KEPLER Deliverable Report

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Context of deliverable within Work Package

KEPLER will consult with the developers of observation sensor technologies and platforms to **determine the maturity of the different types of systems and their practicality** for Polar Regions deployments. Examples include: (a) Remote Piloted Airborne Systems (**RPAS**), (b) off-the-shelf **drone systems, kites, and balloons** that have been used with some success to support ship navigation in ice, and (c) **AUVs, wavegliders** for oceanographic monitoring.

New sensor technology, or new use of existing technology in Polar Regions, will also be considered, such as ultra-wideband (UWB) and ground-penetrating radars (GPR) for measuring, e. g., the active layer depth in permafrost regions (to be soon tested by a team from AWI) or for mapping the internal structure of glaciers and regions of the ice sheets.

This task will evaluate the most recent developments in technologies such as, e. g., airborne hyperspectral imaging or tomographic radar, bio-optical sensors on autonomous platforms such as ITPs or multi-sensor ship towed sledge systems. It will also investigate whether these technologies are practical for use in an operational context to support Copernicus services either in providing ground truth or for providing an additional source of validation data, considering both the technological viewpoint and the operator longevity standpoint. This will be done through KEPLER

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consortium participant’s contacts, and by online surveys and roundtable discussion at meetings and conferences.

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Overview

This deliverable explores some of the options for expanding Copernicus' monitoring capabilities in the Polar Regions over the next phase, 2021-27. There exist a number of systems and technologies that can supplement the in situ and spaceborne capacities described in D3.1 and D3.3 respectively. In evaluating the different technological options, we have limited our investigations to those that are already known to exist and have the potential for routine operational deployment in the current Copernicus services. This does not consider blue-sky technologies the ongoing research efforts are unknown and where significant expenditure is needed to bring these to advance the technological readiness to a state where field deployments are feasible.

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Part 1: Unmanned Aircraft Systems (UAS)

The use of Unmanned Aircraft Systems (UAS) in the Polar Regions is desirable due to the harsh climate of these regions and large areas with little or no infrastructure. Currently, these areas are accessible only by specialised marine vessels or higher risk aviation missions. UAS, including Remotely Piloted Airborne Systems (RPAS), offer the potential to further scientific data collection and assist navigation and search-and-rescue (SaR) missions by providing an aerial view that is more flexible than the limited availability of satellite imaging. UAS can provide additional detailed information for understanding sea ice, ocean, and atmospheric systems, the processes governing energy exchange among them, and processes impacting the location and movement of sea ice.

The use of UAS for environmental monitoring, primarily scientific research, has been limited due to the lack of experience with the rapidly evolving technology, the ability of UAS to comply with international regulations for flight operations, and the need for operational approval. Pan-Arctic missions across international Flight Information Regions (FIRs) have been limited and there has yet to be any attempts to set these up routinely on a basis that can be used for repeat monitoring.

UAS typically fly at low altitude and have the potential to measure environmental parameters in conditions that would be challenging to manned aircraft. They can operate from limited airport infrastructures, can be designed to not be dependent on crew schedules or fueling requirements, and can fly in marginal weather conditions. The lower cost of the systems makes them attractive for missions from field campaigns where the risk of loss is high. In addition, the use of UAS has been proposed for communications relay purposes in areas where satellite coverage is poor or expensive.

We discuss here a number of systems that have been utilised in Polar Regions observation missions, before also introducing systems that could have some use in routine long-term monitoring including Copernicus.

Existing RPAS used for Polar monitoring

The Global Hawk RQ-4 developed by Northrop Grumman for the U.S. military is a high-altitude RPAS system with long endurance of up to 33 hours that can carry a variety of sensors including synthetic aperture radar (SAR). The system is one of the largest UAS systems available, and this allows it to use a turbofan engine with the power to carry a payload up to 1400 Kg at altitudes up to 18,000 meters. A variant of the Global Hawk, EuroHawk, was tested with the German military, and a "Polar Hawk" variant for Arctic monitoring was proposed for the Canadian military.

