PAC²MAN

Photospheric And Chromospheric and Coronal Magnetic field ANalyser

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Abstract: The main goal of the PAC²MAN mission is to understand and predict the initiation and development of potentially hazardous CMEs and flares. In addition, PAC²MAN will determine the speed and direction of CMEs in order to forecast in near real-time solar wind conditions near the Earth. The two spacecraft of the mission each carry a payload carefully designed to fulfil both objectives over a nominal lifetime of 6 years.
The first spacecraft (SCE) will be located at the Lagrange Point 1 of the Sun-Earth system and the second (SC80) at a heliocentric orbit trailing the Earth by 80°. Together they will measure the magnetic field vector at different layers of the solar atmosphere. The mission will also monitor the interplanetary space from the photosphere to the Earth. Solar wind properties are measured in situ by SCE.
A good understanding of the magnetic energy build up and release is essential to determine how and when solar flares and Coronal Mass Ejections (CMEs) occur. Advanced models based on PAC²MAN's observations will lead to a substantial improvement in the quality of the forecast of space weather events. The stereoscopic observations of the solar atmosphere up to 30 $R_\odot$ and the monitoring of the interplanetary space up to 1 AU will allow forecast of the arrival time of space weather events to Earth.

Key words: Interplanetary medium - Sun: chromosphere - Sun: CMEs - Sun: corona - Sun: photosphere – Sun: magnetic field – Space weather

1. Introduction

Space missions, ground based networks, and observatories that monitor the sun currently in operation have significantly improved our knowledge about the physics of the solar atmosphere, the interplanetary medium and the relationship between of space weather events originating on the Sun and Earth's atmosphere. Nevertheless the basic physical processes inducing the most violent eruptive events on the Sun, CMEs and flares, are still elusive to an unacceptable degree. In particular, the build-up of magnetic energy in complex active regions, and the release of this energy producing the most geoeffective space weather events, urgently have to be understood in order to forecast these events precisely and to prevent damage to critical infrastructure that modern society heavily relies upon.
To accomplish these crucial tasks, we propose the two spacecraft mission PAC²MAN. The spacecraft and their orbits are carefully designed to serve both the scientific advancement in the field as well as the operational near real-time space weather forecast in unprecedented quality.

2. Mission Objectives

In 2008 ESA started the Space Situational Awareness programme (SSA). Its objectives are to detect and forecast the impact of potentially hazardous sources stemming from space. One of these sources is energetic solar events that can harm a wide range of critical infrastructures, from satellites to power grids.
The mission proposed here is dedicated to the advancement of the field of solar atmospheric physics as well as the forecast of the geoeffectiveness of CMEs and solar flares. The PAC²MAN mission's objectives therefore cannot be divided into scientific and operational ones but comprise these two in the following form:

PRIMARY OBJECTIVE:
Understand and predict the initiation and development of potentially hazardous CMEs and flares.

SECONDARY OBJECTIVE:
Determine the speed and direction of CMEs in order to forecast near real-time solar wind conditions close to Earth.

The key to fulfilling these objectives is to observe the changing magnetic field throughout the solar atmospheric layers.
Knowing the physical properties of magnetic energy build up and release enable the forecasting of when flares and CMEs are initiated, as well as how strong they become. To understand how and when flares and CMEs occur, we need information about the entire process of magnetic energy build up from photosphere to corona. Currently no continuous measurements of coronal magnetic fields are available.

Measures of a Successful Mission

Fulfilment of the mission's objectives has successive steps, each of which improves the order of success of the PAC²MAN mission:

- Improve existing models of CME propagation by inputting previously unknown data about the initiation of CMEs

