibration testing. The mission progresses toward its planned launch on an Ariane 6 rocket in 2028–2029.

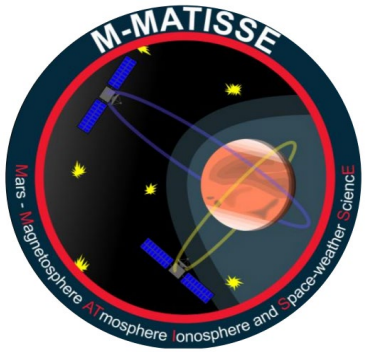
ESA M7-class mission candidates: Plasma Observatory and M-Mattise

The Space Research Centre of the Polish Academy of Sciences (CBK PAN) is actively involved in preparations for two ESA M7-class mission candidates: **Plasma Observatory** and **M-MATISSE.**



The **Plasma Observatory** mission is designed to investigate how energy is transferred and how particles are energised within Earth's near-space plasma environment through coordinated multi-scale observations. It addresses key ESA Medium Mission themes from the Voyage 2050 framework, specifically Magnetospheric Systems and Plasma Cross-scale Coupling. The mission aims to answer fundamental science questions concerning the mechanisms of particle energisation in space plasmas and the dominant processes governing energy transport and coupling between different regions of Earth's magnetospheric system, thereby improving understanding of how the near-Earth plasma environment functions as a whole.

In June 2025, the mission underwent a reformulation, changing its design from one mothercraft and six daughters to a constellation of 7 sister spacecraft (SSCs). Each SSC hosts advanced instrumentation, including magnetic and electrical fields, as well as particle instruments. The Space Research Centre PAS plays a key scientific, technical, and managerial role in the Plasma Observatory mission activities. It is responsible for the PMO BOX-P instrument, selected subsystems for BOX-W and EFI-ADA sensors, and the coordination of the international BOX-P and EFI consortia. Prof. Hanna Rothkaehl serves as Lead Scientist for BOX-P, while Marek Morawski leads the EFI sensor activities. CBK PAN also supports mission definition, instrument integration and testing, milestone reviews, and delivery of compliant flight hardware to ESA.



M-MATISSE (*Mars Magnetosphere ATmosphere Ionosphere and Space-weather SciencE*) aims to investigate how the Martian magnetosphere, ionosphere, and atmosphere respond to space weather and solar wind activity. The mission concept is based on two orbiters performing coordinated multi-point observations from the surface to space, enabling the first global characterization of Mars' plasma environment and atmospheric dynamics. The mission will improve understanding of atmospheric escape, surface radiation hazards, and the effects of space weather on future robotic and human exploration of Mars.

Centrum Badań Kosmicznych PAN (SRC PAS) contributes to the mission through the development of the Electronics Box (EBOX) for the COMPASS instrument and participation in scientific data analysis,

interpretation, and mission science planning. Prof. Hanna Rothkaehl serves as Co-PI of the COMPASS instrument.

By the end of 2025, most of the work for both Plasma Observatory and M-MATISSE for the Mission Selection Review (MSR) data packages and the Yellow Book had been completed, with submission and finalisation planned for early 2026.

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3.2. PLANETOLOGY AND SOLAR SYSTEM DYNAMICS

3.2.1. DYNAMICS OF LONG-PERIOD COMETS

The influence of individual stars on the long-term dynamics of two unique Oort Cloud comets: C/2014UN271 (Bernardinelli-Bernstein) and C/2017 K2 (PANSTARRS), P. A. Dybczyński and M. Królikowska

In April 2022, an article by Piotr A. Dybczyński (Astronomical Observatory Institute of Adam Mickiewicz University, Poznań) and Małgorzata Królikowska, reporting the outcomes given in the above title was published in Astronomy & Astrophysics.

$C/2014UN_{271}$ (BB) will pass through perihelion (10.95 au from the Sun) on 2031 January 22, while C/2017 K2 reached its perihelion on 2022 December 19, at 1.80 au from the Sun. Our main conclusion is that the orbital evolution of these two comets appears to be sensitive to perturbations from several stars that closely approach the Sun. For example, we identified strong perturbations caused by star HD7977, due to its extremely close distance (0.014 ±0.057 pc) from the Sun, about 2.5 Myr ago. Unfortunately, our analysis is weakened by errors in the 6D data for some of these stars, as the latter are too large to obtain definitive results for the studied comets (see Figure 6.2.1); nevertheless, we can deduce that both comets were probably outside the planetary zone in the previous perihelion (a few million years ago).

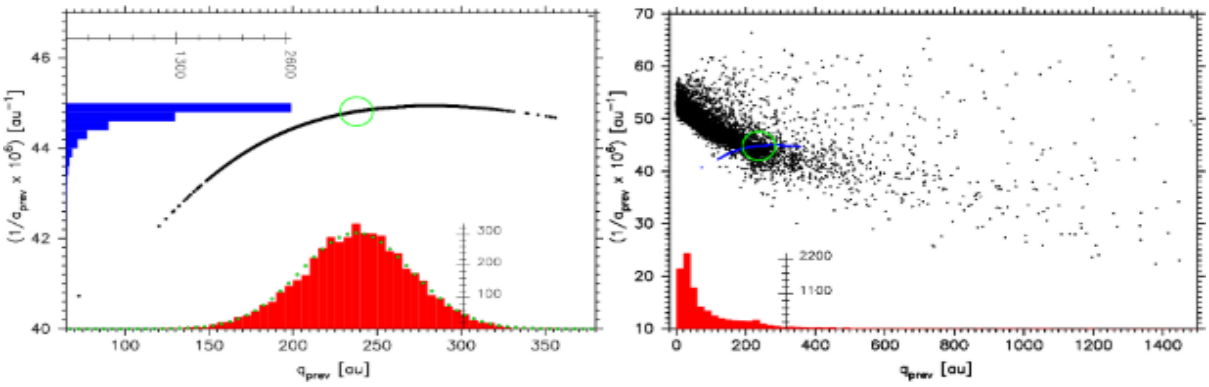

Figure 3.2.1.1. Left: the influence of comet Bernardinelli-Bernstein's (BB) orbit uncertainty on orbit parameters at the previous perihelion (q_{prev}). Black dots show the result of the backward numerical integration of 5001

clones of BB at the previous perihelion with all Galactic and stellar perturbations included. The centre of the green circle marks the nominal result. The red histogram presents the marginal distribution at the previous perihelion, along with the best Gaussian approximation (green dots in the middle of each bar). The blue histogram shows the marginal distribution of the inverse of the previous semimajor axis ($1/a_{prev}$). Right: the influence of uncertainty in HD7977 data on the parameters of the previous BB orbit. This simulation was based on 10, 000 pairs of a comet clone and a star clone. The result of each pair is represented by a black dot. The marginal distribution of the previous perihelion is shown as black dots, and by the red histogram presented below the main plot. For comparison purposes, the main result is superimposed, and the blue swarm of dots show the result of an additional experiment: 5001 BB orbits and the nominal HD7977 track. The nominal result is shown in the centre of the green circle.

Oort Cloud comets discovered far from the Sun M. Królikowska and L. Dones

In 2022-2023, analysis of 32 long-period comets observed over a wide range of heliocentric distances was performed. In October 2023, an article written in collaboration with Luke Dones (Southwest Research Institute, Boulder) appeared in *Astronomy and Astrophysics*, and is also available via an open-access archive.

We found that the motion of comets is often measurably affected by NG forces at heliocentric distances beyond 5 AU from the Sun. The most spectacular example is C/2010 U3 (Boattini), whose perihelion distance is 8.44 AU. NG effects were detectable for 19 of the 32 analyzed comets with large perihelion distances. For five comets, we found asymmetric effects of NG forces – in three cases significantly greater before perihelion than after (C/2017 M4, C/2000 SV75, and C/2015 O1), and, in two others, the opposite (C/1997 BA6 and C/2006 S3). We also found that the well-known observation that original orbits are more tightly bound when NG acceleration is included, compared to purely gravitational solutions, may be related to the specific form of the standard $g(r)$ function describing the sublimation of ices. Further investigation into the latter point is needed.

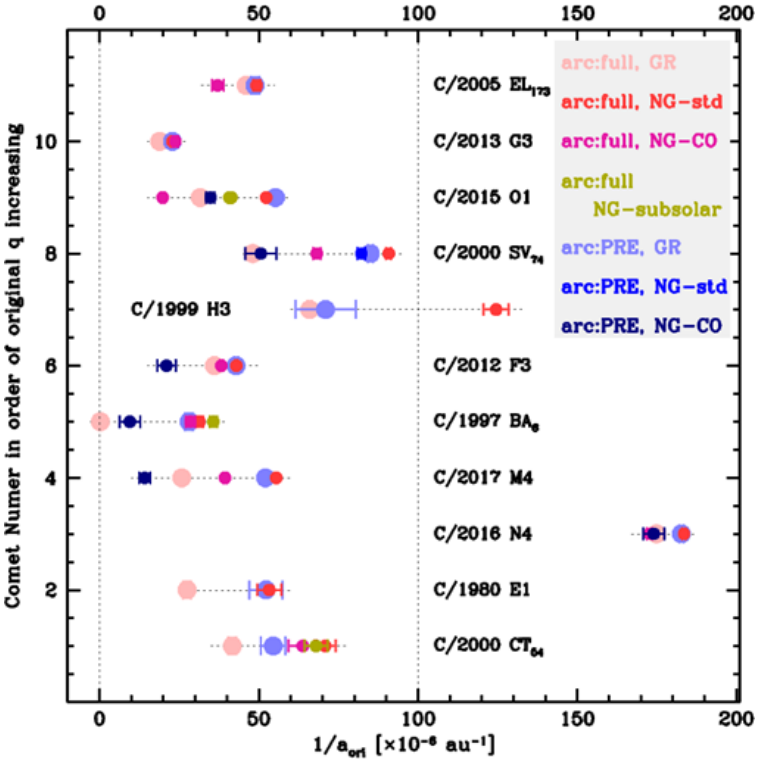

Fig. 3.2.1.2. Original values of 1/a (a heliocentric distance of 250 au, before the comet enters the planetary zone) for eleven comets from the investigated sample. Oort Cloud comets have original semimajor axes greater than 10, 000 au. Comets are ordered from bottom to top as a function of increasing perihelion distance (between 3.1 au and 3.9 au in this plot). Pink dots represent gravitational (GR) orbital solutions based on the entire available data arc, light blue dots show GR solutions using pre-perihelion data arcs only. Non-gravitational (NG) solutions obtained using all data arcs are shown as red dots (the standard g(r) function), and magenta symbols (a g(r)-like function based on CO-sublimation). The remaining colour codes are given in the figure. The figure shows that the original 1/a can vary by up to half the width of the Oort Cloud zone, depending on the data arc and motion model used. This fundamentally affects our conclusions about the origin of each comet.

HD 7977 and its possible influence on solar system bodies P. A. Dybczyński, M. Królikowska, P. Bartczak, E. Podlewska-Gaca, K. Kamiński, J. Tokarek, K. Langner, S. Fiorentino and J. de Bruijne

In 2022, Piotr Dybczyński and collaborators from the Astronomical Observatory Institute in Poznań found that, according to data from the Gaia Early Data Release 3 (2021), 2.47 M years ago the star HD 7977 nominally passed as close to the Sun as 0.014 pc (about 3,000 AU). Next, Małgorzata Królikowska were invited to collaborate with his group, to study the gravitational influence of this star on solar system bodies, with focusing on the Oort Cloud comets.

In May 2024, the paper examining the impact of the very close approach of the star HD 7977 and other stellar perturbers on the population of Oort Cloud comets and other small bodies was published. The paper investigates and discusses in detail HD 7977 data from Gaia and old catalogues, including the possibility that HD 7977 is an unresolved binary star. It is possible that the multiple nature of HD 7977 has not been recognized. In the absence of more detailed data, we based our calculations on data on the bright component, which has been recorded in stellar catalogues for over a hundred years.

Our calculations indicate the dominant role of HD 7977 in perturbations on Oort Cloud comets and that such an event constitutes a dynamic horizon for all studies of the past dynamics of Solar System bodies, in particular Oort Cloud comets. This is illustrated in Figure 3.2.2. There are similar numbers (percents) of comets in the first bin in the upper panel for calculations without stellar perturbers (filled grey histogram, 75.5% of all orbits) and including perturbations from stars except HD 7977 (black-lined histogram, 74.3%). In other words, HD 7977 is solely responsible for about 40% of previous perihelion distances greater than 100 AU, and, in many cases, this number is significantly greater. In contrast, perturbations by Galaxy tides only account for about 20%.

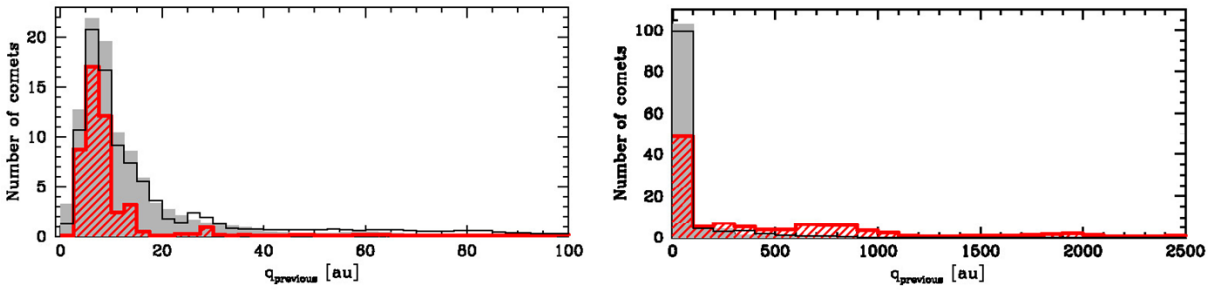

Figure 3.2.1.3. Statistics for 125 long-period comets with an osculating perihelion distance greater than 3.5 AU. Filled gray histograms represent calculations with Galactic tide perturbations (stellar perturbations are ignored). Black-lined histograms show results that include perturbations from all stars except HD 7977. Red-dashed histograms describe the case with perturbations from the Galactic tide, and all stars that have passed close to the Sun in the past ~10 Myr. Both panels show the same distributions of the previous perihelion distance; the upper panel gives the distribution in the range 0–2,500 AU, and the lower panel gives details of the first bin of the upper panel (1–100 AU).

The Catalogue of Cometary Orbits and their Dynamical Evolution (the CODE Catalogue) (Cometary databases: https://pad2.astro.amu.edu.pl/CODE ; https://code.cbk.waw.pl/) P. A. Dybczyński and M. Królikowska

The CODE Catalogue is mainly dedicated to orbital data (rather than observations) related to Oort Cloud comets. Oort Cloud comets are long-period comets with an original semi-major axis greater than 10,000 AU in the pure gravitational model of motion. Since 2020, the Catalogue has been open to the

public via an internet interface hosted by the Astronomical Observatory Institute, Faculty of Physics, Adam Mickiewicz University and the CBK PAN.

In the period 2022-2024, M. Królikowska and P. Dybczyński performed two major updates of this database. Thanks to these work, the CODE Catalogue now offers rich sets of orbital solutions for a complete sample of Oort spike comets discovered between 1900 and 2021 with special care to modelling the non-gravitational effect in these comets. One of important novelty, introduced in 2023, is that 'previous' (previous perihelion, or 120,000 AU from the Sun in the past) and 'next' (next perihelion, or 120,000 AU after leaving the planetary zone) orbits are given in two variants. In the first, the dynamical model is restricted to the full Galactic tide (with all individual stars omitted), while in the second, all currently known stellar perturbers are considered. Calculations of previous and next orbits were performed using the up-to-date database of potential stellar perturbers. At the end of 2025 the article by Dybczyński and Królikowska entitles the *Update of the CODE catalogue and some aspects of the dynamical status of Oort Cloud comets* was published in Astronomy and Astrophysics.

This publication is not only a major update of the Catalogue of Cometary Orbits and their Dynamical Evolution (CODE), but also highlights the scientific value of the updated catalogue through selected samples of comets: (i) objects with large perihelion distances and (ii) comets discovered at large heliocentric distances. Both populations have gained increasing importance in recent years as a result of advances in observational techniques. A particular emphasis is placed on formulating updated criteria for identifying dynamically new objects, using the most recent stellar data. In particular, their numbers are expected to grow substantially with the start of operations of the Vera C. Rubin Observatory. Overall, this work strengthens the role of CODE as a key research database for future studies of the dynamical structure of the Oort Cloud and the origin of long-period comets.

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3.2.2. DYNAMICS OF HALLEY-TYPE COMETS

Future evolution of 12P and other Halley-type comets in near-polar orbits M. Królikowska, P. Kankiewicz, P. Wajer.

In March 2025 the article was published in th Monthly Notices of the Royal Astronomical Society by M. Królikowska, P. Wajer (CBK PAN), P. Kankiewicz (Institute of Physics, Jan Kochanowski University, Kielce).

In 2024, we investigated the long-term dynamical evolution of six Halley-type comets (HTCs; currently with highly inclined orbits) over the next 100,000 years to identify commonalities and differences in their orbital behaviors. To achieve this, we employed three complementary numerical methods:

classical dynamical integrations forward in time, Lyapunov time estimations, and the MEGNO (Mean Exponential Growth of Nearby Orbits) indicator. Our study was based on osculating orbits obtained from observational data, from which we generated swarms of 1,001 virtual comets (VCs) per HTC to account for orbital uncertainties and chaotic effects. We focused on key dynamical phenomena, including the probability of transitioning into a sungrazing state and the likelihood of orbit flipping.