Global Hawk has been used in one reported Arctic field campaign. In March 2011 the Winter Storms and Pacific Atmospheric Rivers (WISPAR) used a Global Hawk belonging to NASA to deploy dropsondes between the North Slope of Alaska and 85°N (Intrieri et al, 2014). This was the first UAS Arctic dropsonde mission of its kind. During this mission, the Global Hawk transected an unusually cold polar vortex and documented polar boundary layer variations. These tested design-limits

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thresholds for fuel and airframe minimum temperature, with ambient temperatures of -76°C being encountered that were close (within 2°C) of the critical skin temperature for Global Hawk. The successful deployment demonstrated the capability of the Global Hawk to conduct operations in harsh, remote regions and highlighted the potential value of Arctic atmospheric dropsonde observations where routine in situ measurements are practically nonexistent.

In Europe, the Norwegian institute NORCE has led the development of RPAS systems for Polar scientific monitoring. These include:

- Cryowing Scout (CW Scout) fixed-wing RPAS.
- Marine mammal monitoring (Aniceto et al, 2018).

High Altitude Pseudo Satellites (HAPS)

A number of systems have been proposed to address monitoring and communications issues at mid- to low-latitudes. High Altitude Pseudo Satellites (HAPS) have the potential to operate for extreme periods of time, days and months rather than hours, at very high, stratospheric altitude and are the subject of a programme (HAPS4ESA) by ESA's Directorates of Telecommunication, Earth Observation and Navigation, and further studies through its Discovery and Preparation Programme. These are identifying how HAPS could bring value to satellite communications and Earth Observation (EO) in terms of performance or cost, highlighting gaps in current HAPS technologies, and planning towards operational services.

The two main HAPS systems being proposed are by Airbus and Thales Alenia Space. Airbus has developed the Zephyr, a fixed-wing solar-electric UAS that operates at stratospheric altitudes of around 21,000 meters. The current production model Zephyr S has a wingspan of 25 meters and weighs less than 75 Kg. The development model Zephyr T has a wingspan of 33 meters and weighs 140 Kg. After take-off and ascent into the stratosphere, the Zephyr navigates to the desired location, which may be hundreds or thousands of kilometers away. Zephyr can be controlled from Ground Control Stations anywhere in the world using beyond line of sight (BLOS) capabilities. The first operational launch site for Zephyr is at Wyndham, Western Australia.

Whilst the Zephyr has the potential for extended operations at mid- to low-latitudes, its use in higher polar latitudes would be restricted to summer periods when the sun is above the horizon. The sun angles of less than 30° are also less than optimal for solar power requirements, with the panels utilising the flat surfaces on top of the aircraft.

The Zephyr carries the SPIDER (Ship Position and Detection Radar). This operates at X-band and has a maximum 40 km swath at 0.5x100 meters resolution, together with a 5 km Stripmap mode with resolution of < 1x1 meters. The senors weighs less than < 5 Kg.

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The rival to Zephyr is the Stratobus by Thales Alenia Space. Unlike the Zephyr this is a lighter-than-air, autonomous stratospheric airship. The Stratobus can survey the ground to several 100 km away, and can remain in place at 20,000 meters altitude through an electric propulsion system. The lighter-than-air design removes the need for a launcher or large runway site.

The Stratobus features a number of innovative technologies that may make it more suitable for polar deployments. These include a solar concentrator inside the balloon envelope coupled with a reversible fuel cell to provide nighttime power. The solar panels are placed on the nose allowing them to be rotated. This, and the propulsion motors maintaining a stationary position, allow the solar panels to be positioned to always face the Sun.

Stratobus is designed to withstand moderate and stable winds of less than 90 km/h at lower latitudes. It would therefore have to be deployed at latitudes above those affected by the polar vortex, where wind speeds can reach 220 km/h. This and the need for solar power would limit its Polar deployments to summer periods. However, it is estimated that it could handle 5-year missions, with a few days per year for ground maintenance.