Table 1: Overview of remote sensing instruments

Instrument	SCE	SC 80	Wavelength	FOV [Rs]	Detector Size [pixel]	Pixel Size [arcsec]	Mass [kg]	Size [cm]	Power [W]	Data Volume per day	Operation Temperature [K]	Heritage
IR/UVP & C1	x	x	UV: HI Lyα line at 121.6 nm IR lines: FeXIII 1074.7 & 1079.8 nm, He I 1083.0 nm Visible Light: 560 nm	1.1 – 2	1024 x 1024	5	50	200 x 60 x 25	80	SCE: 4.7GB SC80: 238 MB	Detector: 223 IR-Polarimeter: 303	
MMI	x		Fe 630.15nm Fe 630.25nm Na 589.59nm Na 588.99nm	1.07	2x 4096 x 4096	0.5	60	150 x 70 x 30	95	37.8 GB	CCD: 233 Tunable Optics: 300	
MI		x	Fe 617.3nm	1.07	4096 x 4096	0.5	73	120 x 85 x 30	95	645 MB	CCD: 233 Tunable Optics: 300	SDO HMI
C2	x	x	400-850nm	2 – 30	1024 x 1024	56	15	140 x 40 x 32	5	3.8 MB	193	SOHO LASCO C3
HI		x	400-1000nm	30 – 216	1024 x 1024	148	15	65 x 33 x 20	10	0.4 MB	193	STEREO SECCHI HI
EUVI	x	x	17.4nm	< 1.6	1024 x 1024	3.2	11	56 x 15 x 12.5	5	21.6 MB	233-333	PROBA 2/SWAP

- Determining the likelihood of flare and CME incidences with high statistical significance within 2-3 days [Reinard et al., 2010]
- Correlate observed events at the solar surface with their effects on the near-Earth solar wind (for secondary objective)

2.2 General mission profile

The PAC²MAN mission is composed of two satellites and a network of ground tracking stations that will monitor the Sun and the interplanetary space between Sun and Earth from two privileged positions: the Spacecraft Earth (SCE) satellite will orbit around L1 and the Spacecraft 80 (SC80) will be placed in heliocentric orbit trailing the Earth by 80°.

Two new instruments will measure the magnetic field of different layers of the solar atmosphere: the photosphere, the chromosphere, the transition region and the lower corona. Improved numerical models will then be able to reconstruct more accurate scenarios of the energy build up and release that gives rise to solar flares and Coronal Mass Ejections (CMEs).

The privileged points of view of the spacecraft will help understand and forecast energetic events on the Sun, and follow their evolution from the Sun to the Earth. The mission will not only help to answer basic solar physics questions but it will also be a tool for space weather monitoring.

3. Scientific goals and background

The scientific goals of the mission are to:

- determine the magnetic field in the photosphere, chromosphere and lower corona by measurement of the full Stokes vector, to enable pre-event space weather forecast.
- map coronal structures by imaging EUV light in the upper corona
- monitor the initiation, speed and direction of CMEs near the Sun and up to the Earth by imaging their scattered light in the interplanetary space, in order to forecast these events
- measure the Interplanetary Magnetic Field (IMF) near the Earth
- measure in situ the density, velocity distribution and energies of solar wind particles at high and low energies.

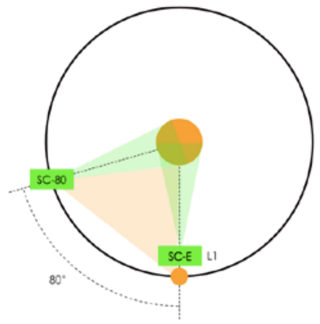

Figure 1: Sketch of the orbit layout

These are key requirements to achieve our goals:

- Continuous observation of the sun
- Observation angle in the range of 70° to 90° in order to measure the coronal magnetic field using the Hanle effect
- Stereoscopic view of the sun in combination with SCE
- Need to follow the evolution of a single active region without any interruptions

- To correlate events at the Sun with their direct consequences near Earth

3.1. Measurement of the magnetic field

The measurement of the magnetic field in the solar atmosphere requires the interpretation of spectro-polarimetric measurements. The magnetic field modifies the state of polarisation of spectral lines formed in the solar atmosphere. The interpretation of the Zeeman and Hanle effect leads to the determination of the vector magnetic field.