Our results indicate that two of the three HTCs with small observed perihelion distances – 161P (q=1.28 au) and 122P (q=0.659 au) – are highly likely to enter a sungrazing state in the future, significantly increasing their risk of decay. Specifically, 161P has an approximately 80% chance of reaching a perihelion distance (q) below 0.005 AU within 13,000 years, while 122P has a 50% chance within the next 100,000 years (Fig. 3.2.3.). These transitions are driven by the Kozai resonance, which induces significant orbital changes due to planetary perturbations. Notably, our analysis highlights that Uranus, rather than Jupiter, plays a dominant role in driving 161P into the Kozai resonance, demonstrating that planetary interactions beyond Jupiter can be critical in the evolution of HTCs.

We also find a correlation between a high probability of sungrazing and orbit flipping for both comets. In contrast, the other four HTCs have a less than 2.2% chance of becoming sungrazers over 100,000 years. However, three of them – C/2014 Q3, C/2015 GX, and C/2002 K4 – exhibit significant orbit flipping (40%–70% probability), demonstrating that orbital flips can occur frequently in the evolution of HTCs. Thus, our study is the first to quantify this phenomenon at the level of virtual comet swarms, providing a statistical perspective on how often such transitions may take place.

Our analysis using Lyapunov time (Fig. 3.2.4.) and the MEGNO indicator provides complementary insights into the orbital stability of these comets over a 10,000-year horizon. Based on this, we rank the comets from most to least chaotic: C/2015 GX, 122P, C/2014 Q3, C/2002 K4, 12P. 161P stands out as a special case due to its extremely high likelihood of disintegration after 13,000 years, driven by the Kozai mechanism. Our results indicate that these above assessments should be performed on a statistically significant sample of VCs, since single-orbit studies (dominating in literature) may lead to incorrect conclusions.

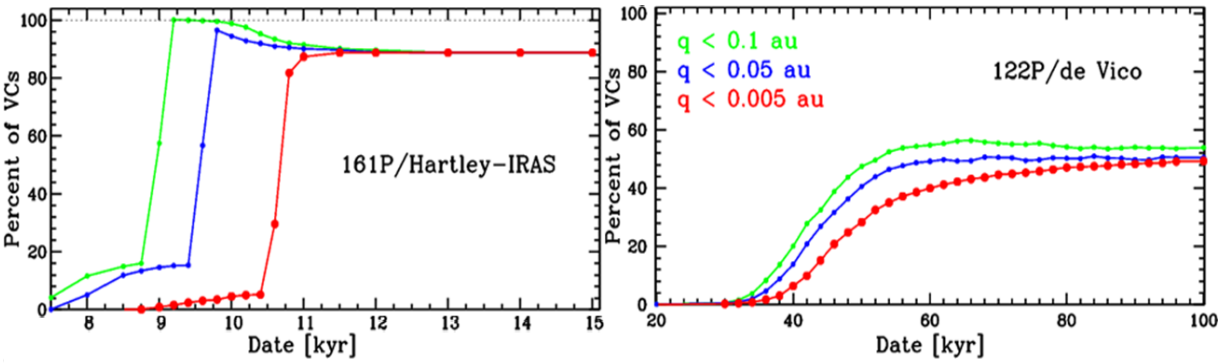

Figure 3.2.2.1. Left panel: Percent of VCs achieving q below 0.10 au (green symbols) 0.05 au (blue) and 0.005 au (red) during the evolution of 161P/Hartley-IRAS (upper panel) and 122P/de Vico (lower panel). Right panel: Evolution of perihelion distance of 161P/Hartley-IRAS in the time interval 2000–15000 AD. Distribution of minimal q (qmin and the moment of approaching this minimum for the swarm of 1001 VCs; nominal orbit evolution is shown by the red cross; the blue dashed vertical line represents the q=0.005 au.

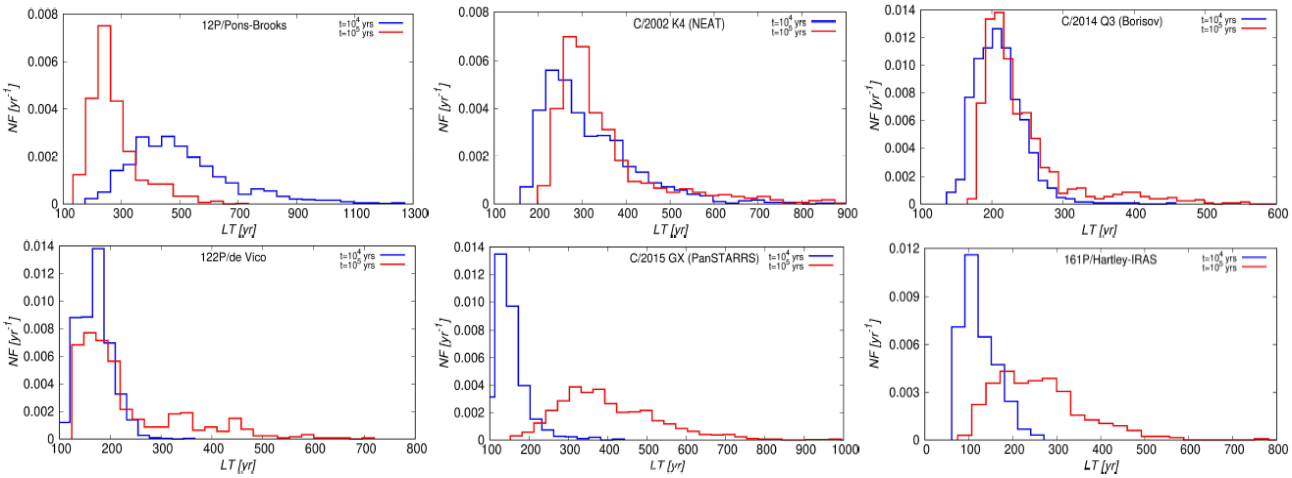

Figure 3.2.2.2. Statistical distribution of Lyapunov time calculated for the swarm of VCs after 10,000 yr (blue lines) and 100,000 yr (red lines) for orbits representing HT objects analysed in this study. The histograms were made for VCs excluding sungrazing cases.

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Paweł Kankiewicz (Institute of Physics, Jan Kochanowski University, Kielce)

3.2.3. OUTER SOLAR SYSTEM DYNAMICS IN A STELLAR CLUSTE

The onset of instabilities in giant planet systems H. Rickman et al.

In 2023, our work in this field was mainly connected to our contribution to an international team at the International Space Science Institute (ISSI) in Bern, under the leadership of Diederik Kruijssen (Astronomisches Rechen-Institut, Heidelberg). It followed the publication of our paper (Rickman et al., 2023, reference below), in which we investigated dynamical breakdowns of planetary systems under the influence of an embedded cluster environment. We concluded that multi-resonant giant planet systems, such as the probable precursor of our solar system, stand a significant risk of being shattered by close encounters during an interval of chaotic motion.

Related work by the ISSI team focuses on the origin of Hot Jupiters (HJs). HJs are exoplanets with masses similar to Jupiter, and orbital periods of less than 10 days around their host stars. The closeness to the host star raises their surface temperatures to ~1000 K. We investigated a mode of origin occurring long after the birth of the corresponding planetary systems and the escape of the host star from its birth cluster. We were motivated by the discovery of Winter et al. (2020, reference below), namely that HJ host stars reside in stream-like features in the Galactic disc, so-called *overdensities*.

At a meeting in Bern in March 2023, we discussed possible mechanisms to understand why HJs are formed in these very specific environments. We concluded that the HJ host star meets another overdensity star at a very low speed, and that the two stars are bound into a wide binary under the influence of a tidal force produced by a nearby Giant Molecular Cloud. The presence of the other star in a highly inclined orbit perturbs a Jupiter-sized planet into a plunging orbit, pushing it into the close vicinity of the host star, then tidal circularization produces a typical HJ orbit.We tested this idea using dynamical simulation, and the ensuing discussions between Rickman and the leading scientists of the

Winter et al. paper (including Kruijssen) led to the formation of a concrete plan, which is expected to be implemented in the near future.

The scope of the work of the ISSI team also includes the dynamical effects of a stellar cluster environment on a newborn planetary system. This connects to the above-mentioned Rickman et al. paper, and ongoing work by Diego Turrini and colleagues that seeks to interpret the statistical distribution of Normalised Angular Momentum Deficits of exoplanet systems, in terms of internally and externally driven instabilities. We will contribute to this work, both theoretically (H. Rickman), and by developing numerical simulations of how instabilities depend on the planet/ star mass ratio, and the spacing of planetary orbits (R. Przyłuski).

Formation of the Oort Cloud H. Rickman, P. Wajer, B. Kowalski and T. Wiśniowski

Rickman, Wajer, Wiśniowski, and Kowalski published two research papers in *Icarus*, which dealt with the extraction of the perihelia of planetesimals from the Jupiter-Saturn accretion zone after planetary scattering into more or less long-period orbits. The agent of such extraction was taken to be the stellar aggregate in which the Sun was formed in the shape of an embedded cluster. The corresponding dynamics was investigated in detail, and the characteristics of the resulting, remote small body populations (sednoids and Oort Cloud comets) were presented and compared to the, as yet, limited knowledge based on observations. It was concluded that the considered scenario for the origin of the sednoids and the Oort Cloud cannot be excluded but suffers from a rather poor match to the observed orbits (see the enclosed figure).

The possibility of sednoid and Oort Cloud formation in a more long-lived solar birth aggregate, evolving into an open cluster, is under examination by the same team together with A. Morbidelli of the Observatoire de la Cõte d'Azur and D. Nesvorný of the Southwest Research Institute at Boulder, Colorado.

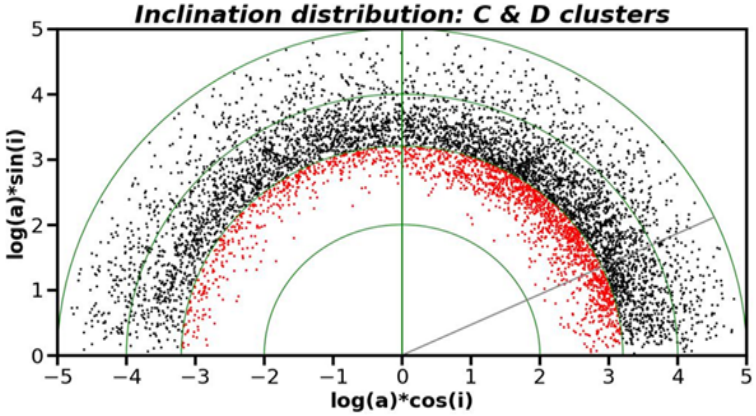

Figure 3.2.3. Orbits of remote objects in the most efficient simulations by Wajer et al. (2024). The distance of the symbols from the origin shows the log of the semi-major axis, and the azimuth angle from the positive x-axis is the inclination. Red symbols show sednoids. The slanted line at 25o shows the maximum inclination of bserved sednoids, while the symbols scatter over a much wider range.

Open clusters H. Rickman, T. Wiśniowski, B. Kowalski and P. Wajer

N-body simulations of stellar clusters from conception until the age of hundreds of Myr are a necessary ingredient of the above-mentioned study of Oort Cloud formation. We have thus simulated the evolution of twelve such clusters of different types with regard to structural parameters – *e.g.,* the degree of central condensation, gas content, and binary frequency. This work involves Rickman, Kowalski, Wiśniowski and Wajer. It allows a comparative study of the dynamics characterizing the

evolutions of typical open clusters like the Pleiades and their younger precursors and thereby to improve the understanding of such stellar systems.

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3.2.4. MAIN BELT ACTIVE ASTEROIDS

Main-belt comets as contributors to the near-Earth objects population R. Gabryszewski, P. Wajer and I. Włodarczyk

Active asteroids are objects on asteroidal orbits that exhibit comet-like activity, such as a coma or tail. Most are located in the Main Belt, where their long-term evolution is shaped by mean-motion resonances with Jupiter and Saturn, the v6 secular resonance, and weak non-gravitational effects. In some cases, the observed activity is most likely driven by sublimation.

The paper investigated the role of cometary-type non-gravitational forces in the orbital evolution of active Main Belt asteroids, focusing on whether sublimation-related accelerations can significantly modify their transport timescales and dynamical pathways.

The model used the standard Marsden formalism, with non-gravitational acceleration components A1, A2, and A3. This formalism was originally developed for comets on more elongated orbits and with relatively continuous activity; a simplified activation scheme was introduced to represent the episodic nature of Main Belt comet activity. The orbital evolution was then integrated numerically using the 15-order RADAU integrator implemented in REBOUND.

The results show that cometary-type non-gravitational forces can substantially accelerate the dynamical evolution of active Main Belt objects. Depending on the activity frequency and Marsden parameters, transition timescales to other dynamical regions may be shortened to only a few thousand years, much faster than in Yarkovsky-dominated scenarios. In particular, objects with negative A2 show an enhanced probability of evolving onto near-Earth-object-type orbits, suggesting that sublimating active asteroids may contribute non-negligibly to the NEO population.

For positive A2, the same forces may drive active asteroids outward, even toward the outer planetary region. Thus, sublimation-driven accelerations can modify the dynamical pathways of active Main Belt bodies in both inward and outward directions, mainly depending on the sign and magnitude of the transverse acceleration component. These forces should therefore be included in dynamical studies of active asteroids for which sublimation is suspected to dominate.The paper “Main-belt comets as contributors to the near-Earth objects population” was published in Astronomy & Astrophysics in 2024: https://doi.org/10.1051/0004-6361/202347278

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3.2.5. CHAOS AND STABILITY IN THE SOLAR SYSTEM

Numerical analysis of Lyapunov times for trans-Neptunian objects and main-belt asteroids: stability, accuracy, and methodological comparisons P. Wajer, M. Królikowska and J. Suchecki

In 2024, we continued our work on numerical methods for determining Lyapunov times of small bodies in the Solar System, focusing on methodological comparisons and the influence of orbital uncertainties on stability estimates. The study, entitled Numerical analysis of Lyapunov times for trans-Neptunian objects and main-belt asteroids: stability, accuracy, and methodological comparisons, was accepted for publication in 2025 in the journal Monthly Notices of the Royal Astronomical Society. The work compared three approaches for Lyapunov time estimation: the variational method and two implementations of the renormalization technique. Calculations were performed for selected trans-Neptunian objects (TNOs) and outer main-belt asteroids (MBAs), both for nominal orbits and for ensembles of 1001 orbital clones reflecting uncertainties in orbital elements.

The results showed that although the methods generally provide consistent estimates, significant discrepancies may occur for some dynamically complex asteroids, while TNOs exhibit greater agreement between approaches. We demonstrated that analyses based on clone ensembles yield more robust and reliable indicators of dynamical stability than calculations limited to nominal orbits. In particular, median Lyapunov times derived from clone populations reduce method-dependent biases and reveal dynamical effects that may remain hidden in single-orbit studies. The developed methodology provides a systematic framework for future large-scale investigations of the long-term dynamical evolution and stability of different populations of Solar System bodies.

Authors and affiliations:
Małgorzata Królikowska, Jakub Suchecki, Paweł Wajer (Centrum Badań Kosmicznych Polskiej Akademii Nauk, Warszawa)

3.2.6. PROCESSES ACTING ON COMETARY NUCLEI AND ON OTHER ICE-RICH BODIES OF THE SOLAR SYSTEM

Water, hydrogen cyanide, carbon monoxide, and dust production from the distant comet 29P/Schwassmann-Wachmann 1 D. Bockelee-Morvan and 16 co-authors including S. Szutowicz

This work aimed to better-characterize the activity of comet 29P/S-W 1, based on multi-wavelength observations undertaken between 2007 and 2021 and performed during its outbursting and quiescent states. The similarity between water and dust production rates suggests that the ice content of dust particles released into the coma is significant. A paper reporting the outcome of investigations was published in August 2022 in *Astronomy & Astrophysics.*

Outgassing of cometary analogues under laboratory conditions. S. Szutowicz

The main process responsible for cometary activity is sublimation of ices which is caused by solar radiation incident on the surface of a comet nucleus. Comets are also composed of non-volatile minerals and organic substances, so after ice sublimation, volatile-depleted materials remain as a porous ice-free layer. To better understand the sublimation-driven processes thermophysical models can be developed based on relevant laboratory experiments. For several years, I have been cooperating with K. J. Kossacki from the Institute of Geophysics, University of Warsaw, and his

collaborators. Our common research topic is the outgassing of cometary analogues under laboratory conditions. The cooperation has resulted in several publications, some results for 2022-2025 are presented below.

Outgassing of selected possible cometary analogs: laboratory simulations. K. J. Kossacki , M. Wesołowski, S. Szutowicz, T. Mikołajków

A laboratory study of the physico-chemical properties of the layers making up the surface of the nucleus can provide important insights into the evolution of a comet. In this work we present the results of our experimental studies on the degassing of porous ice and porous mixtures of ice and sand in a vacuum. Our aim was to find the relationship between the surface recession rate and the subsurface temperature gradient, along with the granulation and composition of the material. We investigated whether our empirical equation could be applied to the rate of sublimation. Our calculations indicate the potential for landslides in inclined areas on the surface of comet 9P/Tempel 1. A paper reporting this research was published in August 2022 in *Icarus*.