The limited information from the manufacturers on Stratobus suggests that the first Prototype Flight Model (PFM) will be ready for trials in late 2020 or 2021. The first qualifying flight of a full-size model would occur in 2022.

Stratobus is part of the project HAPPIEST (High-Altitude Pseudo-Satellites: Proposal of Initiatives to Enhance Satellite Communication) that is focusing on the use of ‘aerostatic’ HAPS in the form of stratospheric balloons, which are then able to carry more payload and generate more power than aerodynamic HAPS.

Other stratospheric balloons for HAPS developers include:

- Zero 2 Infinity (Spain). Development of a service called Elevate to fly payloads to near space for science, communications, satellite testing, meteorology and marketing purposes.
- Avealto (UK). Ascender series of lighter-than-air, solar-powered vehicles to provide telecommunication infrastructure.
- Loon (USA). A subsidiary of Alphabet (Google) working on providing Internet access to rural and remote areas through stratospheric balloons. In July 2019 reported that they had achieved 1 million hours of stratospheric flight with a fleet of balloons designed to stay aloft each up to around 200 days.
- Project AlphaLink (Germany). Fixed-wing UAS system with the capability to couple units together during flight. Intends to be the first to achieve 5 year continuous operation with a payload of around 450 Kg. The combined units provide greater solar panel area for 24/7 operation. A single unit will allow operations of up to 100 days and a payload of 24 Kgs.

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The advantage of HAPS systems is that they operate above the air control altitude limit, usually defined at 20 km. However launch and recovery involve operations below this limit, and so need coordination with air traffic control. The operation of UAS in non-segregated airspace is not yet regulated, with "sense and avoid" being the method of avoiding mid-air collisions. Aspects of International Law relating to the overflight of other countries also need to be investigated.

The future of HAPS will be driven mainly by the evolution of technologies of potential competitors, such as microsatellites constellations, and the availability of financial resources to overcome the HAPS technological challenges.

Recommendations for Pan-Arctic UAS operations

AMAP, 2015a make a number of recommendations for mitigating risks to other aircraft operating in the Arctic:

1. Requirement of an operations and communications plan in accordance with national regulations and that meets ICAO provisions.
2. Filing of an ICAO flight plan by the operator to the appropriate CAA or ATS unit.
3. A common approach to safety risk assessment based on the ICAO framework.
4. Use of an Automatic Dependent Surveillance-Broadcast (ADS-B) transponder (or future equivalent).
5. Require that UAS used beyond visual line-of-sight (BVLOS) operation be registered in a national aircraft registry.
6. Civil UAS operators should provide proof of insurance in Special Drawing Rights (SDR), or equivalent, in accordance with the EU policy EC785/2004, Article 7.1 table, or national equivalent.
7. Recommend that CAAs approve UAS operators similar to manned aircraft operators.
8. Ensure that remote pilots are licensed in accordance with national regulations and that is consistent with ICAO Annex 1, Personnel Licensing.
9. Require CAA-acceptable proof of proficiency of training or competency for the specific UAS.
10. Recommend CAAs establish type certification and airworthiness certification requirements to enable cross-flight information region (c ross-FIR) operations.
11. Arctic nations can reserve the right to impose additional requirements in their airspace as needed.
12. Include Arctic UAS operations in Aeronautical Information Publication (AIP) supplements.
13. Recommend charting of UAS coastal launch sites.
14. Require deconfliction plans to be coordinated with Arctic CAAs and the operators approval authorities.

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Part 2: Other Airborne Systems

Off-the-shelf drone systems

UAS are cheap, very capable, very portable and can be deployed in the field for research with a fraction of the risk to human life and financial cost compared to traditional methods and quality data can be gathered rapidly.