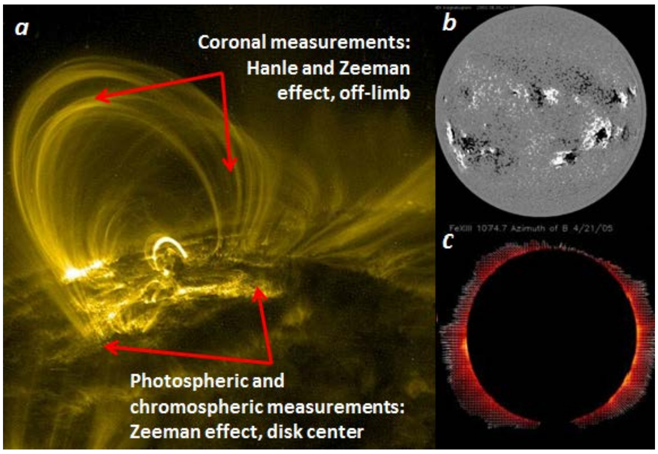

Figure 2: Strategy to measure the vector magnetic field of one active region in the photosphere, the chromosphere and the corona, from two different lines of sight (at right-angles). a) Summary of our measurements in active regions; b) example of on-disk photospher photospheric measurement of the magnetic field by SoHO/MDI; c) example of off-limb coronal measurement of the magnetic field by the CoMP instrument in Hawaï.

Due to the Zeeman effect, spectral lines are split into three components in presence of a magnetic field. These three components have different polarisation, so that a measurement of the vector magnetic field can be achieved by spectro-polarimetry in one spectral line. This effect can be measured as long as the line width is not too broad. Therefore, in the transition region and the corona, where the temperature increases, the line broadening becomes too significant and the measurement of the Zeeman effect is possible only for strong magnetic fields.

The Hanle effect concerns the scattered light in the corona of spectral lines produced in the lower layers (chromosphere, transition region). This scattering introduces a linear polarisation in the 90° direction: it can be seen for structures in the off-limb corona. In the presence of a magnetic field, the direction of this polarisation is rotated and the degree of polarisation decreases. Therefore a measurement of the vector magnetic field is possible by combining observations in several lines.

Combining the observation and interpretation of the two effects for different spectral lines gives a full measurement of the magnetic field in different layers of the atmosphere, as illustrated in Figure 2. In order to perform all the measurements at the same time, we need observations from two lines of sight: one to perform on-disk measurements of the Zeeman effect in the photosphere (Fe 630.15, 630.25 and 617.3 nm) and the chromosphere (Na 589.59 and 588.99 nm), and one perpendicular to that to perform off-limb measurements of both Zeeman and Hanle effect in the corona and TR (HI Lyman alpha 121.6 nm, FeXIII 1074.7 and 1079.8 nm, HeI 1083.0 nm), using a coronagraph.
The observation of doublets in the photosphere and chromosphere (Fe and Na doublets) means that a calculation of three components of the current density in those layers can be made. These measurements provide the first insight of the magnetic energy stored in active regions. All the magnetic field measurements also provide constraints to the coronal field extrapolations.

4. Instruments and drivers

4.1. Mission drivers

The technical decisions proposed for this mission are limited by the space environment, the observational methods and the requirements of the primary and secondary goals. The main drivers of this mission are:

- the length of the mission: 6 years with an extension up to 11 years,
- the need for a permanent stereoscopic observation of the Sun,
- the high load of data from the SC-80,
- the need for a permanent tracking of the satellites from ground stations,
- the electromagnetic cleanliness of the plasma environment for in-situ measurements
- the application of observations for Space Weather forecasting solutions

Instrument	Extracted parameters
IR/ UV-P and C1	Magnetic field of lower corona
MMI	Magnetic field of photosphere and chromosphere
C2	Velocity of CMEs near the Sun
EUVI	Coronal structures
MAG	IMF components near the Earth
HEPS	Properties of the high energy solar wind
LEWiS	Solar wind electron and proton properties