Production of water from a dynamically new comet. K. J. Kossacki and S. Szutowicz

In our paper, we presented the results of numerical simulations of the production of water from the nucleus of a dynamically new comet. We considered one possible scenario, namely, when the dust mantle does not accumulate on the surface of the nucleus. Simulations were performed using empirical equations, based on the results of laboratory experiments using ice agglomerates. The model nucleus is a prolate ellipsoid of rough surface. Our results were compared with the observed production of water from the nucleus of comet C/2012 K1 PanSTARRS. Our simulations indicate that the observed production of water can be reproduced without assuming the presence of highly volatile ices when the dust slides down the slopes and the thermal conductivity of the nucleus is very low. The results of this research was published in December 2023 in *Monthly Notices of the Royal Astronomical Society.*

Outgassing of ice agglomerates. K. J. Kossacki, M. Wesołowski, S. Szutowicz, T. Mikołajków

Our research aimed to experimentally verify different mathematical approaches to calculating the outgassing rate of cometary analogues. We investigated both new and known formulations applicable to the mass flux of water vapor. Our experiments in a vacuum used samples composed of approximately uniform agglomerates, and others composed of agglomerates with a hierarchical structure. The largest agglomerates have diameters of the order of a centimetre. We found that the ratio of two pressures – the vapor pressure between agglomerates, and the pressure of the phase equilibrium – is temperature dependent. In addition, we proposed a simple method to calculate the lifetime of large, centimetre-sized porous ice-dust particles present in cometary comae. A paper reporting our results was published in July 2023 in *Icarus*.

Comets, sliding surface dust on illuminated surfaces. K. J. Kossacki, T. Mikołajków, S. Szutowicz and M. Wesołowski

This work aimed to investigate conditions for the formation and sliding of desiccated nonvolatile granular material down samples of potential cometary analogs. We performed laboratory experiments using samples composed of porous aggregates containing water ice, quartz sand and charcoal. We found that under special conditions, the sand released due to the sublimation of ice may almost continuously slide down the surface and leave it almost free of sand. The results of our experiments

were compared to observations of scarps on the nucleus of comet 67P/Churyumov–Gerasimenko. A paper describing this study was published in March 2024 in *Icarus*.

Dynamics of landslides on ice-rich space objects. K. J. Kossacki, T. Mikołajków , S. Szutowicz

We investigated the velocity of landslides on ice-containing cosmic bodies of low gravity. The considerations were based on a series of laboratory experiments dealing with the sliding of desiccated sand on ice and ice-containing mixtures on inclined surfaces of samples. The measurements were performed both in vacuum and at normal pressure in different spatial scales. The values of the velocity derived from the results of experiments were then appropriately scaled using the gravitational acceleration relevant for the selected cosmic objects: the nuclei of comets and the dwarf planet Ceres, orbiting in the main asteroid belt. We have found, that the average velocity of material sliding down a hundred meters long slope on the nucleus of a comet should be of the order of 0.01 meters per second, while the velocity of dry landslides on Ceres should be two orders of magnitude higher. A paper reporting this research was published in October 2024 in *Icarus*.

Degassing of Comet Analogs: New Laboratory Measurements of Vapor Pressure between Sand–Ice Agglomerates. K. Kossacki, S. Szutowicz, M. Wesołowski, T. Mikołajków, M. Zawadzki, and M. Jagodziński

In 2025, we investigated the rate of production of vapor from the nuclei of comets when they are composed of porous dust–ice agglomerates. The reason for starting the research was the discrepancy between the values of vapor pressure between agglomerates required by different theoretical models to reproduce the results of experiments. Some models of ice sublimation from the interiors of dust–ice agglomerates assume zero pressure between agglomerates. In the work, we present direct measurements of the gas pressure within samples composed of porous agglomerates. The measured pressure is clearly higher than zero. The results of the experiments are compared with the results of mathematical simulations. The paper describing our results was published in January 2026 in *Publications of the Astronomical Society of the Pacific*.

Authors and affiliations:

Dominique Bockelée-Morvan (LESIA, Observatoire de Paris, Meudon, France), Michał Jagodziński, Konrad Kossacki, Tomasz Mikołajków, Mikołaj Zawadzki (Faculty of Physics, University of Warsaw), Marcin Wesołowski (Faculty of Exact and Technical Sciences, University of Rzeszów)

3.2.7. Mars and other Earth-like planets

The formation of some cone chains in Chryse Planitia on Mars L. Czechowski, N. Zalewska, A. Zambrowska, M. Ciążela, P. Witek and J. Kotlarz

In 2023, we published the paper "THE FORMATION OF CONE CHAINS IN THE CHRYSE PLANITIA REGION ON MARS AND THE THERMODYNAMIC ASPECTS OF THIS PROCESS", in which we investigated the origin of arcuate chains of small cones located at the boundary between the Acidalia and Chryse regions (centered at approximately 38°13'N, 40°35'W; Fig. 3.7.1).

We considered three possible formation mechanisms: (i) grain ejection, (ii) extrusion of mud or fluidized sand, and (iii) explosive processes. Mechanisms (ii) and (iii) require an additional heat source, such as a magma intrusion. We also performed three-dimensional, time-dependent numerical

modeling of the interaction between a magma intrusion and an aquifer, based on the heat conduction equation.

Our main conclusions are as follows: (1) the cones could have formed as a result of regolith degassing caused by a pressure drop, while additional heating may have led to complete degassing and explosive cone formation; (2) subparallel cone chains most likely developed along outcrops of volatile-rich sediments, whereas non-subparallel chains may represent rootless cones; and (3) numerical modeling indicates that magma intrusions alone may not be sufficient to completely degas some aquifers.

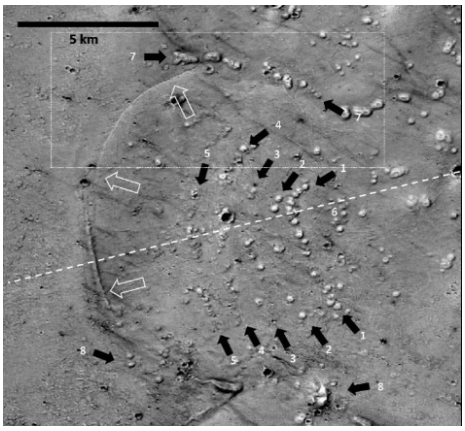


Figure 3.2.7.1. The region considered in the paper. The subparallel chains of cones are indicated by black arrows and labeled by 1, 2, 3, 4, 5. According to our hypotheses, some of these chains were formed along the outcrops of sediments with high content of volatiles. The chains 7 and 8 may be rootless cones formed at the bottom of the valleys. NASA, P22_009485_2187_XN_ 38N040W.

Interpreting data from the Mini-TES spectrometer along the Opportunity rover's path N. Zalewska and L. Czechowski

In this study, we analyzed selected Mini-TES infrared spectrometer data from the Opportunity rover, focusing on observations that have received limited interpretation to date (Fig. 3.7.2). The results show that neighboring sections of the rover traverse have broadly similar mineralogy, suggesting that similar geological processes operated across the Meridiani Planum region. At the same time, distinct mineralogical differences are also present along the studied route.

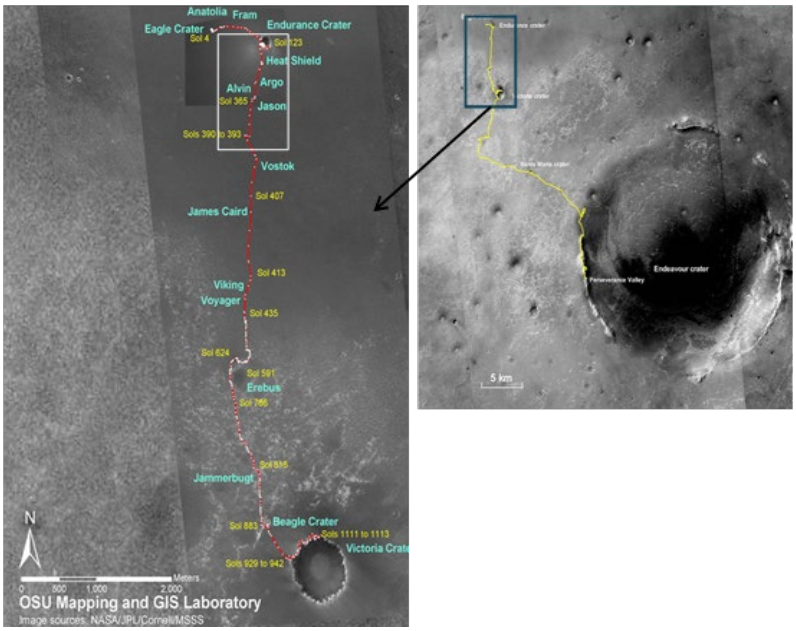


Figure 3.2.7.2.We covered the area from sol 313 to 325, 329-331 and 382-395 (between the Endurance and Erebus craters) due to very little research on this section in the literature.

One of the most important findings is the variable abundance of hematite. Although spherules occur throughout the analyzed area, hematite is absent in some sectors. We interpret this as evidence of hematite leaching from the concretions, a process also observed in terrestrial spherules, which supports the idea of a similar origin for Martian and Earth concretions.

We also detected a small but consistent presence of pyrite. Since pyrite commonly occurs with economically significant minerals, this observation may be important, although the available data are insufficient to confirm any direct association .

These results were presented in the Remote Sensing study “Meridiani Planum Mineralogy Along Part of the Opportunity Rover Track Based on the Mini-TES Spectrum.”

Authors and affiliations: Marta Ciążela (Institute of Geological Sciences, Polish Academy of Sciences), Leszek Czechowski (Centrum Badań Kosmicznych Polskiej Akademii Nauk; Faculty of Physics, University of Warsaw), Jan Kotlarz (Łukasiewicz Research Network – Institute of Aviation), Piotr Witek (Centrum Badań Kosmicznych Polskiej Akademii Nauk; Copernicus Science Centre), Anita Zambrowska, Natalia Zalewska (Centrum Badań Kosmicznych Polskiej Akademii Nauk)

References:

[1] Bockelee-Morvan, D. and 15 colleagues 2022. Water, hydrogen cyanide, carbon monoxide, and dust production from distant comet 29P/Schwassmann-Wachmann 1. Astronomy and Astrophysics 664.

[2] Ciążela, J. and 15 colleagues, 2023. Lunar ore geology and feasibility of ore mineral detection using a far-IR spectrometer. Frontiers in Earth Science 11.

[3] Ciążela, J. and 19 colleagues, 2022. Concept and Design of Martian Far-IR ORE Spectrometer (MIRORES). Remote Sensing 14.

[4] Czechowski, L., Zalewska, N., Zambrowska, A., Ciążela, M., Witek, P., Kotlarz, J., 2023. The formation of cone chains in the Chryse Planitia region on Mars and the thermodynamic aspects of this process. Icarus 396.

[5] Davidsson, B.J.R. and 26 colleagues, 2022. CO2-driven surface changes in the Hapi region on Comet 67P/Churyumov-Gerasimenko. Monthly Notices of the Royal Astronomical Society 516.

[6] Dybczyński, P.A. and 7 colleagues, 2024. HD 7977 and its possible influence on Solar System bodies. Astronomy and Astrophysics 685.

[7] Dybczyński, P.A., Królikowska, M., 2022. The Influence of Individual Stars on the Long-Term Dynamics of Comets C/2014 UN271 and C/2017 K2. Astronomy and Astrophysics 660.

[8] Dybczyński, P.A., Królikowska, M., 2025. Update of the CODE catalogue and some aspects of the dynamical status of Oort Cloud comets. Astronomy and Astrophysics 702.

[9] Gabryszewski, R., Wajer, P., Włodarczyk, I., 2024. Main-belt comets as contributors to the near-Earth objects population. Astronomy & Astrophysics 691.

[10] Kossacki, K., Szutowicz, S., Wesołowski, M., Mikołajków, T., Zawadzki, M., Jagodziński, M. 2026. Degassing of Comet Analogs: New Laboratory Measurements of Vapor Pressure between Sand─Ice Agglomerates. Publications of the Astronomical Society of the Pacific 138.

[11] Kossacki, K.J., Mikołajków, T., Szutowicz, S. 2024. Dynamics of landslides on ice-rich space objects. Icarus 421.

[12] Kossacki, K.J., Mikołajków, T., Szutowicz, S., Wesołowski, M., 2024. Comets, sliding of surface dust on illuminated surfaces. Icarus 410.

[13] Kossacki, K.J., Szutowicz, S. 2023. Production of water from a dynamically new comet. Monthly Notices of the Royal Astronomical Society 526.

[14] Kossacki, K.J., Wesołowski, M., Szutowicz, S., Mikołajków, T., 2022. Outgassing of selected possible cometary analogs: laboratory simulations. Icarus 388.

[15] Kossacki, K.J., Wesołowski, M., Szutowicz, S., Mikołajków, T., 2023. Outgassing of ice agglomerates. Icarus 398.

[16] Kowalski, B., Wiśniowski, T., Rickman, H., Wajer, P., 2025. Evolution of Intermediate Mass Stellar Clusters. Acta Astronomica 75.

[17] Kozakiewicz, J. and 19 colleagues, 2025. Planetary science in Poland – selected research on planetary bodies of the inner Solar System. Przegląd Geologiczny 73.

[18] Kozakiewicz, J. and 12 colleagues, 2025. Selected aspects of planetary physics. Acta Physica Polonica B Proceedings Supplement 18.

[19] Królikowska, M., Dones, L., 2023. Oort Cloud comets discovered far from the Sun. Astronomy and Astrophysics 678.

[20] Przyłuski, R. and 9 colleagues, 2025. Disruption of Planetary System Architectures by Stellar Flybys. Universe 11.

[21] Rickman, H., Wajer, P., Przyłuski, R., Wiśniowski, T., Nesvorný, D., Morbidelli, A., 2023. Breakdown of planetary systems in embedded clusters. Monthly Notices of the Royal Astronomical Society 520.

[22] Turrini, D. and 24 colleagues, 2022. Exploring the link between star and planet formation with Ariel. Experimental Astronomy 53.

[23] Valsecchi, G.B., Rickman, H., Morbidelli, A., Wiśniowski, T., Gabryszewski, R., Wajer, P., 2022. Direct-retrograde orbit flips at planetary close encounters. The role of the Tisserand parameter. Astronomy and Astrophysics 667.

[24] Wajer, P., Rickman, H., Kowalski, B., Wiśniowski, T., 2024. Oort Cloud and Sednoid formation in an embedded cluster, I: Populations and size distributions. Icarus 415.

[25] Wajer, P., Rickman, H., Kowalski, B., Wiśniowski, T., 2024. Oort Cloud and Sednoid formation in an embedded cluster. II. Dynamics and orbital evolutions. Icarus 410.

[26] Wiśniowski, T., Rickman, H., Wajer, P., 2022. A new model for simulating circumstellar dynamics in young stellar clusters. Monthly Notices of the Royal Astronomical Society 510.

[27] Zalewska, N. and Czechowski, L., 2025. Meridiani Planum Mineralogy Along Part of the Opportunity Rover Track Based on the Mini-TES Spectrum. Remote Sensing 17.

3.3. SOLAR PHYSICS DIVISON OF SPACE RESEARCH CENTRE PAS

The Solar Physics Divison of Space Research Centre, Polish Academy of Sciences (SPD SRC PAS) is a team of scientists and engineers with 50+ years of experience in building space instrumentation and interpretation of satellite observations. The main area of exploration is solar eruptions observed in a variety of wavelengths, with special attention given to X-rays. The main results of the teamwork are:

Solar Orbiter/STIX is one of the main projects for our present activity on data analysis and interpretation. We are developing an image reconstruction algorithm (MARLIN) as well as an algorithm for detailed analysis of STIX spectra with special attention given to abundance analysis (TEMIRA).

MARLIN, with its high reliability, allowed to investigate HXR sources produced during failed filament eruptions, performed statistical analysis of physical properties for hundreds of compact flares, and allowed for the first in history triangulation of HXR sources observed from two (Solar Orbiter/STIX and ASO-S/HXI) vantage points. TEMIRA provides unprecedentedly precise (1-2%) determinations of temperature (T) and iron abundance (A_{Fe}) based on the STIX spectral shape in the 4–9 keV energy range. Statistical analyses of STIX lightcurves allowed us to investigate solar flares quasi-periodic pulsations (QPPs) and so-called elementary flares, revealing the simplest observed time profiles. The detailed analysis of STIX data from Solar Orbiter's perihelion passage allowed for a detailed analysis of the chromospheric evaporation process with clear signatures of dichotomy in plasma speed. Flare's energetics was investigated with STIX and other instruments (SO/EPD, SO/EUI, SDO/AIA), leading to the definition of HXR productivity factor (Qf), which quantitatively associates SXR and HXR emissions, allowing a more comprehensive understanding of the flare's energy release mechanism. Apart from solar flares, we are analysing data from TESS and XMM/Newton to investigate stellar flare properties. In statistical analysis of TESS data for 320 000 flares, based on the scaling laws, we estimated the average values of the magnetic field strength and length of the stellar flare loops. Case studies of selected stellar flares allowed us to model the stellar spots distribution on the photopsheres and revealed that the DEM distributions are two-component. The hotter component can be interpreted as the contribution of flaring plasma.