The use of off-the-shelf drones as cheap, expendable aerial observing technology has taken off in the past 5 years. Today’s drones are sophisticated, readily-available, and have good range and capabilities. In the Arctic, the *Arctic Science Remotely Piloted Aircraft Systems (RPAS) Operators Handbook* (AMAP, 2015a) provides some guidelines to operations. In the Antarctic, the International Association of Antarctic Tour Operators (IAATO) has prohibited clients from using drones for non-commercial activities and the Antarctic Treaty Committee of Managers (ATCM) has asked for input on UAS use.

Ivey and others, 2013 evaluated UAS systems for polar deployments and presents a summary of required measurements, predominantly atmospheric, and UAS suitability (Fig. 1).

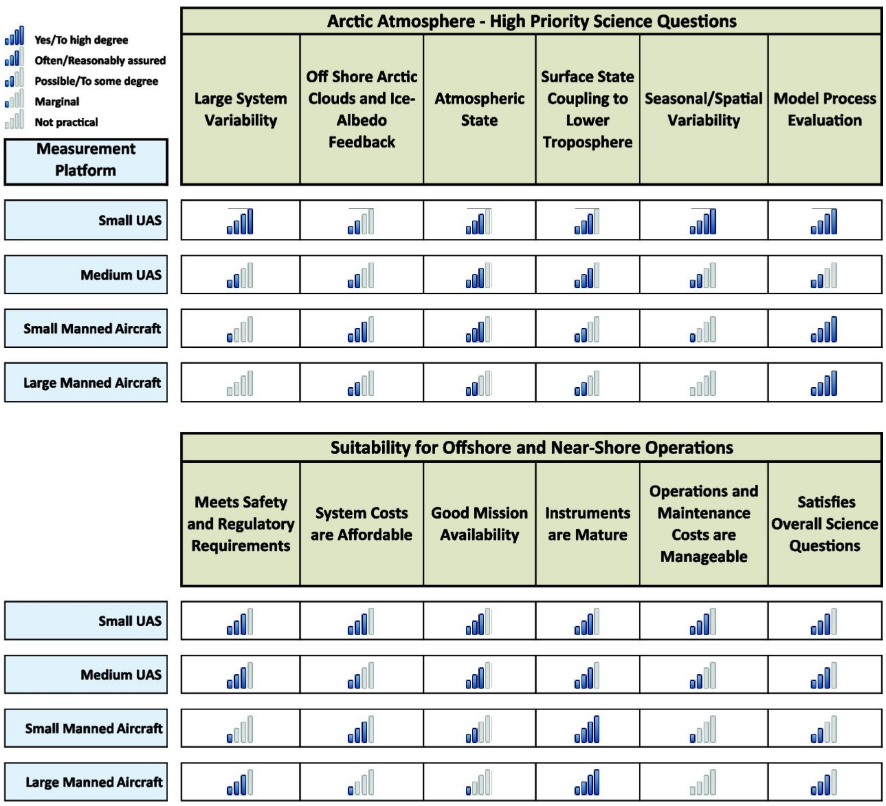

Figure 1: Key observational requirements and UAS suitability.

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The United States Antarctic Program (USAP) has adopted the Ops Policy Master Draft (2014) is as a temporary stand in policy for US operating airspace in Antarctica. This requires UAS operators to comply with Federal Aviation Administration (FAA) requirements within US National Air Space.

Kites

These provide an inexpensive method for aerial photography, and Kite Aerial Photography (KAP) competes with the rapid advance of other methods of small format aerial photography (SFAP) and the popularity of unmanned aerial vehicles (UAV) (Marris, 2013) in the field of scientific data collection (Sander, 2014).

