The overarching goal of the proposal is to **enrich** and **strengthen** our <u>physical understanding</u> of the inner heliosphere to <u>better-predict solar wind features, transient structures, and SW, significantly raising Europe's profile throughout such scientific areas of research.</u> Data analyses, interpretations, and modelling using existing international ground-based radio-telescope networks, spacecraft, and new technologies will be used.

The **RASWS Science Team** are assembled as follows: **Dr. Mario M. Bisi** (MB - PI) (Y1-Y5), **Dr. Richard A. Fallows** (RF - Senior Staff) (Y1.5-Y5), **Charlotte Sobey** (CS - PDRA) (Y1.5-Y5), **PhD1** (Y1-3 + 4), and **PhD2** (Y2-4 + 5). The team are also supported by a part-time **project administrator (PA)**.

<u>The Central Science Question:</u> How can we predict if non-ambient solar wind structure is going to impact Earth's near-space environment, and, if so, how "geoeffective" is it going to be?

The RASWS proposal is broadly divided into eight overlapping and highly-complimentary Work Packages (WPs), each aimed at answering the central science question, and by necessity, many of them overlapping.

WP1: Cutting-edge observations of interplanetary scintillation (IPS), IPS dynamic spectra, and in-depth solar-wind parameterisation (these will also lead into developments for WP2, WP3, WP4, WP6, and WP7) {MB, RF, CS, PhD1, PhD2} [Y1-Y5].
- When will the large-scale solar-wind disturbances seen closer-in to the Sun arrive at Earth orbit?
- What is the relationship between interaction regions and solar wind structures in the low corona?
- Determining and studying the solar wind parameters (including structures within the solar wind) such as the plasma density and outflow velocity from observations of IPS and the fundamental scale sizes at different observing frequencies and how these relate to the bulk outflow.
- Design and implementation of the phase scintillation experiment with natural astronomical radio sources.
- Adaptation and implementation of single-site IPS analyses and comparisons with multi-site analyses of the same simultaneous observations to evaluate both broad methods of investigation.
- Use of the present UCSD 3-D CAT routines for visualisation and mass and energy determinations.
- Large-scale mapping of CMEs and their shocks via IPS, 3-D reconstructions, and investigating their type II burst plasma emissions from propagating shocks.
- Provide better-quantified IPS results (*i.e.* improved end results from analyses of various IPS data sources) for final distribution throughout the IPS and wider relevant radio-astronomy and related communities.

WP2: Investigate and characterise the solar wind and CME outflows with respect to flow direction, size, source regions, and emphasis on small-scale transients entrained in the slow solar wind outflow (linked to WP1 and WP3) {MB, RF, PhD1} [Y2-Y4].
- Where does the slow solar wind originate and what relation is there to small- and large-scale disturbances?
- What is the distribution of solar wind velocities as a function of solar latitude and distance during different solar conditions (especially given the previous solar cycle's characteristics)?
- How do small-scale density enhancements evolve and contribute to the solar wind?
- How do CMEs "evolve" and interact with the solar wind?
- Extension of the ELB IPS experiment to cover the new systems of KAIRA and LOFAR along with EISCAT, the ESR, and MERLIN (as previously used) and investigate how far the ELB IPS experiment can be extended in terms of the coherence of signals over increasingly-long baselines between a pair of antennas.
- Ascertain roles played by solar wind interactions and with CMEs in modifying their outward trajectories.
- Determining the non-radial extent of solar wind flow, of interactions in the solar wind, and of CMEs.
- Investigate the small-scale ("micro" and "meso") solar-wind structure up to large-scale (CME) solar-wind transients to ascertain key characteristics of such structures between Sun and Earth's distance to investigate the hypothesis that CMEs are a large-scale extension of (and of a similar nature to) the small-scale slow solar wind highly-variable "blob-like" structure and the overall large-scale slow solar wind structure as a whole.
- Investigate solar-wind transients on all scales as they propagate out in the inner heliosphere.

WP3: Multi-frequency IPS products and dynamic spectra, and investigating the scale-size micro-structure of the solar wind, its relation to IPS, the different inherent radio-source structures, and what the inner-scale of IPS can tell us about the scale sizes of, for example, sources of type III solar flare radio emission (linked to WP1 and WP2) {RF, CS, MB, PhD2, PhD1} [Y2-Y4].
- What does the multi-frequency observations of varying scale sizes with IPS tell us about the underlying fundamental solar wind physical structure?
- What is the radial dependence of the inner-scale of IPS and how does this relate to bulk solar wind flow?
- Investigate coherent type III radio bursts dynamic spectra in relation to multi-frequency IPS and possible transient solar wind activity, and examine how these relate to the scale size of IPS (and vice versa) at varying observational frequencies as well as with increasing distance out from the Sun.