Another important project of our present activity is **Proba-3/ASPIICS**, we are involved in Science Operation Centre of the mission, and focusing on data analysis and interpretation, e.g. studying origins of slow solar wind.

We study Solar coronal cavities through entire solar cycle (3500+), believed to be magnetic flux ropes—twisted magnetic field structures that can eventually erupt as coronal mass ejections (CMEs).

We still analyse and interpret archived data from old instruments. Investigation of SMM/BCS spectra led to important results about observed changes of Ca abundances seen in the flare decays. Each loop in the flaring region has its own characteristic calcium abundance A(Ca), which is, in general, different from the main loop, either smaller or larger depending on each flare.

References: http://www.cbk.pan.wroc.pl/?l=EN&act=7

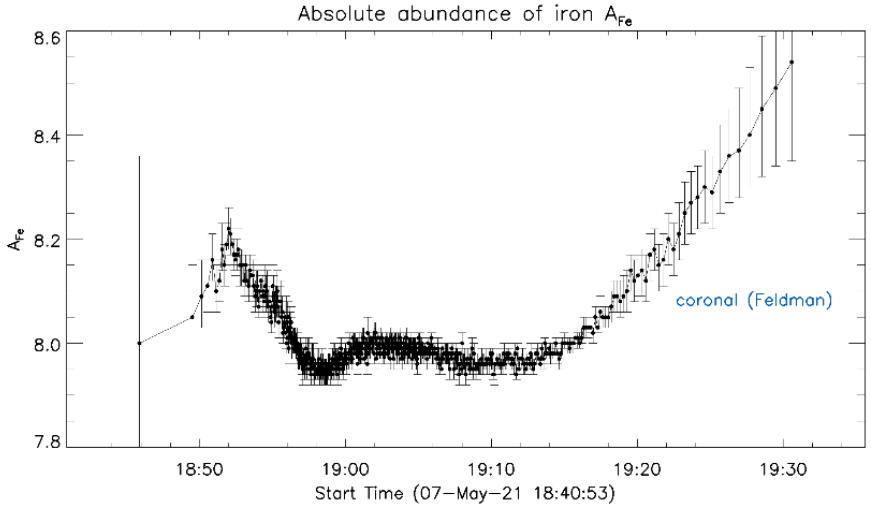


Figure 3.3.1. Time evolution of plasma iron abundance (AFe) for the studied flare. Significant variation is observed, with values fluctuating around the level currently assumed to represent the average coronal iron abundance (defined by Feldman).

Lichens research.

Our team, together with scientists from the Institute of Botany at the Jagiellonian University, is investigating the ability of lichens to maintain metabolic activity under conditions simulating the Martian surface. These include low atmospheric pressure (~6 mbar), a CO_2-dominated atmosphere, thermal cycling, and—crucially—exposure to ionizing X-ray radiation (figure 1). Our research focuses on characterizing the structural and chemical changes induced by X-ray interactions within the lichen thalli. This work advances our understanding of how ionizing radiation affects biological systems and supports applications in astrobiology, radiation biology, and environmental sciences.

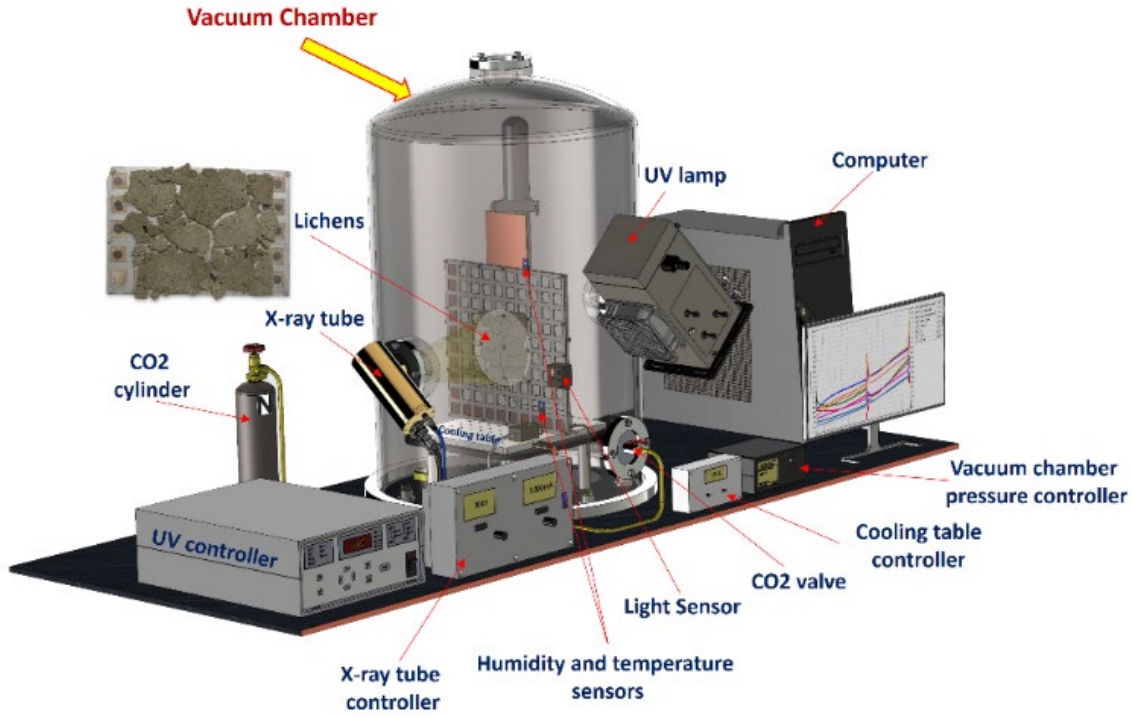
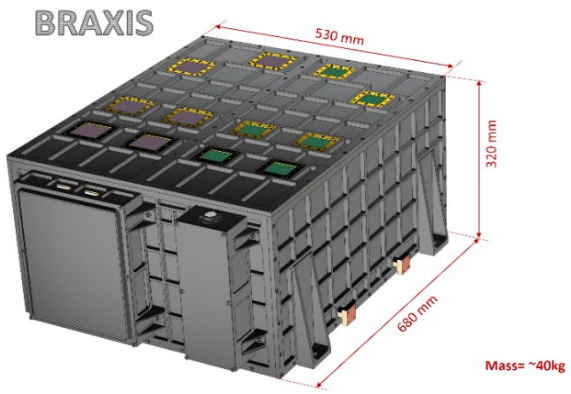


Figure 3.3.2. The figure illustrates an experimental setup for the investigation of lichens exposed to X-ray radiation.

In parallel with this work, the Solar Physics Department is developing the **BRAXIS** instrument (Figure 2), an X-ray spectrometer designed to study the Sun's high-energy radiation. Its operation is based on Bragg's law, with measurements obtained through the reflection of X-ray photons from precisely aligned crystals.



The spectrometer will observe both **solar flares** and **active regions**, enabling high-resolution spectral diagnostics of solar plasma. By leveraging Bragg diffraction for accurate registration of X-ray reflections, BRAXIS will provide valuable insights into the dynamics and energetics of solar phenomena, thereby deepening our understanding of plasma behavior under extreme astrophysical conditions.

Figure 3.3.3. Design view of the BRAXIS spectrometer.

Authors and Afiliation: Mirosław Kowaliński, Marek Stęślicki, Tomasz Mrozek, Janusz Sylwester, Centrum Badań Kosmicznych PAN

3.4 GATACTIC COSMIC RAYS

Changes in the Galactic Cosmic Ray (GCR), such as Fd, ACRE and GLE, were studied in a wide-international collaboration. Ground-Level Enhancement (GLE) is an event occurring when intense solar eruptions produce solar energetic particles (SEPs) that are accelerated to high energies and become detectable by ground-based instruments such as neutron monitors (NMs). These SEPs can initiate cascades in the Earth's atmosphere, resulting in an increase in the count rate of neutron monitors above the background level caused by GCRs. This increase is observed as a GLE. Revision of the 1956 solar energetic particle event, the GLE #5, the strongest ground-level enhancement recorded was performed (Hayakawa et al., 2024), by critically reanalyzing original archival neutron monitor data (unpublished materials located in the University of Chicago Archives). Discrepancies in previous datasets, which were often based on secondary sources or interpolations, were addressed, by digitizing and verifying original measurements from archival records. SEP energy spectrum during the event was shown to be slightly softer than earlier estimates. A high degree of anisotropy in the early phase was confirmed. These revised datasets and analyses provide a more reliable reference for modeling extreme solar particle events, offering insights into their spectral and angular characteristics that were less certain before. It led to the production of a new neutron monitor dataset for GLE #5, which is publicly available in the International GLE Database (IGLED, https://gle.oulu.fi). Anisotropic Cosmic-Ray Enhancement (ACRE) is a short-term, highly directional increase in GCR flux observed near Earth. Specifically, it is characterized by a few percent rise in count rates detected by NMs, with the enhancement being strongly anisotropic and arriving from a nearly anti-Sun direction. The discovery of a third ACRE event observed on 5 November 2023 was presented (Gil et al., 2024). A modest increase in NMs counts from mid- and high-latitude stations, with a highly directional anisotropy was reported. The EUHFORIA model was used to simulate the heliospheric conditions during and around the time of the ACRE event. This event resulted from the scattering of GCRs on a passing interplanetary flux rope associated with complex CME activity, which created disturbed heliospheric conditions. A Forbush decrease (Fd) is a suppression of the GCRs flux observed by ground-based neutron monitors. These decreases are usually caused by interplanetary shocks and/or magnetic flux ropes, such as those associated with coronal mass ejections, passing near the Earth, which temporarily reduce the GCR intensity. The Forbush decrease that occurred on 24–25 March 2024 was highly unusual, characterized by a rapid recovery and significant anisotropy in GCR fluxes detected by a global NM network (Mishev et al., 2024). It was found that the event involved a narrow, anti-sunward anisotropic cone and a complex interplanetary magnetic structure likely resulting from interacting CMEs. A rigidity-independent recovery phase and spectral flattening during the deep Fd were observed. The event's anisotropic nature and spectral evolution strongly differ from typical Fds.

Investigations the long-term GCR variations measured by AMS-02 from 2011 to 2018, focusing on how these variations depend on particle rigidity across the solar cycle were performed (Modzelewska et al., 2025). The rigidity dependence of the amplitude of GCR flux changes was examined. The spectral index γ varies with solar activity, tending to be higher during solar maximum and lower during solar

minimum. The relationship between these variations and heliospheric magnetic field turbulence, characterized by spectral exponents of magnetic fluctuations, was analyzed. The rigidity spectrum of GCR variations is energy-dependent, softening at higher energies, and that the observed patterns are consistent with theories linking magnetic turbulence to GCR modulation.

Author and Afiliation: Agnieszka Gil, Centrum Badań Kosmicznych PAN

[1] Hayakawa H., Koldobskiy S., Mishev A., Poluianov S., Gil A., Usoskina I., Usoskin I.: Revision of the strongest solar energetic particle event of 23 February 1956 (GLE #5) based on the rediscovered original records, Astronomy & Astrophysics, 2024, vol. 684, A46. DOI:10.1051/0004-6361/202348699

[2] Gil A., Asvestari E., Mishev A., Larsen N., Usoskin I.: New Anisotropic Cosmic-Ray Enhancement (ACRE) event on 5 November 2023 due to complex heliospheric conditions, Solar Physics, 2024, vol. 299, 7, 97. DOI:10.1007/s11207-024-02338-3

[3]Mishev A., Larsen N., Asvestari E., Sáiz A., Shea M., Strauss D., Ruffolo D., Banglieng C., Seunarine S ., Duldig M,Gil A., Blanco J., García-Población O., Cervino-Solana P., Adams, Jr. J., Usoskin I.: Anisotropic Forbush decrease of 24 March 2024: First look, Advances in Space Research, 2024, vol. 74, 8, 4160-4172. DOI:10.1016/j.asr.2024.08.027

[4] Modzelewska R., Gil A., Siłuszyk M., Kozak-Superson D.: Rigidity Dependence of the Long-term Galactic Cosmic Ray Variation by AMS-02, Astrophysical Journal, 2025, vol. 990, 2, 178. DOI:10.3847/1538-4357/adf440

3.5. SPACE WEATHER SERVICES

3.5.1. Heliogeophysical Prediction Service

Space Research Centre Polish Academy of Sciences hosted Regional Warning Centre of the International Space Environment Service. Data from Polish observatories are collected and real-time provided and from the past. Three components of geomagnetic field are presented: the Central Geophysical Observatory PAS in Belsk (IGF, Poland), Geophysical Observatory (IGF, Hel) and Polish Polar Station Hornsund (Svalbard). Ionospheric characteristics from two ionosondes Warsaw and Olsztyn. Riometer data from Borowiec (CBK PAN, Poland). Global maps of Total Electron Content. Regional and global maps of ionospheric characteristics and parameters for HF use. Near real-time ionospheric disturbance index W for European area.

RWC Warsaw provides continuous now-casting of ionospheric conditions over selected areas and operates as national warning space weather center. In 2019, RWC Warsaw is a founding member of the PECASUS consortium, which provides 24/7 space weather services for the International Civil Aviation Organization (ICAO).

Research activities focused on monitoring and analysis of ionospheric conditions and their impact on satellite navigation and radio communication systems within the framework of PECASUS, SWESNET, and GMOP projects. The work included continuation of studies on the performance of GNSS and EGNOS systems under disturbed space weather conditions, with particular emphasis on ionospheric modeling and Total Electron Content (TEC) estimation. Comparative analyses were performed for different ionospheric models, including NeQuick, NTCM, and the H2PT model, to assess their influence on positioning accuracy and ionospheric delay estimation. Additional activities involved processing and

validation of observational data from ground-based monitoring instruments, including ionosondes and GNSS receivers. Work was also carried out on the development and maintenance of operational tools for automatic data acquisition, processing, and quality control focused on space weather related services. The activities supported both research and operational space weather services related to aviation and technological infrastructure.

Polar Radio Link - monitoring tool that allows to monitor the connection to the polar region parameters like Signal to Noise Ratio (SNR) using WSPR protocol at 1.8 MHz. The data are obtained by area analysis on one reflection connections over Scandinavian region. The data is calculated as hourly median for those connections. The value -9999 is generated when connection is not possible. Direct SNR data measurements database is a valuable tool for monitoring and optimizing the performance of a radio network, and monior inpact of ionospheric distrubances for radio links.By analysing this data over time, users can gain insights into signal quality, troubleshoot issues, and make informed decisions to improve network performance such as adjusting equipment settings, upgrading equipment, optimizing frequency allocation, or implementing interference mitigation techniques.

As part of the Pan-European Consortium for Aviation Space Weather User Services (PECASUS), the Space Research Centre of the Polish Academy of Sciences (CBK PAN) traditionally provides global experimental maps of *foF2* depression and *foF2* depression alerts, calculated in near real-time using the data from ionosonde networks. Examples of the maps are shown in the Figure 1. Software based on artificial neural network aimed at automatic measuring critical frequency of the ionosphere (*foF2*) from the ionograms in near real-time base was developed and deployed in 2024 at the Ukrainian Antarctic Station *Akademik Vernadsky* (UAS). Measured values of *foF2* are transferred from UAS to the server in Warsaw and used in operational space weather services of the Regional Warning Center (RWC Warsaw) and PECASUS working for the needs of civil aviation. Since then, the ionospheric conditions at the region of Antarctic Peninsula are represented on the maps (Fig. 3.5.1.1).

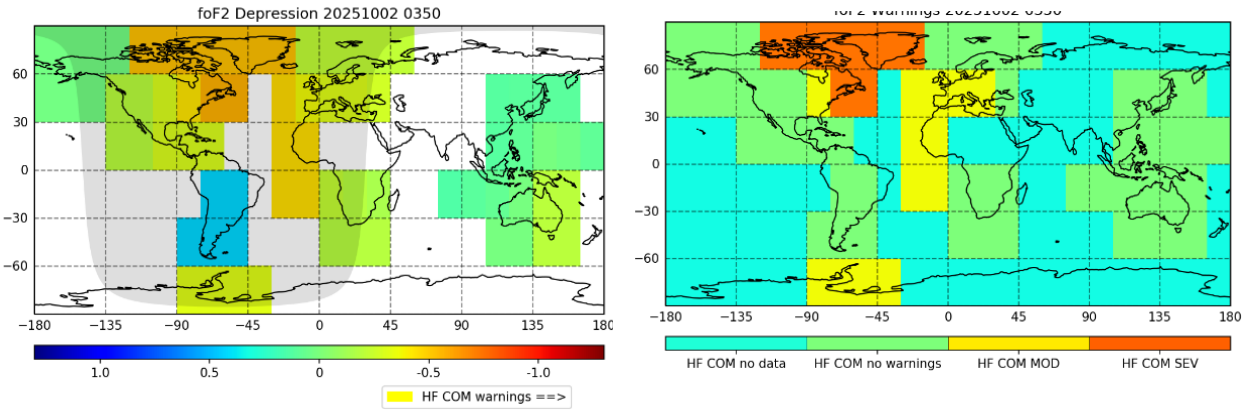


Figure 3.5.1.1 – Global maps of ionospheric foF2 depressions and areas where the warnings about dangerous levels of foF2 depressions.