The main drawbacks of these systems is that the low costs necessitates a more labour intensive approach to deployment. Larger kite systems have been used for supplementary vessel propulsion, and these have included development of automated systems for management (Maaß, 2013)

Kites are also highly reliant on wind conditions. The issues with their use in deploying iceberg GPS trackers has been discussed (McGill et al., 2011). Their opinion is that more ships are hostile environments for kite deployments due to the masts and cabling, and turbulence from the ship's superstructure. A kite deployment ideally needs to take place from a location with an unrestricted 360° view of the sky. Targets such as icebergs also need to be downwind, and there is a strong likelihood that shifting winds around the iceberg would require a change in the ship's heading, entangling the kite's strings in some part of the ship's superstructure. A tethered balloon would suffer the same fate.

Kites are therefore more useful from land-based, or on-ice, locations well removed from any surrounding infrastructure. In the Antarctic, the technique has been used to monitor penguin populations (Fraser et al., 1999) and for localised atmospheric measurements over leads (Guest, 2007).

Balloons

Radiosondes are widely used in meteorology for atmospheric profiling, and these are the prime balloon-based measurements in the polar regions. However long-term routine deployment of these is expensive, requiring a manned coastal or shipboard observing station, the data receiving equipment, and the consumables (balloons, sondes, helium gas).

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The use of tethered balloons compared to UAVs is discussed in Ivey et al., 2013 and de Boer et al., 2016. These were seen as advantageous for polar regions deployments as they negated the risk, for UAVs or manned aircraft, of flying in clouds likely to result in icing.

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Part 3: Systems for Oceanographic Monitoring

Autonomous Underwater Vehicles (AUVs)

Autonomous Underwater Vehicle (AUV) technology has been in use in polar regions since the early 2000's with varying degrees of success. Early experiments included Maridan, Gavia and Autosub AUV's and use of these is reviewed in Wadhams and Krogh, 2019. This resulted in a number of scientific papers, especially in the field of sea ice thickness mapping (Wadhams et al., 2004; Nicholls et al., 2006; Wadhams and Doble, 2008, Doble et al., 2009).

More recently there has been some successes with WHOI AUV's on limited area surveys under-ice.

The key limitations of AUV technology are accurate underwater navigation and battery technology. Whilst navigation can be improved by reference stations or seabed-tracking in shallow waters, fully inertial navigation is still difficult. Battery technology limits the range of deployments, and the sensor load.

Wadhams and Krogh, 2019 point to a number of lessons learnt that could contribute to future, more consistent AUV data gathering:

1. Good communication between the AUV team and the deployment vessel crew.
2. Technology is constantly advancing and improving.
3. Slow-moving vehicles where depth control is by vertical propeller (e.g. WHOI) are not suitable for use in marginal ice zone (MIZ) conditions where shear currents may occur.
4. A single (Ultra-Short BaseLine (USBL) acoustic tracking system is potentially better, for ease of deployment, than a multiple transponder system.
5. A low cost AUV-buoy-sonar system will be very valuable in improving the understanding of the critical processes of ice deformation and summer ice decay, as well as validation of airborne and satellite altimetry, especially when combined with a surface mapping system (laser or photogrammetry from an RPAS system).

Gliders

Gliders have become more ubiquitous in polar waters monitoring in the past decade. However, their use is limited to open water areas. Wavegliders derive additional power from wave energy and remain on the surface. True gliders have a deployment limited by battery endurance and minimise power requirements through gliding underwater. The low power requirements of these systems limit them to basic oceanography sensors and cameras. Gliders can be fully or semi-autonomous.

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Part 4: New sensor technologies

Ultra wideband (UWB)

This type of radar is widely used for measuring snow thickness on sea ice and internal ice layers. The concepts and development of systems took place in the 1990's (Kanagaratnam, 1995), with reliable instruments being available from the late 2000's (Gogineni and others, 2003; Holt and others, 2009; Kanagaratnam and others, 2007; Panzer and others, 2013). A system was also deployed on the NASA Ice Bridge campaigns (Kwok, 2011).

Lower radar frequencies penetrate the snow cover and are signals are returned from the sea ice / snow interface. Higher radar frequencies are returned from layers close to the snow surface. The combination of both provides a measure of snow thickness.