Table 2: Instruments planned on SCE

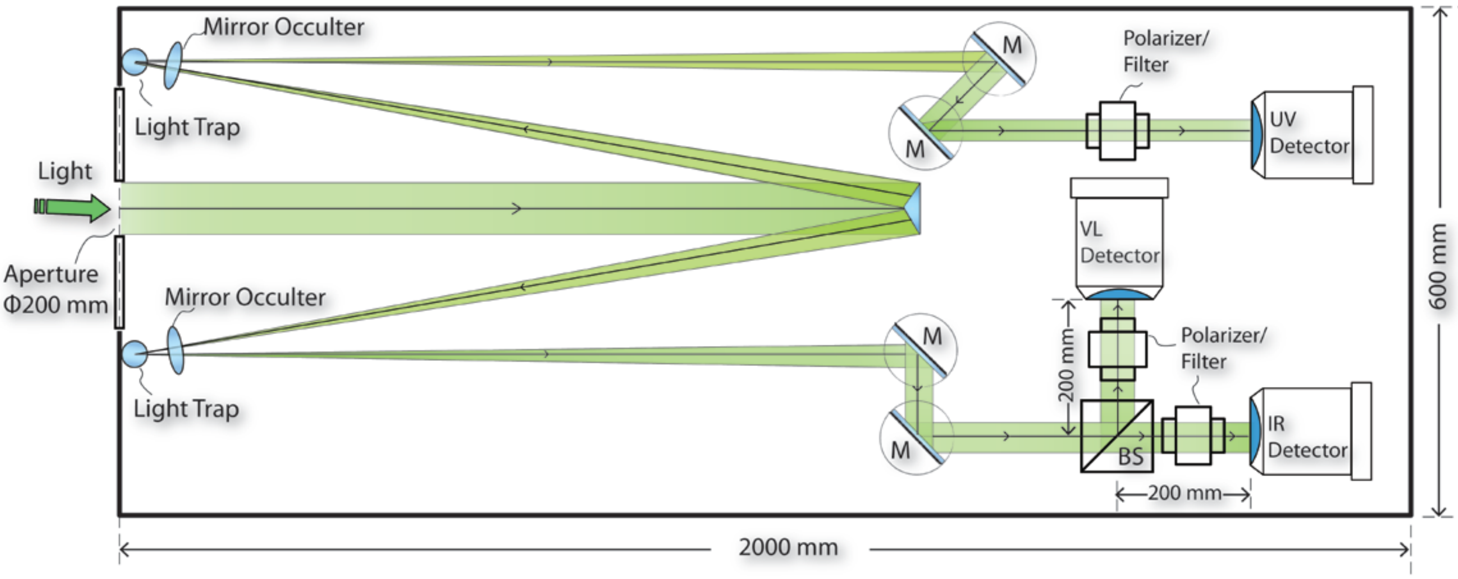

Figure 3: Schematic of the IR/UV Polarimeter

	Subinstruments	FOV	Mass [kg]	Size [cm]	Power [W]	Data Volume/day	Operation Temperature [K]	Heritage
LEWIS	EAS, PAS, HIS	EAS: 360° PAS: 65°A, 45° E HIS:96° A 34° E	18.65	EAS: 11.6 x dia 13.6 PAS: 30 x 20 x 20	15.6	32.7 MByte	248 - 338	Ulysses, ACE, STEREO, Solar Orbiter
HEPS	EPT, SIS, LET, HET, STEIN, CDPU/LVPS	EPT: 30° SIS: 22° LET: 40° HET: 50° STEIN: 60° x 70°	15.68	EPT: 11 x 7 x 12 SIS: 35 x 13 x 11 LET: 22 x 15 x 11 HET: 13.6 x 17 x 16.2 STEIN: 10 x 13 x 13 CDPU/LVPS: 15 x 15 x 10	29.95	10.5 MByte (79.8 MByte in burst mode)	233 - 333	STEREO, SOHO, ACE, Solar Orbiter
MAG		N/A	1.94	Sensor: 9.75 x 4.9 x 6.7 Electronic: 15.9 x 16.2 x 9.8	4.39	147.7 MByte	233 - 333	VEX, THEMIS, Rosette Lander, Double Star, Solar Orb

Table 3 Overview of the in situ instruments on SCE

4.2. SC80

Instrument	Extracted parameters
IR/UV-P and C1	Magnetic field of lower corona
MI	Magnetic field of photosphere
C2	Velocity of CMEs near the Sun
EUVI	Coronal structures
HI	Properties of the propagation of CMEs through interplanetary space

Table 4: Instruments planned on SC80

4.3. IR/UV polarimeter and coronagraph

Measuring the coronal magnetic field in the solar corona is a challenging task. Our two satellites are equipped with two identical coronagraphs for spectro-polarimetric measurements in infrared and ultraviolet spectral lines, as well as visible light. The sketch illustrating the principles of the instrument is presented in Figure 3. The low corona, between 1.1 Rs and 2.0 Rs, will be observed with an internally occulted coronograph with an aperture of 20 cm.

The same aperture will be used for infrared, visible and ultraviolet light. The ultraviolet light will be separated from the visible/infrared with a conical mirror. The design of the coronagraph is inspired by the LYOT+ instrument proposed by Auchère et al. The pointing accuracy is constrained by the occultation (1/15 of 1.1 Rs): therefore the instrument requires a pointing accuracy of 72 arcsec. The stability of 3 arcsec has to be kept during the longer exposure time, i.e. 20 seconds.