To improve the regional space weather services the automatic calculating and visualizing the provisional local K indices for the Belsk Geomagnetic Observatory (BEL) in near real time base was realized on the web page of RWC Warsaw: http://rwc.cbk.waw.pl/rwcnew/kind.html. An example of provisional K indices for BEL observatory is shown in Figure 3.5.2.

Both above mentioned updates were made within the project «Studying the geospace plasma irregularities for the needs of Space Weather operational services» as a part of the Long-term program to support Ukrainian research teams at the Polish Academy of Sciences.

Last years the HF signals at diferent frequencied from the CHU time service station (Canada) are recorded and analysed at the LOFAR PL610 observatory (Borowiec, Poland). This radio path is located in close vicinity to transatlantic air routes between Europe and North America. We start using this and plan using similar data for monitoring the HF propagation conditions along the popular civil aviation routes. Recentely we installed a specialized WSPR (Weak Signal Propagation Reporter) radio beacon at the UAS and plan to use the data of WSPR network.

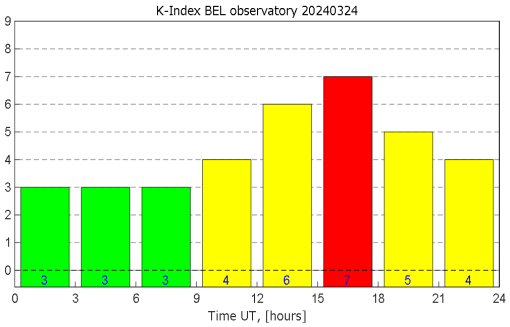


Figure 3.5.1.2. – Provisional K-indices calcu- lated in real time for March 24, 2024 for the BEL observatory.

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3.5.2. Space Weather Satellite

A feasibility study was conducted for a small-satellite mission dedicated to investigating magnetosphere–ionosphere–thermosphere coupling in the context of space weather. The mission, named SAWA, is intended to provide near-real-time data products to the ESA Space Weather Service Network, including:

- geomagnetic field measurements at a sampling frequency of 1 Hz (MFD instrument),
- electric-field spectra of plasma waves in the 10 kHz–10 MHz frequency range (POLARIS instrument),
- thermospheric neutral particle density measurements (ANDREW instrument),
- thermospheric atomic oxygen density measurements (ANDREW instrument).

A low Earth, Sun-synchronous orbit at an altitude of 500–600 km and a local time of ascending node between 10:30 and 11:30 was selected as the mission baseline. The mission consortium comprises Creotech Instruments S.A. (CTI), Space Research Centre of the Polish Academy of Sciences (CBK PAN), and Wroclaw University of Science and Technology (WUST). CTI serves as the prime contractor and is responsible for the satellite platform. CBK PAN is responsible for the development of the MFD and POLARIS scientific instruments, as well as the Payload Interface Controller (PIC), while WUST is responsible for the development of the ANDREW instrument. See

https://doi.org/10.1016/j.actaastro.2026.05.057

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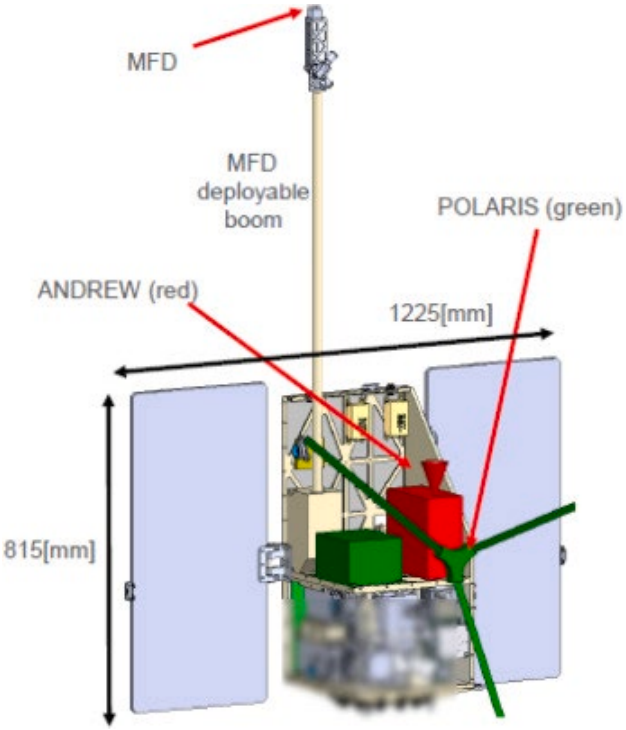

Figure 3.5.3. Mechanical design of SAWA. The non-scientific instrumentation of the platform is deliberately kept out of focus at the request of a consortium member.

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4

ASTRONAUTICS AND SPACE TECHNOLOGIES

4.1. ŁUKASIEWICZ RESEARCH NETWORK – INSTITUTE OF AVIATION

4.1.1. Space Transportation

In 2024, the ILR-33 AMBER 2K rocket developed by Łukasiewicz - Institute of Aviation achieved a major technological milestone with the successful completion of its qualification flight campaign. Launched from the Andøya Space Suborbital range in Norway, the rocket exceeded the Kármán line, becoming the first Polish-developed rocket in decades to reach space, and advancing it to Technology Readiness Level 7. Designed as a cost-effective, scalable, and environmentally responsible suborbital platform, AMBER rocket enables rapid validation of space technologies, atmospheric sounding missions, and microgravity experimentation. The vehicle's hybrid propulsion architecture, based on highly concentrated hydrogen peroxide (HTP 98%+), has also attracted international attention as an example of emerging green propulsion technologies in the European space sector. Current development activities are focused on achieving TRL 8 through further system maturation and operational validation.

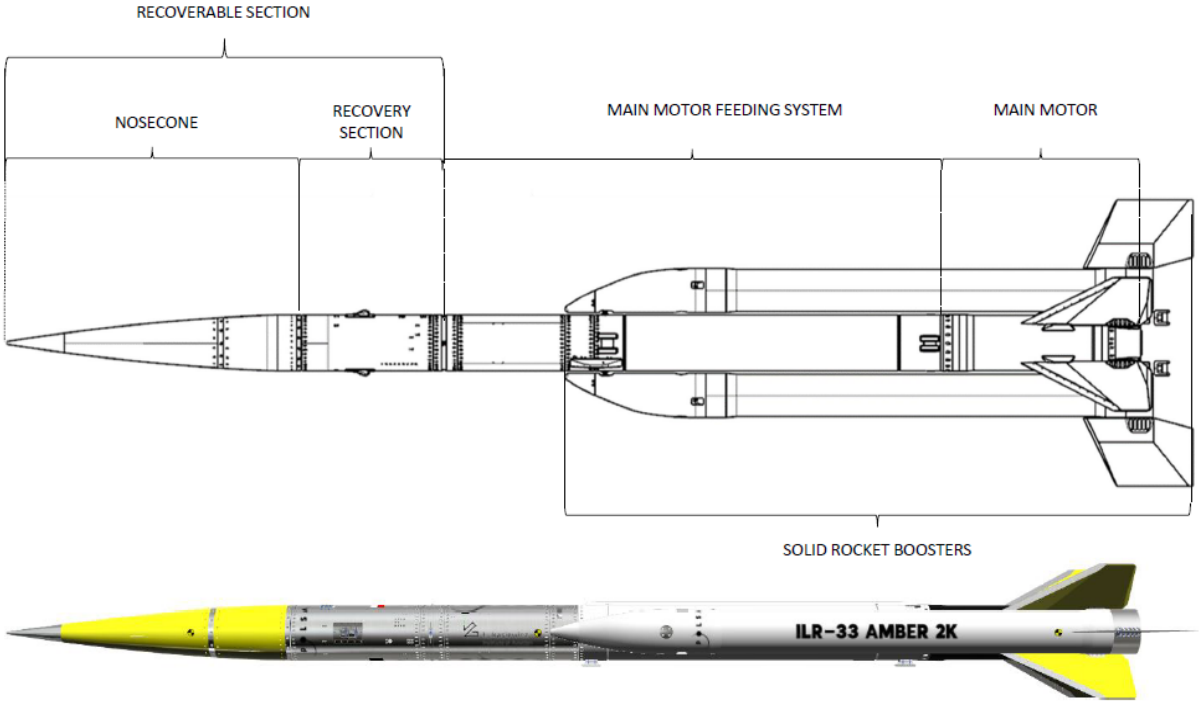

Figure 4.1.1.1. ILR-33 AMBER 2K rocket outline

In 2025, as leader of the consortium with SpaceForest, Lukasiewicz Research Network – Institute of Aviation participated in a project funded by the Polish Space Agency focused on the selection and qualification of payloads for flight aboard the Perun suborbital rocket. Within the project, 23 payload proposals were submitted, of which four were ultimately selected for qualification and flight preparation. The project provided valuable experience in payload assessment, safety verification, and mission integration procedures, establishing a foundation for future payload qualification campaigns dedicated to the ILR-33 AMBER 2K platform.

Figure 4.1.1.2. ILR-33 AMBER 2K on its mobile launch pad during the 2024 launch campaign in Andøya Space and a caption from its on-board camera from the historic launch above the Von Karman line

In 2026, the AMBER program of Łukasiewicz - Institute of Aviation is expected to reach another important milestone through its participation in the SUBCOM project co-funded by the National Centre for Research and Development, alongside its partner Thorium Space, in which the AMBER platform will be used to demonstrate and validate communication links between the ground segment, the rocket vehicle, and satellite infrastructure during flight operations.

In early 2026 Łukasiewicz Research Network has also announced its broader Space Research Program, under which development efforts will expand toward a small orbital launch vehicle capable of delivering payloads of up to 200 kg into Low Earth Orbit.

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4.1.2. Space Propulsion

In late 2025 Łukasiewicz - Institute of Aviation gained space flight heritage of its space propulsion in-house developed components. Key activities in the last years include developments of Łukasiewicz - Institute of Aviation related to:

- Green propulsion (98% hydrogen peroxide) spacecraft propulsion systems and components (incl. flight heritage)
- Green bipropellant rocket engines for kick-stages and upper-stages of launch vehicles (including use of Łukasiewicz – ILOT's engine in the kick-stage of MaiaSpace launch vehicle)
- Green deep-throttleable propulsion based on green liquid propellants with 98% HTP as oxidizer (throttling down to 10% of nominal thrust)
- Additive manufacturing for Space Propulsion including single-piece regeneratively-cooled combustion chambers
- Propulsion for suborbital vehicles (including successful launch of the ILR-33 AMBER rocket above the Von Karman Line)
- Solid propulsion compliant with modern Space Debris Mitigation regulations

- Detonative propulsion (Łukasiewicz – ILOT demonstrated the world's first flight of a rocket using a Rotating Detonation Engine with liquid propellants and achieved successful firings of various airbreathing RDE during ground hot-firings)

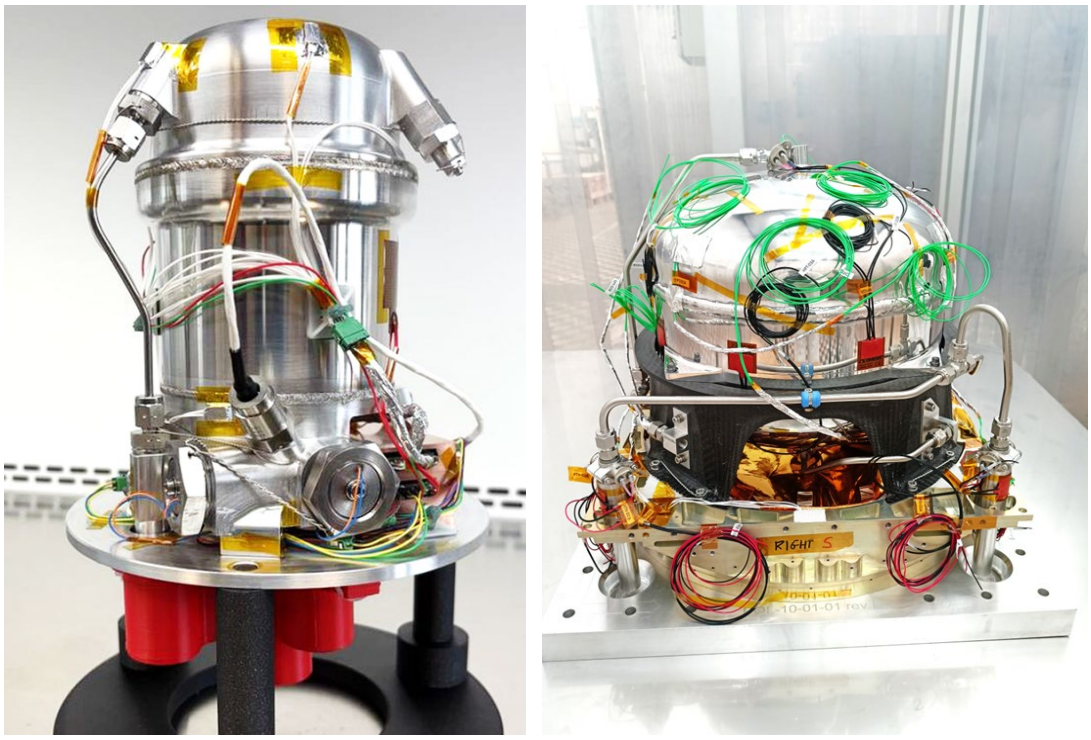

Figure 4.1.2.1. Polish green propellant (98% HTP) spacecraft propulsion modules during their qualification campaigns

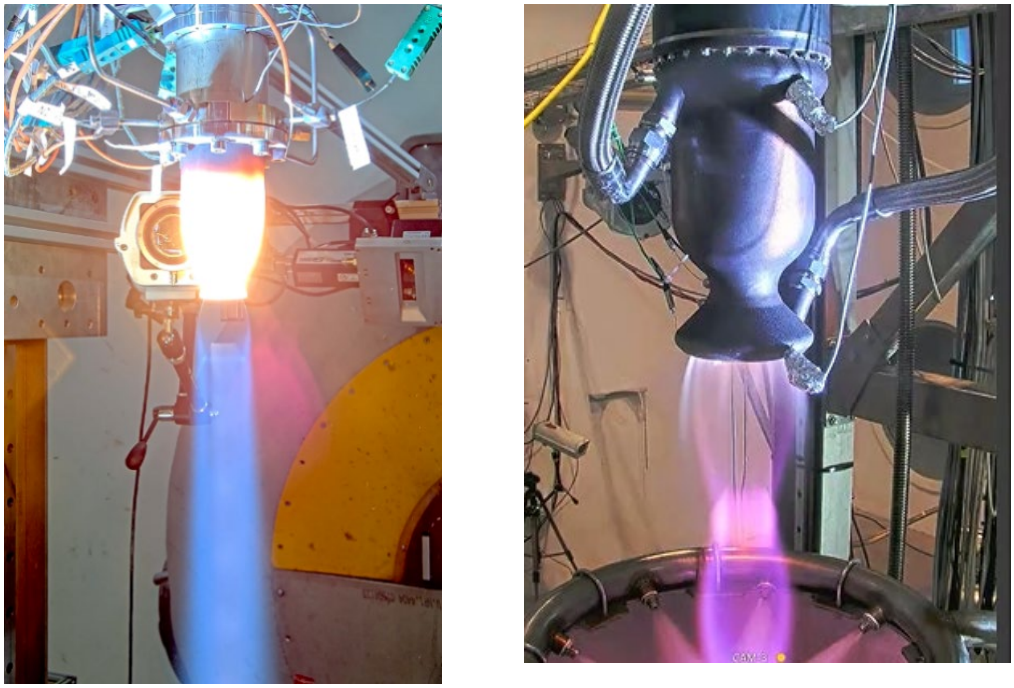

Figure 4.1.2.2. Green bipropellant engines using 98% HTP as oxidizer: 420 N engine (left) and throttleable 6 000 N engine (right) funded via projects of the European Space Agency

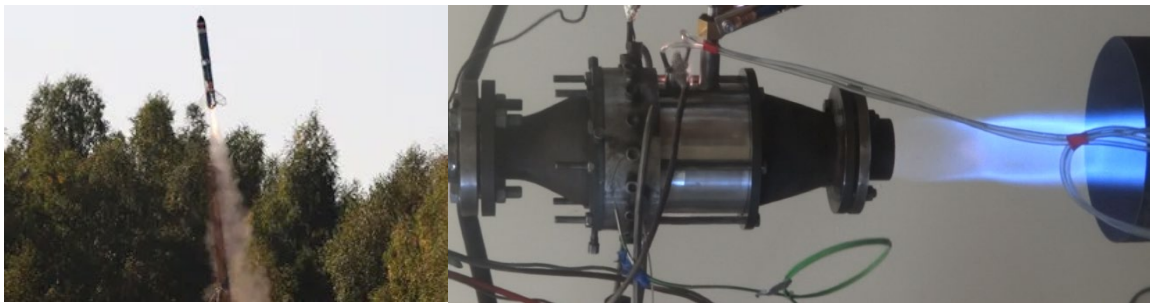

Figure 4.1.2.3. Rotating Detonation Engines: flight demonstration of rocket engine (left) and ramjet engine firing (right)

Importantly, the developments listed would not be possible without key investments of Łukasiewicz - Institute of Aviation in infrastructure:

- Extensive laboratories dedicated to hydrogen peroxide (focus on 98% HTP), green hypergolic propellants, advanced catalyst beds etc.
- Multiple test stands for green space propulsion hot-fire testing (including Europe's largest high-altitude hot-firing facility dedicated to engines and thrusters using green propellants, co-funded via EU funding from the 2014-2020 Regional Operational Programme of the Mazowieckie Voivodeship)
- Detonative propulsion test stands (both for air-breathing and rocket mode engines)
- Facilities for solid and hybrid propulsion developments
- Metal additive manufacturing laboratory with focus on Space Propulsion
- Extensive laboratories for environmental testing, fluidic testing, material testing etc.