Ground penetrating radars (GPR)

GPR has a longer history of use on freshwater, lake or river ice. Its non-destructive nature, with excellent depth penetration and ready deployment over large areas has resulted in extensive and routine application. The use of GPR to study sea-ice is, however, much less common, despite its potential to provide valuable information related to, for example, regional effects of global warming. This is because GPR signal propagation in ices with high brine contents is characterized by a lossy behaviour which reduces radar signal penetration (Mattei and others, 2019). Initial reports on attempts to use GPR on sea ice were published in the 2000's (Nyland, 2004; Galley and others, 2009). GPR has been used for helicopter-borne surveys on dedicated campaigns, requiring low altitude flying (Lalumiere, L., and Prinsenberg, 2009). Use in routine surveys may become feasible with increasing UAV payloads and endurance.

Hyperspectral imaging

These types of sensors can detect an entire electromagnetic spectrum of information, typically at optical frequencies. However, the large similarities between many of the frequency bands for sea ice often reduce the accuracy of the classification methods, and researchers have focused on how to increase the classification accuracy (Han and others, 2017). This paper introduced an improved similarity measurement method based on linear prediction (ISMLP) for hyperspectral sea ice detection.

Satellite deployments include the Compact High Resolution Imaging Spectrometer (CHRIS) instrument on ESA's Proba-1 satellite from 2001 onward, the Hyperion instrument on the EO-1 satellite operated by NASA from 2000 to 2017, the Indian HySIS satellite launched in 2018, and the Italian PRISMA satellite launched in 2019. The German Aerospace Center (DLR) anticipate to launch the EnMAP (Environmental Mapping and Analysis Program) in 2020.

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As hyperspectral instruments operate at optical frequencies, their use is limited to cloud-free areas. The full spectrum of data results in large data volumes so only small areas (100's of square kilometers) can be covered, albeit at very high resolution.

Hyperspectral images may provide the potential to estimate the density of new ice types (Liu and others, 2014).

Tomographic radar

For sea ice and icebergs, this approach involves simultaneous imaging by two synthetic aperture radar (SAR) satellites. The capability has been available since the launch of the TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurement) satellite in 2010, and could be provided in a scenario envisioned for the ROSE-L L-band SAR high priority candidate mission (HPCM) currently under consideration for Copernicus expansion. The use of two satellites provides a stereographic imaging from which surface height can be determined. As for hyperspectral imaging, the data volumes and need for high levels of detail and thus the very high resolution imaging modes of the SAR limit this approach to small regions.

Bio-optical sensors

Biosensors are defined by the International Union of Pure and Applied Chemistry (IUPAC) as integrated receptor-transducer devices, which are able to provide selective quantitative or semi-quantitative analytical information using a biological recognition element. The main advantages of biosensors over the traditional analytical techniques for the detection of environmental parameters are their cost cost-effectiveness, fast and portable detection. Biosensors can be divided based on the type of recognition element used to enzymatic, whole-cell or affinity-based. Enzymatic biosensors measure the selective inhibition or the catalysis of enzymes by a specific target. Second class, used frequently for the monitoring of environmental pollutants are whole cells, such as bacteria, fungi, yeast, plant or animal cells. These sensors detect responses of cells after exposure to toxins. The toxic response can be either non-specific, such as DNA-cleavage, heat shock and oxidative stress or specific to a class of environmental pollutants, such as metals, organic compounds and compounds with biological importance e.g. nitrates, ammonia, antibiotics. The affinity-based biosensors have recognition elements that can detect individual targets or a group of structurally related targets with high sensitivity. Detection can rely on antibodies, bacteria-infecting viruses (phages), nucleic acids (Van Dorst et al., 2010). Biosensors including immunosensors, aptasensors, genosensors, and enzymatic biosensors have been reported for the detection and monitoring of various environmental pollutants, e.g. organophosphorus pesticides, toxic heavy metals such as mercury and uranium, phenol and phenol derivatives, perfluorooctanesulfonic acid (PFOS), antibiotics, drugs and drug metabolites, small organic molecules including toxins and endocrine-disrupting chemicals (Justino, Duarte, & Rocha-Santos, 2017)(R. Li, Feng, Pan, & Liu, 2019)