WP4: UCSD 3-D CAT usage/development (linked to WP1) {MB, PhD1, RF} [Y1-Y3].
- Addition of the observing frequency into the weighting function for determining the contributions of IPS along each line of sight from telescope to radio source.
- Take account of source structure variations of different astronomical radio sources and how this affects the inputs and results of the reconstructions.
- Inclusion of additional L_1 *in-situ* spacecraft data into the tomography for in-depth post-analyses of CME events with higher-level IPS data compared with real-time IPS and *in-situ* data reconstructions investigating ways to improve the real-time forecasting using a relatively-high number of 'isolated' events and comparisons with other data sets where possible (such as with the aforementioned white-light imaging).

WP5: Design and implementation of the low-frequency heliospheric Faraday rotation (FR) experiment for LOFAR {CS, RF, PhD2, MB} [Y3-Y5].
- Can we predict the effects of incoming larger-scale solar-wind disturbances on the near-Earth space environment and the ultimate consequences on the Earth itself by measuring the North-South component of solar wind magnetic field through the method of heliospheric FR with low-frequency radio astronomy?
- Can we account for the ionosphere and the radio source's natural FR when attempting to calculate the FR response due to interplanetary material flowing out into the inner heliosphere?
- To what extent can we use FR with respect to heliographic latitude and elongation from the Sun to accurately determine the FR and resulting magnetic-field direction and magnitude?
- What is(are) the correct relationship(s) between the magnetic and density structures in the solar corona and the inner heliosphere?

WP6: Can we explain the discrepancies between polar fast solar wind detected close-in to the Sun with radio astronomy techniques such as IPS compared to those measured *in situ* much further out from the Sun beyond ~1.4 AU by the Ulysses spacecraft mission (1990-2009) (linked to WP1) {MB, PhD1, RF} [Y2-Y3]?
- Ascertain if there are different fast solar wind flows with regards to high polar latitude in terms of velocity and density, *i.e.* is there a two-mode polar fast solar wind?
- What implications would a two-mode fast solar wind have on space weather forecasting (if any)?
- How different in terms of velocity and density is the non-polar fast solar wind and can we better characterise that for non-CME-causing space-weather events?

WP7: Investigate the effects at Earth that can be seen from the radio astronomy experiments carried out throughout the proposal (linked to WP1 and WP5) {RF, CS, PhD2, MB} [Y3-Y5].
- Thus far, up until the most-recent joint EISCAT-ESR-KAIRA-LOFAR IPS observation campaign, any ionospheric effects have been simply ignored and/or filtered out without studying them further. However, with the new capabilities of LOFAR, the implementation of the low-frequency receivers on part of the EISCAT system, and especially of KAIRA, a great opportunity arises now for studying the ionospheric effects of space weather simultaneously using cutting-edge radio-astronomy telescopes and our techniques with that of the incoming solar wind structure.
- Identification of the ionospheric irregularity structures capable of affecting communications and position-finding techniques, and attempting to quantify their effects at the varied radio-telescope geographic latitudes.

WP8: Final solar-wind parameterisation including 'going after' the all-important magnetic-field North-South parameter and possible implications for other Sun-like systems (results from all previous WPs feed incrementally into this WP) {MB, RF, CS, PhD2} [Y4-Y5].
- This WP directly follows on from all of the previous WPs combining the findings and outcomes into a final solar wind parameterisation and visualisation with the improvements to the forecasting installed.
- If possible, incorporation of the FR observation results into the UCSD CAT analyses to allow for full velocity, density, and transient magnetic-field orientation determinations and forecasts to be undertaken.
- What can studying our Sun in such great detail with regards to space-weather events tell us about other Sun-like stars and what can this tell us about the possibility of life elsewhere in our galaxy (if anything)?

The proposal will involve a variety of qualitative and quantitative methods, encompassing the current state-of-the-art in radio astronomy for SW science and going beyond that to push the boundaries of science through advanced data analyses, experimental techniques, 3-D visualisation, targeted WPs with specific aims, goals and science questions, and will ultimately lead to answering the Central Science Question putting Europe at the forefront of this research area while allowing the PI the appropriate research independence he craves in order to move this research forward.