Figure 4.1.2.4. High-altitude hot-firing facility dedicated to green thruster and engine development

Relevant publications:

[1] Okninski, A., Surmacz, P., Sobczak, K., Florczuk, W., Cieslinski, D., Gorgeri, A., Bartkowiak, B., Kublik, D., Ranachowski, M., Gut, Z. and Parzybut, A., 2025. Development of Green Bipropellant Thrusters and Engines Using 98% Hydrogen Peroxide as Oxidizer. *Aerospace*, *12*(10), p.879.

[2] Surmacz, P., Parzybut, A., Ranachowski, M., Gut, Z. and Alaszkiewicz, M., 2025. Game-Changing Technologies for Green Propulsion Operating with 98% Hydrogen Peroxide. *Small Satellite Conference*, 2025.

[3] Cieśliński, D., Okniński, A., Ranachowski, M., Molik, M., Bartkowiak, B., Matysek, K., Kutnik, K., Gorgeri, A., Ogórek, G. and Borys, M., 2025. On development of green storable liquid rocket engine with thrust variation. *Acta Astronautica*, *234*, pp.560-574.

[4] Perkowski, W., Bilar, A., Augustyn, M. and Kawalec, M., 2024. Air-breathing rotating detonation engine supplied with liquid kerosene: propulsive performance and combustion stability: W. Perkowski et al. *Shock Waves*, *34*(2), pp.181-192.

[5] Surmacz, P., Parzybut, A., Gramatyka, J., Bodych, D., Rugor, Ł., Uwarowa, I., Mariani, M. and Guerzoni, M., 2024. Concept of a green propulsion system for IOSHEX, designed to perform in-orbit randezvous and docking. *Transactions on Aerospace Research*, *276*(3), pp.58-76.

[6] Kawalec, M., Wolański, P., Perkowski, W. and Bilar, A., 2023. Development of a liquid-propellant rocket powered by a rotating detonation engine. *Journal of Propulsion and Power*, *39*(4), pp.554-561.

[7] Parzybut, A., Surmacz, P., Gut, Z. and Ranachowski, M., 2023, October. Additive Manufactured Fuel Injector as a Way Forward to Improve Green Propellant Liquid Apogee Engine. In *Proceedings of the 74th International Astronautical Congress, Paris, France* (pp. 2-6).

[8] Parzybut, A., Surmacz, P. and Gut, Z., 2023. Impact of hydrogen peroxide concentration on manganese oxide and platinum catalyst bed performance. *Aerospace*, *10*(6), p.556.

[9] Okninski, A., 2022. Solid rocket propulsion technology for de-orbiting spacecraft. *Chinese journal of aeronautics*, *35*(3), pp.128-154.

[10] Okninski, A., Surmacz, P., Bartkowiak, B., Mayer, T., Sobczak, K., Pakosz, M., Kaniewski, D., Matyszewski, J., Rarata, G. and Wolanski, P., 2021. Development of green storable hybrid rocket propulsion technology using 98% hydrogen peroxide as oxidizer. *Aerospace*, *8*(9), p.234.

Authors and Afiliation: Adam Okniński, Kamil Sobczak, Łukasiewicz Research Network – Institute of Aviation

4.1.3. Remote Sensing

Between 2024 and 2026, the Łukasiewicz Research Network – Instituite of Aviation implemented a series of Research and Development (R&D) projects in the field of Remote Sensing. The primary activities focused on the development of advanced sensors and mobile platforms, data analysis, and the design of dedicated algorithms, as well as work on key subsystems supporting robotic solutions. Additionally, initial activities were undertaken to establish a ground segment for the satellite data acquisition**.** The majority of these efforts were aligned with previously identified priority areas considered critical to national security. Furthermore, research activities were initiated in the domains of drone swarm technologies and the application of remote sensing for monitoring and supporting agricultural processes.

A) Internal Project SMILE

Łukasiewicz Research Network – Institute of Aviation has strong potential to expand its international, particularly European, involvement in Remote Sensing by building on the experience gained in the SMILE project. The project demonstrated the Institute's ability to develop a high-readiness, real-time monitoring system for linear infrastructure using both passive and active sensors, AI/ML-based defect detection, and a flexible architecture adaptable to different UAV platforms and operational scenarios. This creates clear relevance for European markets, where automation, speed, and reliability of infrastructure inspection are increasingly important. A major asset is the Institute's competence in integrating multisensor airborne acquisition, onboard and cloud-based processing, mission management, and post-processing into one scalable system. The use of advanced solutions such as Starlink connectivity and the CREODIAS cloud environment further shows readiness for cross-border, data-intensive operations aligned with European digital and Earth observation ecosystems.

The project's extensive testing, market consultations with infrastructure stakeholders, and transfer of results toward SAR-related applications indicate that the Institute can act not only as a technology developer, but also as a service provider and R&D partner in European initiatives related to infrastructure resilience, security, emergency response, and operational remote sensing services.

B) Internal Project GDNAV (GNSS-denied navigation)

The objective of the "GNSS-denied navigation" project was to develop a vision-based localization system for unmanned aerial vehicles (UAVs). The system was designed to perform navigation calculations based on an orthophotomap and a digital elevation model (DEM), without relying on Global Navigation Satellite Systems (GNSS). Furthermore, it had to be robust against dynamic changes in flight altitude, inclinations of up to 25 degrees, vibrations, and varying lighting conditions. The core concept of the project was to base the system on image analysis utilizing artificial intelligence (AI) algorithms. Their operation involved matching the live camera image to a properly prepared photogrammetric image of the terrain. It was demonstrated that under real-world conditions, AI algorithms exhibited significantly higher effectiveness compared to conventional image analysis methods, in terms of both accuracy and processing time. This enabled the development of a GNSS-independent localization algorithm for UAVs that met the aforementioned robustness requirements while maintaining the required positioning accuracy and update rate.

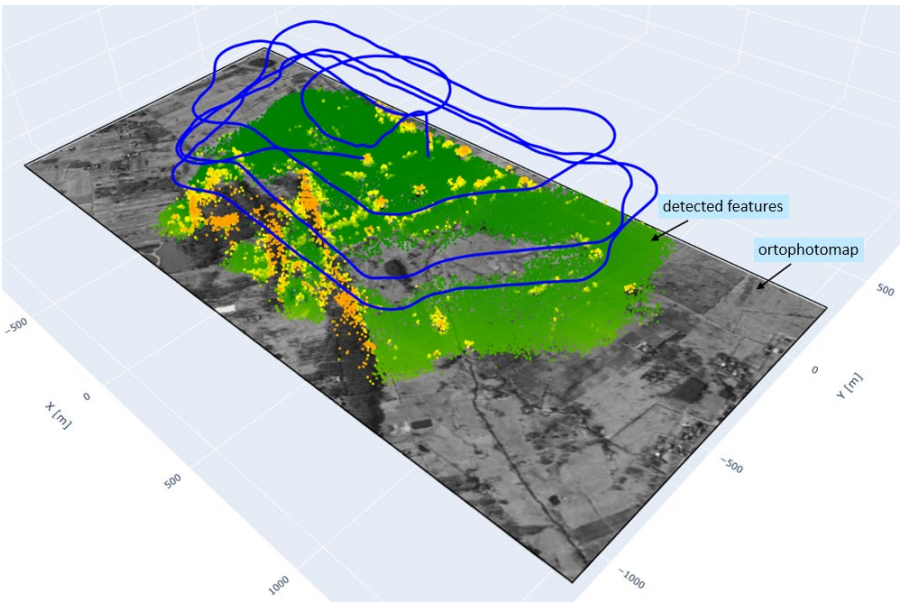

Figure 4.1.3. Visualization of the UAV trajectory over the orthophotomap with overlaid DEM points. Altitude color scale relative to the take-off point: from green (0 m) to orange (30 m)

Key research of Łukasiewicz – Institute of Aviation on Remote Sensing has been published in international journals and in conference proceedings.

(Bęben, 2025) presented a reinforcement learning based framework for coordinating UAV swarms in photogrammetric missions. The study evaluates how RL policies improve collision avoidance, coverage efficiency, and adaptive trajectory planning under dynamic conditions. Results show that RL driven

swarm control can shorten mission duration while maintaining high quality image acquisition. The work highlights the potential of autonomous swarm strategies for next generation photogrammetry.

(Spiralski, 2025) outlined recent advances in remote sensing–based monitoring of pesticides and heavy metals. Building on the WEPR pilot and informing the larger WORZ project, it develops methods for assessing soil contamination. Using UAV imagery, multispectral satellite data, and vegetation indices, the researchers linked spatial patterns in soil and crop conditions with pollutant levels. Machine learning models, including Random Forest, classified contamination, supported by laboratory validation. Despite challenges such as limited samples and class imbalance, combining multi source data produced promising results. Future work will emphasize multi temporal analyses, improved prediction accuracy, and environmental risk mapping, supporting scalable monitoring aligned with European sustainability goals.

(Stypułkowska, 2024) described the use of deep neural networks. Deep learning significantly supports key tasks in science, engineering, and precision agriculture. In this study, a method for automatically determining maize developmental stages on the BBCH scale (phases 10-19) using RGB and multispectral images, deep neural networks, and a voting classifier. The method was evaluated using RGB images and multispectral data from the MicaSense RedEdge MX-Dual camera, with training conducted on HTC_r50, HTC_r101, HTC_x101, and Mask2Former architectures. The models were trained on RGB images and separately on individual spectral channels from the multispectral camera, and their effectiveness was evaluated based on classification performance. For multispectral images, a voting classifier was employed because the varying perspectives of individual spectral channels made it impossible to align and merge them into a single coherent image. Results indicate that HTC_r50, HTC_r101, and HTC_x101 trained on spectral channels with a voting classifier outperformed their RGB-trained counterparts in precision, recall, and F1-score, while Mask2Former demonstrated higher precision with a voting classifier but achieved better accuracy, recall, and F1-score when trained on RGB images. Mask2Former trained on RGB images yielded the highest accuracy, whereas HTC_r50 trained on spectral channels with a voting classifier achieved superior precision, recall, and F1-score. This approach facilitates automated monitoring of maize growth stages and supports result aggregation for precision agriculture applications. It offers a scalable framework that can be adapted for other crops with appropriate labeled datasets, highlighting the potential of deep learning for crop condition assessment in precision agriculture and beyond.

(Stypułkowska, 2026) proposed a method for semantic segmentation of RGB images captured by UAVs to detect railway infrastructure elements, including tracks, level crossings, and surrounding vegetation. The study was conducted at the Łukasiewicz Research Network - Institute of Aviation, where a proprietary, manually annotated UAV RGB dataset was created. Five deep neural network architectures were trained and compared: DeepLabV3+, Feature Pyramid Network (FPN), LinkNet, Pyramid Attention Network (PAN) and X-Unet. These models were chosen for their distinct approaches to semantic segmentation and feature processing. Training was performed on a desktop computer with an NVIDIA GeForce RTX 3080 GPU and tests were made also on an NVIDIA Jetson AGX Orin to assess deployment feasibility under real-time conditions. Experimental results confirm the strong performance of the analyzed models in segmenting railway tracks and surrounding vegetation. FPN achieved the highest scores, followed by X-Unet, DeepLabV3+, LinkNet, and PAN. All models operated reliably on the NVIDIA Jetson AGX Orin edge platform. The proposed solution can support remote monitoring of railway infrastructure and vegetation. It can also be adapted to other applications by

adjusting the training dataset and object categories. This research demonstrates the potential of deep learning as a powerful tool for analyzing UAV RGB imagery in engineering and environmental contexts.

(Pogorzelski, 2025) focused on descriptor-based Image Matching Techniques for UAV applications. Unmanned aerial vehicles (UAVs) require high operational reliability. One of the key issues is ensuring uninterrupted localization. Unfortunately, the Global Navigation Satellite System (GNSS) is susceptible to interference. This problem can be overcome by redundant localization using vision, where the UAV position is determined by comparing satellite images assigned to a given area with images recorded by an onboard camera. It is a real-time process, so a reliable image-matching technique is crucial. This article presents the results of comparative studies of typical image feature-matching algorithms. Pre-processed images recorded during flights and satellite orthophotomaps are used for these studies. The comparison results are presented graphically. The work consists of three stages: – image labelling, – automatic imagematching, and – analysis of the results. The research goal is to identify the image-matching method that gives the most precise result and is not computationally demanding. The data were collected during flights at various altitudes, with various tilt angles and route lengths. The data diversity allows us to assess the quality of map-matching methods, considering various flight parameters. The flights were carried out in good weather conditions. The most effective image-matching methods, such as DKMv3 and ROMA, were indicated, and their ability to perform efficient matching was highlighted. Additionally, the limitations of vision-based localization, including challenges related to illumination changes, occlusions, and viewpoint variations, are discussed. The presented research is relevant for designing resilient localization systems.

Relevant publications:

[1] Bęben, Karol Piotr; Głębocki, R.; Kacprzak, M.; 2025. Towards Efficient UAV Swarm Control for Photogrammetry: Evaluating a Reinforcement Learning Approach. In: S. Y. Yurish (Ed.), Proceedings of the 1st International Conference on Drones and Unmanned Systems (DAUS 2025), Granada, Spain, 19–21 February 2025, pp. 237–242. IFSA Publishing. doi:10.13140/RG.2.2.18747.94240

[2] Spiralski, M.; Miszczak, A.; Siebielec, G.; Piasecka, Ż.; Trojnacki, R.; Kwaśnik, P.; Kotlarz, J.; Kubiak Siwińska, K. A.; Kacprzak, M.; Marciniak, S.; Rotchimmel, K. A.; Bęben, Karol Piotr; Szymański, J.; 2025. Integrating Remote Sensing and AI for Precision Monitoring of Soil and Vegetation contamination. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLVIII G 2025, 1373–1379. doi:10.5194/isprs archives XLVIII G 2025 1373 2025

[3] Stypułkowska, J. S., & Rokita, P. (2024). Classification of maize growth stages using deep neural networks with voting classifier. Machine Graphics & Vision, 33(3/4), 29–53. doi:10.22630/MGV.2024.33.3.2

[4] Stypułkowska, J. S. (2026). Deep learning for semantic segmentation of linear infrastructure from UAV imagery using NVIDIA Jetson AGX Orin. Machine Graphics & Vision, 35(1), 51–70. doi:10.22630/MGV.2026.35.1.3

[5] Pogorzelski Tomasz, Zielinska Teresa; 2025; Comparative Studies of Descriptor-based Image Matching Techniques for UAV Applications; IEEE Access; 13; 85461; doi: 10.1109/ACCESS.2025.3566953

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4.2. Composite technologies Space Research Centre PAS

Thermoplastic composite small satellite structure

Łukasiewicz Research Network - Institute of Aviation is a leader in thermoplastic composite technology, including the use of high-performance thermoplastics such as PEEK, LM PAEK and PEI. The space industry is currently showing a greater interest in these materials. In cooperation with Creotech Instruments, the Łukasiewicz – Institute of Aviation has developed an engineering model of a satellite structure that is fully fabricated from thermoplastic composites.

The small-satellite market is driven by trends such as the miniaturization of payloads, the deployment of large constellations, and the demand for faster time-to-orbit. At the same time, developers face challenges such as tight mass/volume budgets and issues with thermal and radiation management.

As part of the ESA ARTES programme, Łukasiewicz – Institute of Aviation and Creotech Instruments used a weldable, high-performance thermoplastic composite (LM-PAEK) to quickly fabricate an engineering model (EM) of a telecommunications satellite. The project aimed to build a satellite made entirely of thermoplastics using methods and technologies suitable for automation in preparation for future medium- to large-scale production. To achieve rapid and scalable manufacturing, the following approach was taken: use of thermoplastic composite technologies with potential for automation,

- simplification of the design geometry (solid laminates with rib grids stiffeners),
- reduction of joining steps and number of parts,
- use of minimal amount of tooling,
- fabrication as many features as possible, such as walls, joining interfaces and stiffeners in one process.