The infrared lines FeXIII 1074.7 nm, FeXIII 1079.8 nm, and HeI 1083.0 nm, will be analysed using a Liquid Crystal Variable Retarder device for both the polarimetry and the tunable wavelength selection, and a narrow-band tunable filter. A six-stage birefringent filter will be used, which drives the thermal requirements: it needs to be maintained at a temperature of 30°C, with a variation less than 5 mC in 24 hours. The detector is a Teledyne imaging HgCdTe 2048x2048 detector with pixel size of 15 µm. A beam-splitter followed by a tunable broad-band filter and a

dichroic linear polarizer enable the observation the K-corona, with an APS sensor 2048x2048 with pixel size of 15 µm.
The UV HI Lyman alpha line at 121.6 will be isolated with a high reflectivity Brewster's angle linear polarizer, and an APS sensor 2048x2048 with pixel size of 15 µm will be used.

4.4. MMI - Multichannel Magnetic Imager

To fulfill our primary objective, it is essential to measure the vector magnetic field (Stokes Vector) of the photosphere and the chromosphere. This can be achieved by imaging different spectral lines in the visible spectrum. To measure the fields in the photosphere we use the iron lines at 630.15 nm and 603.25 nm. For the chromosphere the sodium lines D1 (589.592 nm) and D2 (588.995 nm) are used. For each one of the four lines, Full-Disk images will be recorded by a Multichannel Magnetic Imager (MMI).
Figure 4 shows the design of the new instrument to be developed. It is roughly based on existing imagers such as HMI (SDO) and ASPIICS (Proba 3). The refracting telescope with a diameter of 14cm ensures the required spatial resolution. The two lines are measured in parallel. The selection of iron and sodium lines and the protection against overheating due to sun light is done by external filters (FWHM 5 nm) in a filter wheel. The different lines are selected using tunable liquid crystal Lyot filters which have to be heated to 300±0.1K. Two CCD cameras (4096x4096 pixel) with a resolution of 0.5 arcsec/pixel allow to distinguish between different important zones within an active region. These are passively cooled to 233K and will take a series of 24 pictures for two spectral lines simultaneously within 2 minutes, before the filter wheel switches to the alternative lines. Each of these series is then preprocessed on-board to obtain images of continuum intensity, line of sight velocity and magnetic field components. With this configuration we get a whole set of observations every four minutes.

4.5. MI - Magnetic Imager

The mission can monitor active regions in the sun for two weeks before they are aligned with the Earth. The magnetic field vector (Stokes Vector) of the photosphere is measured using the Fe I line at 617.3nm. This type of observation has been already done in previous missions. The MI is inspired by the HMI on SDO. A set of 24 images every hour will allow monitoring of the magnetic field components, line of sight velocity and continuum intensity of the photosphere.

4.6. Coronagraph C2

Due to our scientific objectives, white-light coronagraphs on SCE and SC80 are essential. They provide a view on the solar corona by blocking the much brighter light of the photosphere. This is achieved by an occulter disc. The most important criterion for the quality of a coronagraph is its ability to supress stray light from the lower solar atmosphere. Due to the sharp decrease in intensity of the outer corona the C2 has to cover a large intensity range over several orders of magnitude. We decided to use the heritage of the LASCO C3 coronagraph of the SOHO mission (Brueckner et al. 1995) in order to gain a FOV of 2 R_s to 30 R_s and cover a brightness range from 10^{-8} to 10^{-11} of the Mean Solar Brightness (MSB). The Cor2 Coronagraph of STEREO uses the same technology but has a smaller FOV. The LASCO C3 has now been in space for 18 years and still produces high-quality images of the outer corona and interplanetary space. The external occulter guarantees a low stray light contamination. Due to the low density as well as the low brightness higher exposure times are needed than for normal imagers. The time cadence of LASCO C3 (24 min) is yet still enough in order to fulfil our requirements. With the Coronagraph C2 our mission will be able to observe the outer corona and beginning CMEs such that their speeds and directions can be determined.