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A distinct category of affinity-based sensors are molecularly imprinted polymers (MIP). These chemical sensors are mimicking the target-biological receptor interaction and are due to this sometimes called “plastic antibodies”. These sensors could be of special interest for the detection of both organic and inorganic targets in the extreme polar environment. The recognition surfaces of these sensors are highly stable in a wide temperature and pH range, resistant to biological degradation, have small footprint, weight and coupled detection system make can be designed to use a minimal amount of power. One of the major drawbacks of the MIP sensors is the size of the detectable target. Due to the mass-transfer effect these sensors cannot effectively detect targets with high molecular weight (S. Li, Cao, Whitcombe, & Piletsky, 2014).

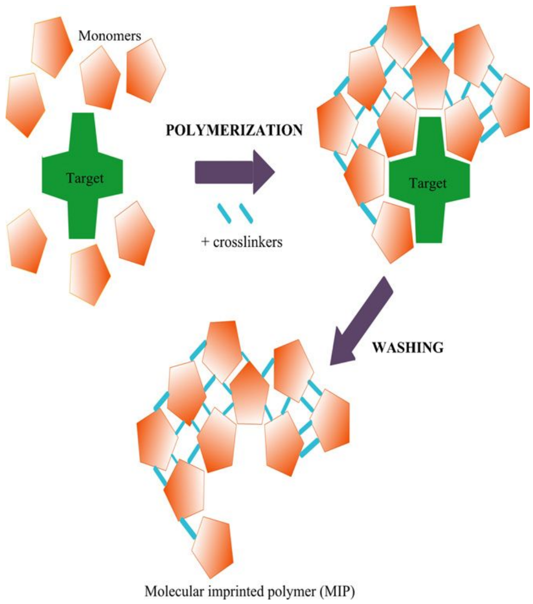

Figure 2: Formation of MIP

Molecular imprinting (Fig. 2) involves the preparation of a “mould” consisting of polymerizable functional monomers around a template molecule (the target). The monomer is allowed to bind to the template molecule. The resulting complexes are then copolymerized with cross-linkers. After polymerization, the template molecule is removed by extensive washing steps to leave specific recognition sites in the polymer that are complementary to the template molecule in size, shape, and position of the functional group(s). MIPs can be synthesized following different approaches according to the way the template is linked to the functional monomer (by covalent, or non-covalent bonds) and subsequently to the polymeric binding sites. The resulting MIPs can bind their targets with affinities similar to the antibody-antigen interaction.

The detection of the signal generated by the binding of the target can base on the optics (including fluorometry, luminescence, colorimetry, surface plasmon resonance), electrochemistry (including amperometry, impendence measurement) or piezoelectrics (including quartz crystal microbalance

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measurements). The class of MIPs-based electrochemical biosensors (ECBSs), where the sensing film is deposited directly on a transducer surface seems to be the most suitable for long-term deployment due to its built simplicity and sensitivity. These sensors can also take advantage of the recently developed electroactive nanomaterials, such as carbon nanotubes, noble metal nanoparticles tubes or rods, nanoporous gold leaves, graphene, etc. MIPs cannot only accumulate on such electrode templates to enhance the sensitivity of the sensor, but also separate templates from other, non-target analytes to improve their selectivity (Gui, Jin, Guo, & Wang, 2018).

In spite of a large number of publications and the outstanding results reported in the literature, the majority of these sensors do not reach the market and remain mere proof-of-concept studies. For the real commercial application of biomimetic sensors, the open challenges concern mainly: the miniaturization of the devices, the automation of sensor production, the development of user-friendly protocols and their applicability and reproducibility in real sample analysis (Moro et al., 2019).

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