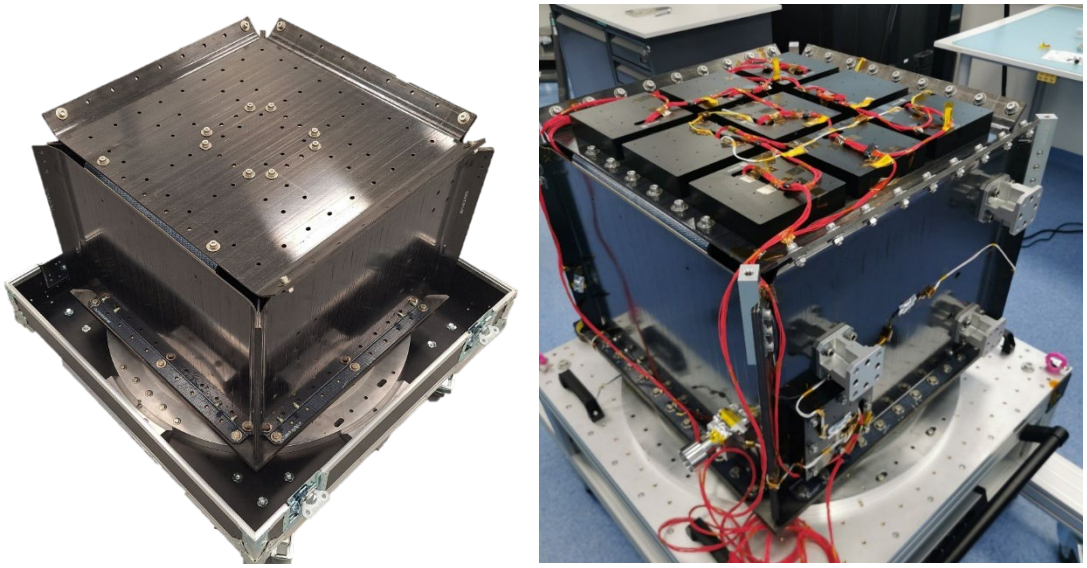

Figure 4.2.1. Small satellite structure fabricated from thermoplastic composites (left) and engineering model of the thermoplastic composite satellite integrated and prepared for testing (right)

The structure's design aimed to enable manufacturing using either a press or AFP. The tooling enables most of the satellite's walls to be fabricated on one set of tools. The side walls, top wall and internal walls of the structure were made using one tool. The base wall was fabricated separately as a flat panel. The number of parts and joining steps was reduced by fabricating the walls, joining interfaces and rib grid stiffeners in one process.

The full development of fabrication and joining technologies was carried out, with validation at the specimen level and up to the full EM structure. The research included the development of in situ AFP

fabrication using tapes and press thermoforming using fabric; the characterisation of materials; the design of the platform; the fabrication of parts; the development of inserting technology; the development of resistance welding; the fabrication of tooling for machining and joining; the joining of the structure (welding and screws); and the integration with instruments.

The benefits and limitations of thermoplastic technology were explored and validated. A full thermoplastic engineering model of a telecommunication satellite measuring 655 × 655 × 506 mm, mass of 30 kg in composite form and 90 kg when fully instrumented, was built using advanced fabrication techniques suitable for automation:

- Automated Fiber Placement (AFP),
- Press thermoforming,
- Resistance welding,
- Inserting using heat.

The EM passed the TVAC and vibration tests required for launchers such Falcon 9, Ariane 6 or Vega, proving the validity of the technologies used, which have reached TRL 5.

The tested methods enable high-speed, repeatable production while maintaining structural integrity and performance. This approach is a significant step towards redefining how future satellite platforms can be built: faster, more efficiently and with the potential for medium/large-scale production.

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Composite structures for optical payloads

In recent years, the space industry has experienced a tremendous increase in the number of satellites deployed in Low Earth Orbit (LEO). Alongside communication and navigation systems, Earth Observation (EO) missions constitute another crucial category of spacecraft. EO satellites provide essential data related to weather monitoring, oceanography, wildfire detection, climate studies, and numerous other applications. The design of optical payloads requires a unique combination of material and structural properties. In particular, instrument structures must exhibit high stiffness and exceptional dimensional stability over a wide operational temperature range. Such structures are typically manufactured either from ceramics or carbon-fiber-reinforced polymer (CFRP) composites. Due to their high cost and challenging manufacturing processes, ceramic structures are generally limited to scientific missions requiring the highest levels of precision and thermal stability. Consequently, most commercial missions rely on CFRP-based solutions.

In response to the anticipated demand within the Polish and European space sectors, Łukasiewicz – Institute of Aviation has carried out two projects focused on the development of optical bench technologies. The Institute possesses extensive expertise in composite technologies, covering the entire development chain from structural design and numerical analysis to manufacturing, testing, and qualification. Within these activities, cyanate ester/carbon fiber composites were selected as the baseline material system for the structures. Autoclave curing trials were conducted, accompanied by extensive thermal, mechanical, and physicochemical characterization in the temperature range from −100°C to 177°C. Based on DSC, DMA, TGA, LFA, dilatometry, and outgassing investigations, optimal processing routes were established. Furthermore, a comprehensive material database was developed to support numerical simulations and future space projects.

Figure 4.2.2. Engineering model of the composite optical bench developed in Łukasiewicz – Institute of Aviation

On this basis at Łukasiewicz – Institute of Aviation, a technology demonstrator was designed and manufactured in the form of a simplified optical bench incorporating a composite-aluminum sandwich panel, composite struts with a near-zero coefficient of thermal expansion (CTE), and bonded inserts. Finite Element Analysis (FEA) demonstrated the possibility of achieving extremely low thermal deformations, on the order of only a few micrometers under an 80°C temperature variation. In parallel, the manufacturing campaign confirmed the capability to implement advanced autoclave composite processing methods and insert integration techniques representative of modern satellite structures.

Authors and Afuliation: Jakub Wilk, Maciej Giżyński, Łukasiewicz Research Network – Institute of Aviation

5

ASTROBIOLOGY AND SPACE MEDICINE

SATELLITE GEODESY, GEODYNAMICS, GRAVIMETRY, GNSS, AND SPACE GEODETIC TECHNIQUES

Life in the Universe, its origin, evolution, and distribution, is one of the fundamental subjects of study. It requires a highly interdisciplinary approach and naturally stimulates scientific collaboration. Like in many other countries, research activities, education, and outreach in astrobiology in Poland are conducted within the framework of a national centre. Moreover, one of the divisions of the Committee on Space and Satellite Research of the Polish Academy of Sciences (PAS) is devoted to astrobiology and space medicine.

The name of the Polish national centre is the Centre for Advanced Studies in Astrobiology and Related Topics (CASA*), a virtual scientific institution in Poland that began its activities in 2003. Since 2007, CASA* has been formally organized as a consortium of five Founding Institutions. Three of them - the Space Research Center (CBK), the Nicolaus Copernicus Astronomical Center (CAMK), and the Institute of Paleobiology (IP), all belonging to the Polish Academy of Sciences (PAS) - are based in Warsaw. The Nicolaus Copernicus University (UMK) and the University of Szczecin (US) are located in Toruń and Szczecin, respectively. The headquarters of CASA* are at the University of Szczecin. The scientific policy of the centre is governed by its Scientific Board.

Currently, CASA* comprises ten research teams with expertise in astronomy, astrophysics, biopolymer physics, statistical physics, space physics, medical genetics, space medicine, microbiology, biogeology, biosedimentology and geomicrobiology. One of the largest CASA* programmes „Through Cosmic Dust to DNA", focuses on five core scientific areas:

1. The origins, structure, and evolution of planetary systems;
2. The mutagenic effects of cosmic radiation;
3. The effects of ionizing radiation on organic and inorganic molecules;
4. The search for life under extreme conditions;
5. Carbonate and siliceous minerals and sediments as carriers of traces of extant and past microbial life.

Collaborative research has been carried out by members of CASA* together with the Committee on Space and Satellite Research of the Polish Academy of Sciences, the European Astrobiology Network Association (EANA), the European Astrobiology Institute (EAI), the EUROPLANET Society, and several research institutions and universities worldwide. In 2023, the COST Action CA22133 - The birth of solar systems (PLANETS) - started, providing the structure and funding needed to develop the research framework, train the next generation of investigators, and disseminate the findings to key stakeholders. Poland is one of 32 participating countries. There are three cornerstones in this multi-disciplinary network: experiments, models, and observations. Experimental data are needed to accurately prescribe physics in models of disc evolution and planet formation, and to correctly interpret observations of dust and gas emission. Models are a "virtual laboratory" within which the impact of physics can be explored, and from which observational diagnostics can be created. Finally, observations provide us with the tests needed to confirm or refute our picture of how planetary systems are born.

Here we summarise activities relevant to astrobiology and space medicine for the period 2022-2025, focusing on participation in space missions, Earth expeditions and selected outcomes.

5.1 IGNIS MISSION

IGNIS was the first Polish science and technology mission to the International Space Station (ISS) and part of Axiom Mission 4 (Ax-4), the most research-intensive private astronaut mission to date. It conducted over 60 experiments across biomedical science, advanced materials, neuroscience, agriculture, and space technology, 13 of which were Polish-led. The SpaceX Dragon spacecraft, carrying the Ax-4 crew - Commander Peggy Whitson (USA), Pilot Shubhanshu Shukla (India), and Mission Specialists Sławosz Uznański-Wiśniewski (Poland) and Tibor Kapu (Hungary) - was launched on June 25, 2025, and returned to Earth on July 15, 2025.

IGNIS was sponsored by the Polish government and supported by ESA, the Polish Ministry of Economic Development and Technology (MRiT), and the Polish Space Agency (POLSA). It has advanced science and technology, inspired students and strengthened the ties between space and society. Polish experiments were developed in collaboration with universities, research institutions, and companies, all coordinated by ESA and POLSA. The educational programme for all age groups included lessons from space, competitions, microgravity experiments, and two amateur radio contacts.

Scientific and technological experiments carried out during the IGNIS mission are as follows:

- **AstroMentalHealth:** an examination of the psychological well-being of astronauts during space missions;
- **AstroPerformance:** an investigation of how spaceflight affects the soft tissues in astronauts' legs;
- **EEG Neurofeedback:** a brain training technique that helps individuals learn to regulate their mental states;
- **Human Gut Microbiota:** an anaysis of changes in the gut microbiota during a short-duration space mission;
- **Immune Multiomics:** an evaluation of the effects of spaceflight on the human immune system;
- **LeopardISS:** a validation of artificial intelligence (AI) algorithms in real spaceflight conditions;
- **MXene in LEO:** a technology demonstration testing an advanced nanomaterial – Mxene - in the unique environment of space;
- **PhotonGrav:** tests of the muscle-free communication in microgravity using a brain-computer interface based on near-infrared spectroscopy;
- **RadMon-on-ISS:** Scalable Radiation Monitor measurements of the parameters of the radiation environment on the International Space Station in the European Columbus module, and investigations of how cosmic radiation affects the operation of integrated circuits;
- **Space Volcanic Algae:** studies of the extremophilic microalgae from volcanic regions in space conditions;
- **Stability of Drugs:** an investigation of whether commonly used drugs can retain their effectiveness longer in space when incorporated into a biodegradable polymer carrier;
- **Wireless Acoustics:** continuous noise monitoring on the International Space Station to determine the astronauts' personal noise exposure;
- **Yeast TardigradeGene** (shown in Figure 5.1): an investigation of the survival of genetically modified yeast - enriched with tardigrade protein - in space conditions.

Astrobiology and Space Medicine are well represented in this set of experiments, advancing our knowlwedge in these fields and preparing the ground for the present and future exploration of our Solar System. After exploring low Earth orbit with the ISS for more than two decades, scientists now want to go further into the Moon and Mars.

One of the experiments, Yeast TardigradeGene (full name „Before going to Mars: Can tardigrades help in protecting other organisms in space?"), was designed with exactly this goal in mind. Furthermore, it aligns perfectly with the ESA SciSpaceE Strategy Roadmap. The most relevant SciSpacE spotlight is „**Humans living on the Moon and Mars",** as this experiment aims to increase the survivability of organisms crucial for forming ecosystems in space or on planets like Mars. The results will also be applicable to long-duration space travels. The yeast S. C, used in the experiment, is the best-studied and most widely used yeast species in industrial applications and is widely regarded as a valuable tool in advanced biomanufacturing. In particular, S. CEREVISIAE is considered a strong candidate for developing a complete food-production system. In addition to providing nutrients for humans during space exploration, similar experiments can also help address global food security on Earth.

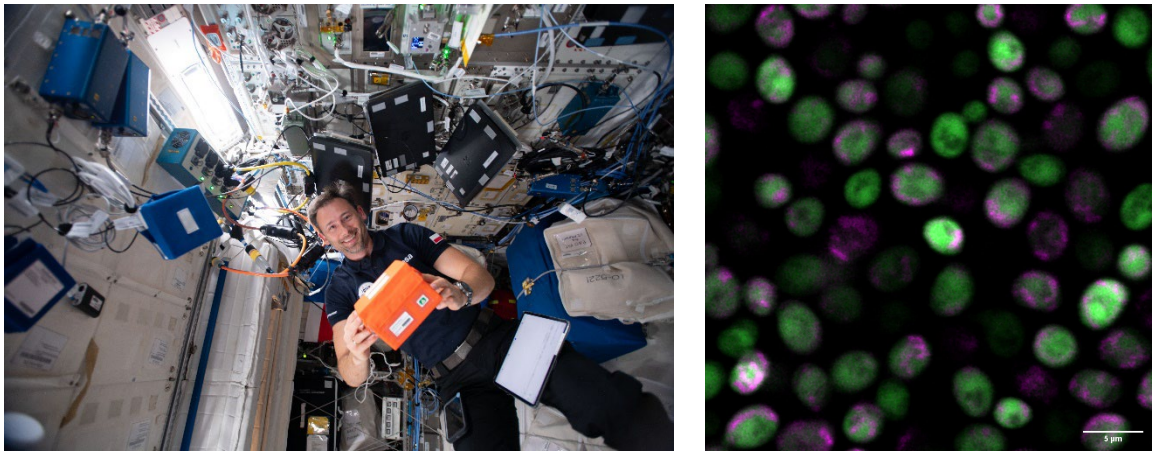

Figure 5.1. (Left): ESA project astronaut Sławosz Uznański-Wiśniewski with the payload for the Yeast TardigradeGene experiment. This research will explore whether yeast enhanced with a protein from the ultra-resilient tardigrade can survive harsh space conditions, opening doors to food and fuel production away from home. Credits: ESA. (Right): Confocal microscope image of yeast cells expressing the eGFP protein (green) with stained mitochondria (violet). Credits: Andonis Karachitos.

The biological samples from the Yeast TardigradeGene experiment were returned from the International Space Station in excellent condition. Researchers are currently analysing the space-flown samples while simultaneously conducting a parallel control experiment on Earth. The broader aim of the experiment is to explore how growing yeast in microgravity provides insight into gravity's role in the evolution of life. Ultimately, gravity is the fundamental force that has continuously influenced all living organisms throughout Earth's history.

5.2 SUBORBITAL ROCKET FLIGHTS

The extreme physical conditions of spaceflight (such as high g-force, vibration, and microgravity) can also be simulated during suborbital rocket flights, which serve as an excellent, cost-effective testbeds for biological payloads. Understanding organisms' adaptability is vital for treating astronauts, preventing damage to spacecraft structures, and exploring Mars. Therefore, the rapid development of Polish suborbital rockets (such as Perun by SpaceForest and ILR-33 AMBER 2K by the Łukasiewicz

Research Network – Institute of Aviation) provides advanced microgravity and atmospheric research platforms for astrobiological and biotechnological experiments. In 2024, the suborbital rocket ILR-33 AMBER 2K - which used 98% concentration hydrogen peroxide as a rocket propellant - reached an altitude of 101 km highlighting the achievements of Polish engineers in the field of space technologies.

5.3 IWST MISSION

Poland's involvement in the James Webb Space Telescope (JWST) mission focuses mainly on scientific exploitation and data analysis. An excellent example of a recent scientific achievement relevant to the field of astrobiology is the study of UV-irradiated outflows from low-mass protostars in the Ophiuchus molecular cloud, observed with JWST's Mid-Infrared Instrument (MIRI) Medium Resolution Spectrometer (MIRI/MRS) [1]. This research is important because the structure and composition of emerging planetary systems are strongly influenced by their natal environments. It has been found that planets begin to form much earlier than previously thought, specifically already during the ongoing process of star formation. Therefore, it is essential to identify and study the physical processes at play in the gas and dust near young protostars. Ophiuchus is one of the closest and most active low-mass star-forming regions to Earth. It contains a dense cluster of prestellar cores and young stellar objects shrouded by interstellar dust. JWST's MIRI can see through these opaque dust clouds, providing vital information about star formation and the connection between the birth of a star and its surrounding gas discs. A prominent H_2 outflow has been observed from the protostar GSS30-IRS 1, as shown in Figure 5.3.

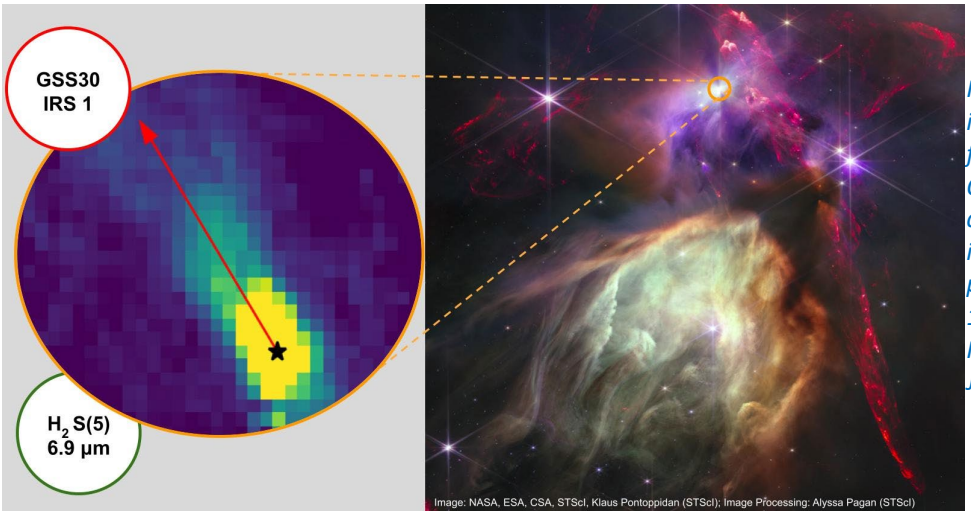

Figure 5.2. A close look into the ongoing star formation within the Ophiuchus Molecular clouds with a zoom-in into one of the protostars (GSS30- IRS 1) with a prominent H_2 outflow, studied by JWST.