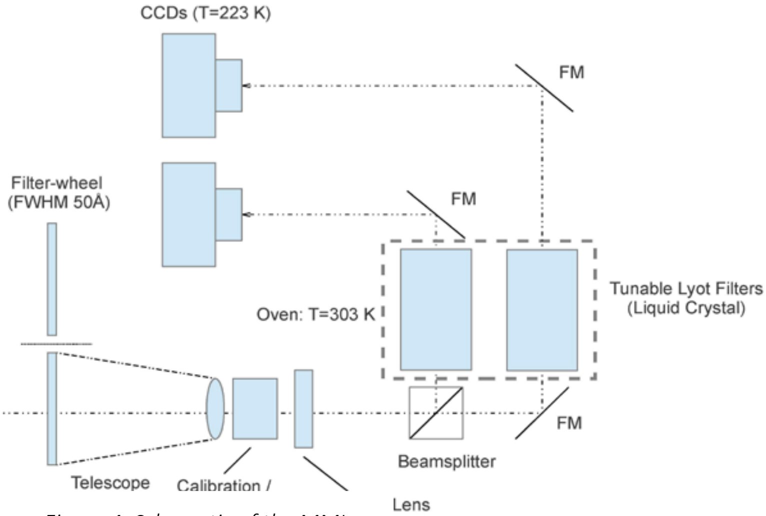

Figure 4: Schematic of the MMI

4.7. EUV Imager

Compared to the other parts of the solar atmosphere the corona emits light in fewer spectral lines. Current observations (STEREO, SDO, PROBA2) concentrate mainly on the Fe IX/X line in Extreme UV (EUV). In particular, coronal loops, which are indicators of closed magnetic field lines, are visible in this line. In order to investigate the onset of flares and CMEs images of the whole solar disc in this line are essential. Measurements of the intensity in this line are achieved with imaging devices that use a narrow-band filter. We will use the SWAP EUV imager (Seaton et al. 2013) from the PROBA2 mission (Santandrea et al. 2012) which takes images at 17.4 nm. Due to its novel and compact Ritchey-Chrétien scheme with an aperture of 33 mm it can be built in a compact form. It uses a new CCD technology and has a low power consumption of 5W. The time cadence can be controlled and is currently on PROBA2, between 110 and 120 s. The FOV ranges up to 1.6 R_s measured from the disc centre. We do not need to adapt the SWAP instrument for our mission because it exactly fulfils the requirements. It enables us to observe coronal dynamics on short time scales, e.g. the onset of a CME.

4.8. Plasma Instruments

There are nine plasma instruments:

- High Energy Particle Sensors (HEPS)
  - Supra-thermal Electrons, Ions and Neutrals (STEIN)
  - Supra-thermal Ion Spectrograph (SIS)
  - Energetic Particle Detector (EPD)
  - Low Energy Telescope (LET)
  - High Energy Telescope (HET)
- Low Energy Solar Wind Sensors (LEWiS)
  - Electron Analyser System (EAS)
  - Proton Alpha Sensor (PAS)
  - Heavy Ion Sensor (HIS)
- Fluxgate Magnetometer (MAG)

The instruments (LEWiS, HEPS and MAG) measure the interplanetary plasma conditions near the Earth.

The required observations are the composition of the solar wind, compositional changes, and magnetic connectivity. With regards to the energetic particles, the required observations are the timing, the velocity distributions, and the spectra and their number densities. Measurements of the distribution of thermal energies, the particle acceleration and bulk kinetic energy, as well as the suprathermal seed population are also necessary. The magnetic field properties are required as well.

LEWiS measures proton and electron E/q spectra and measures ion E/n spectra. It also measures temperatures, densities of alpha-particles and 3D velocity distribution functions.

MAG determines local magnetic field vector and magnetic pressure.

HEPS measures full composition of the energetic particles, anisotropies, velocity dispersion and proton/electron intensities in various energy ranges.

4.9. The Heliospheric Imager

The general design of this instrument is inspired by the two Heliospheric Imagers installed on the STEREO spacecraft. The HI is designed for a stray light suppression of 10^{-14} B_0 (B_0 = solar disc intensity) and a wide angle field of view. For this mission the HI-1 imaging system is removed completely and the HI-2 field of view is reduced to 42° with a pointing to 29° elongation. The other main characteristics of the HI are listed in Table 1.

5. Spacecraft design and subsystems

5.1. Spacecraft Design

Based on the scientific requirements several possible spacecraft mission designs were identified, all utilizing one satellite trailing the Earth and one closer to the Earth. Both satellites were required to have one side constantly viewing the Sun. After a trade-off it was decided to place one satellite (SC80) at Earth's orbit with a true anomaly 80° behind the Earth and to place one (SCE) in the Sun-Earth L1 point.