Credit:Left: Astronomy& Astrophysics (2025). DOI:10.1051/0004-6361/ 202554977; Right: NASA, ESA, CSA, STScI, Klaus Pontoppidan (STScI), Processing: Alyssa Paghan (STScI).

5.4. PLATO MISSION

PLATO (PLAnetary Transits and Oscillations of stars) is the third medium-class mission in ESA's Cosmic Vision programme and it is dedicated to the search for exoplanets using the transit method. It is scheduled for launch in January 2027. The main scientific objective of PLATO is to detect and characterise rocky planets in habitable zones (the region around a star where the temperature is just

right for liquid water to exist on a planet's surface) around Sun-like stars. It will characterize hundreds of planets by providing high precision measurements of their radii (5% precision), masses (better than 10% precision) and ages (10% precision). PLATO will also analyse their host stars. Therefore, the mission outcome will be of great value for the understanding of star and planet formation as well as the evolution of entire planetary systems. PLATO has the potential to detect a second Earth and evaluate the habitability of a variety of different worlds.

Polish participation includes theoretical studies of the formation and evolution of planetary systems, focusing on planetary habitability. The members of the PLATO Mission Consortium (PMC) conduct studies in three Work Packages: WP 116 310 – Protoplanetary disc models, WP 116 320 - Disc-planet interaction and WP 116 340 – Long-term dynamical evolution of planetary systems. They will examine formation and evolution scenarios for individual systems discovered by PLATO, focusing on the early phases of the planetary system evolution, where forming or already formed planets are embeded in a protoplanetary disc. This research covers the orbital migration of planets in discs and their mass growth. Additionally, they will predict the nature of commensurabilities formed as a function of planet mass, relative planet mass ratio, and discuss their longer term stability. PMC members will perform dynamical studies of resonance planetary systems, taking into account tidal interactions with the central star. Magnetohydrodynamical simulations, analytic models and N-body techniques will be used for these studies.

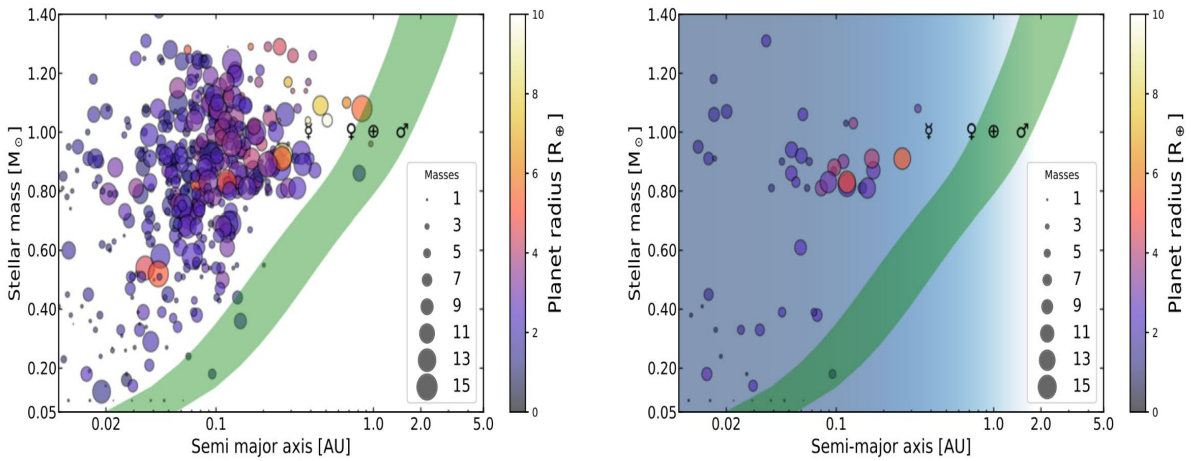

Figure 5.4.. Illustration of the PLATO objectives: populating the still quite empty HZ. Known small-low mass planets are shown in a stellar mass – orbital distance diagram, with symbol size and colour scaled with their masses and radii, respectively. The green band indicates the approximate position of the HZ, accounting for a potential early Mars or Venus in our Solar System, based on Kopparapu (2013). Telluric planets in the Solar System are labelled according to their symbol. Left panel: planets ≤ 10 R_{Earth} and ≤ 15 M_{Earth} ; Right panel: same, but only showing planets with precision better than 5% and 10% in radius and mass, respectively. The blue shaded area emphasises PLATO targeted detection domain. Data retrieved (on Sept. 2024) from the Planetary System Composite Data of the NASA Exoplanet Archive, excluding planets with mass or radius estimates from calculations. Credits: Rauer et al. (2025) https://doi.org/10.1007/s10686-025-09985-9.

A summary of the mission to the community, in preparation of the upcoming operational phases, is given in [2]. This paper reviews the science objectives and presents PLATO's target samples and fields. Moreover, it provides an overview of expected core science performance, as well as a description of the instruments and the mission profile.

5.5 ARIEL MISSION

ARIEL (Atmospheric Remote-sensing Infrared Exoplanet Large-survey) is the fourth medium-class mission in ESA's Cosmic Vision programme and the first one dedicated to measuring the chemical composition and thermal structures of hundreds of transiting exoplanets. It is scheduled for launch in 2029. The main scientific objective of ARIEL is to answer three key questions: (1) What processes take place in exoplanet atmospheres? (2) What are the interiors of exoplanets like? (3) How do planets and planetary systems form and evolve?

The main Polish contribution to the ARIEL mission is the development and construction of the Fine Guidance System (FGS**)**, led by the Space Research Centre of the Polish Academy of Sciences in Warsaw, which is crucial for the pointing and characterisation of the ARIEL targets. This point is covered in other sections of the present report. Here, instead, we mention the scientific topics relevant to astrobiology, as ARIEL will make it possible to identify which types of planets outside the Solar System could be suitable for life. The ARIEL Planetary Formation Working Group carriers out research relevant for planetary habitability, namely planet-forming environments, planet population models and multi-planet systems. In particular, the OPAL (Origin of Planets for ArieL) Key Science Project has been started with the aim of creating a library of realistic synthetic atmospheres spanning tens of elements and hundreds of molecules, on which the Ariel consortium will test and validate its codes and pipelines ahead of the mission's launch.

5.6 NEW ATHEN MISSION

NewATHENA is the recently redesigned ESA large X-ray mission ATHENA (Advanced Telescope for High Energy Astronomy), due to launch in the 2030s. It will provide unprecedented X-ray survey and spectroscopic capabilities. The Polish team is involved in building two important instruments, namely the X-IFU, an X-ray spectrometer, and the WFI, a powerful survey instrument. The WFI will enable studies of the geometry of the hot corona-accretion disc system through reverberation mapping to constrain the origin of the hot corona, and to measure spins in supermassive and Galactic black holes.

Polish researchers are active in several Working Groups of the mission, among them WG2: Galaxies and supermassive black holes (mainly focusing of accretion processes taking place in AGN); WG4: Compact objects (with a particular focus on low-mass and high-mass X-ray binaries hosting neutron stars and black holes, as well as on ultra-luminous X-ray sources); and WG3: Stars and their Environment (concentrating on planetary systems, star-planet interactions and the physics and chemistry of the Interstellar Medium).

5.7 EXPEDITION: VOLCANIC GLASS SHARDS AS PLANETARY BIOSIGNATURES.5

This research focuses on a comparative study of modern and Paleoarchean volcanic glass shards sampled by project investigators during: (1) the 1998 German-Polish expedition to Niuafou'ou island, Tonga Kingdom (Southern Pacific) (see Figure 5.7.), co-financed by the Deutsche Forschungsgemainschaft and the Polish Academy of Sciences; and (2) the Polish-South African expeditions to Barberton greenstone belt (BGB) in 2007 - financed by an inter-governmental project

for scientific cooperation between Poland and the Republic of South Africa - and in 2010 - funded by National Science Center (NCN, Poland).

Analysis of the mineralogy and microbiology of the collected shard envelopes began in 2022. Electron microprobe spectroscopy (Geology Dept, University of Warsaw) was used for detailed elemental analysis. Scanning electron microscopy (Institute of Paleobiology PAS) provided basic information on the elemental composition and the morphological preservation of the microfossils. Finally, ion microprobe spectroscopy (Prague) was used for detailed elemental analysis.

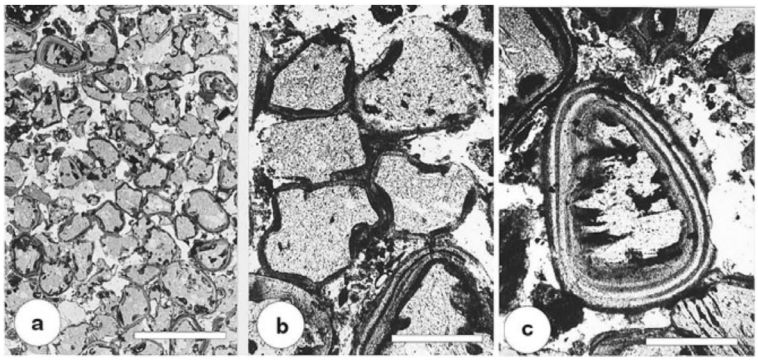

Figure 5.7. (a and b) Thin sections of weakly, with $CaCO_3$, cemented volcaniclastic sand with microlaminated coatings over some grains. (c) Enlargement of a volcanic glass shard with microlaminated calcium carbonate envelope. Scale bar equals: a – 3 mm, b and c – 250 µm.

Credits: Kempe, S., Kazmierczak, *J. (2012), doi.org/10.1007/978-94-007-4966-5_13* .

Deciphering life in Archean deposits is of fundamental importance to understanding the history and evolution of life on our planet and beyond. It has been suggested that certain volcanic rocks (pumices and basaltic rocks) could have had significance in the origin and evolution of early life on Earth. Here, it is argued that volcanic glass shards (volcaniclastics) also could have played a key role in the preservation of primitive microbial signatures. The project aims to conduct a sedimentological, geomicrobiological and petrological study of modern and Paleoarchean volcanic glass shards deposited in aqueous settings, with the purpose of evaluating their significance as a substrate and source of nutrients for microbes that induce precipitation of mineral phases preserved in the geological record. Analyses of glass shards encompass the study of organo-mineral envelopes, as well as shard petrology, the composition of material filling shard vesicles, and the composition of infilling of surficial cavities and "pockets". The authors of [3] show that modern (Holocene) and Paleoarchean volcanic glass shards deposited in aqueous settings (hyaloclastites) preserve evidence of alteration by microbial activity.

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References

[1] Skretas, I. M., Karska, A., Francis, L., Rocha, W. R. M., van Gelder, M. L., Tychoniec, Ł., Figueira, M., Sewiło, M., Wyrowski, F. and Schilke, P. (2025), UV-irradiated outflows from low-mass protostars in Ophiuchus with JWST/MIRI, A&A, 703, A139 (2025)

[2] Rauer, H., Aerts, C., Cabrera, J. *et al.* The PLATO mission. *Exp Astron* 59, 26 (2025). https://doi.org/10.1007/s10686-025-09985-9

[3] Kremer, B., Słaby, E., Wirth, R., Krzysztof, O., Maciej, B., Marcin, W., Agata, K., Anja, S., Stephan, K., and Jozef, K.: Volcanic glass shards as a substrate for early life, EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-12998, https://doi.org/10.5194/egusphere-egu25-12998, 2025.

6

LAW AND THE SPACE POLITICS

The Members of the Section of Law and Space Policy of the Committee on Space and Satellite Research affiliated with Presidium of the Polish Academy of Sciences cooperated with different academic institutions.

As highlighted in previous years, Poland attaches great importance to the contribution of the academic community to the progressive development of international space law. Over the past year, the Polish academic community has continued to play an active role in fostering legal scholarship and dialogue on contemporary challenges related to the exploration and use of outer space. A central role in these efforts has been played by the Manfred Lachs Centre for Space Law at the University of Warsaw, which has organized a number of high-level academic events bringing together scholars, practitioners, and representatives of public institutions.

In particular, a series of academic seminars has addressed key legal and policy developments at both the European and global levels. A seminar on the future EU Space Act – hopes and risks explored the potential impact of upcoming European regulatory initiatives, with contributions from Professor Lorin-Johannes Wagner, offering both doctrinal and practical perspectives on regulatory harmonization and its implications for Member States. Another seminar, devoted to the protection of dark skies and the role of Indigenous knowledge systems in shaping legal frameworks, featured Dr Shea Esterling as the main speaker, bringing an interdisciplinary perspective to discussions on space sustainability and cultural heritage protection. Furthermore, practical aspects of legal work in the space sector were addressed in a dedicated lecture on the role of lawyers in the space business, delivered by Ms Debbra Wilcox, President of the Colorado Space Business Roundtable, and Mr Kevin Strait of Anzen Legal.

Members and experts from the Section of Law and Space Policy of the Committee on Space and Satellite Research were involved in the preparation of the first handbook on international, European and national space law in 40 years. The publication was released in June 2025.

Among the most significant initiatives was a national expert meeting entitled “Quo vadis, Polish space sector?”, organized in cooperation with the Polish Space Professionals Association. This event provided a comprehensive platform for discussion on the current state and future development of the Polish space sector. It included the presentation of a detailed sectoral report prepared by the Association, followed by expert discussions involving representatives of academia, industry, and public administration. Particular attention was devoted to the regulatory environment governing space activities in Poland, including practical aspects of space law, challenges related to the implementation of international and European legal frameworks, and the need for further development of national legislation in response to the growing involvement of private actors in space activities.

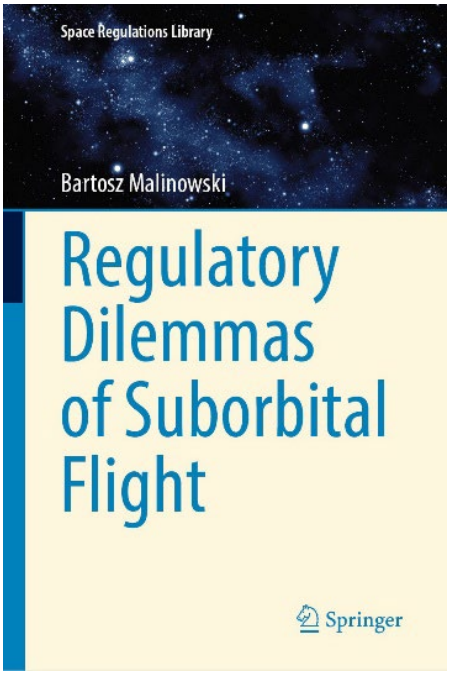
In parallel, broader discussions on space security and governance have also been developed within Poland through interdisciplinary and strategic forums. In particular, the SpaceShield Summit 2026, held

on 3–4 March in Stalowa Wola, brought together representatives of academia, industry, public administration, and the defense sector to address the future of space, defense, and dual-use technologies, highlighting the growing interconnection between space law, security considerations, and regulatory frameworks.

In addition, an important nationwide scientific and educational initiative was carried out in Poland in the form of the technological and scientific tour "IGNIS – Poland Reaches for the Stars", led by ESA project astronaut Dr Sławosz Uznański-Wiśniewski. The tour covered numerous academic centers across the country and culminated in a high-level final event at the University of Warsaw, strengthening dialogue between academia, public institutions, and the space sector, while promoting scientific research, innovation, and education in the field of space activities.

At the same time, the Polish scientific community has suffered a profound loss. On 3 November 2025, Professor Zbigniew Kłos, a distinguished physicist and long-standing Chair of the Space and Satellite Research Committee of the Polish Academy of Sciences, passed away. Professor Kłos made an outstanding contribution to the development of space research in Poland and actively supported interdisciplinary cooperation, including close collaboration with the legal academic community. He was a valued friend of the Department of International Aviation and Space Law and the Manfred Lachs Centre for Space Law at the University of Warsaw. Professor Kłos consistently supported the development of space law scholarship in Poland and frequently participated in the work of COPUOS and its Scientific and Technical Subcommittee. His engagement greatly contributed to strengthening the dialogue between technical and legal experts. He will be remembered not only for his scientific achievements, but also for his openness, kindness, and dedication to the advancement of the space community.

These initiatives demonstrate the growing importance of academic institutions and interdisciplinary platforms as spaces for dialogue between legal scholars, policymakers, and industry representatives. They also underline the role of academia in identifying emerging regulatory challenges and contributing to the development of a coherent and forward-looking legal framework for the governance of outer space.



The Section of Law and Space Policy of the Committee on Space and Satellite Research remains committed to supporting such initiatives and to strengthening the engagement of the academic community in the work in the field of space activities.

Finally, in March 2026, Poland adopted its first domestic space legislation. This new act incorporates conceptual developments in international space law scholarship to ensure the proper implementation of international obligations. It was drafted with particular attention to legal clarity for space entrepreneurs, as well as the responsible and sustainable use of the space environment. In doing so, it reflects the calls of the Polish space law academic community.

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