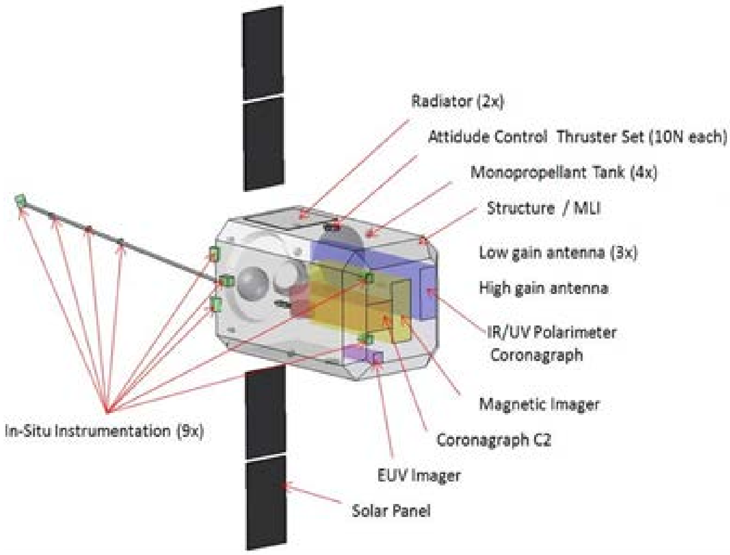

Figure 5: 3D model of the SCE

To fulfil the payload placement requirements and verify the sizing of the spacecraft 3D-CAD models of the two spacecraft were designed, shown in Figure 5. From a technical point of view the SC80 features more complex designs of the TT&C and propulsion subsystems, but the other subsystems will have high similarity. Figure 5 shows the placements of major subsystems and payloads (coloured). For SC80 all instruments have to face into the Sun with a narrow field of view, except the HI Instrument which has a field of view of 45° into earth direction. Due to scientific requirements SCE in situ instrumentation has to be placed at designated positions at one side of the spacecraft and certain instruments at a minimum distance behind the spacecraft.

5.2. Orbit design

For our satellites we considered different kind of orbits that would meet the scientific requirements:

Keeping in mind these requirements we chose a two spacecraft system with the following orbits.

5.2.1. SC80

Among the considered options, we chose an elliptical orbit with the exact shape of that of the Earth but with a smaller True Anomaly (80° less than the Earth's) meaning that the satellite will actually trail the Earth during its orbit.

To put the spacecraft into orbit two main manoeuvres are going to be performed:

The first one at Earth's apoapsis with a ΔV value of 1.02 km/s given by the Soyuz launcher that will put the satellite into a different elliptical orbit with an eccentricity ε = 0,0678.

The spacecraft will than make two lapses in this transfer orbit in order to build up the required tilt, this operation taking a total time of 26,7 months.

After that another ΔV value of 1.02 km/s (but in the opposite direction) is going to be applied again at apoapsis, putting the spacecraft in its final orbit. This final burst is going to be applied by the spacecraft thruster itself.

5.2.2. SCE

This second satellite is going to be put into a Halo Lissajoux orbit around L1. The Soyuz launcher will provide the necessary C3 energy to enter the orbit, while the 10 N thrusters will provide the ΔV for orbit maintenance that is necessary since this kind of orbit is unstable. The estimated transfer time is 3.5 months.

Using the STK numerical simulator we constructed a free non escape orbit through velocity increments along the escape direction and, based on that, we calculated the amount of ΔV required for orbit maintenance.

We found a ΔV value of roughly 13.5 m/s. Comparing those values to the ones of SOHO and Herschel of 2.4 m/s and 1 m/s respectively we decided to use a nominal value of 10 m/s per year. For the nominal mission lifetime of 6 years this means a ΔV of 60 m/s. If we add another 65 m/s for corrections during orbit entrance we get a total value of 125 m/s.

Axis	Amplitude of oscillation/$10^{5\ km}$	Orbital period
X	2.6	177.566
Y	8.3	
Z	4	184

Table 5: Orbital parameters

5.3. Propulsion system

Engine design is dictated by the ΔV necessary for orbit acquisition and represents a fine balance between fuel efficiency, thrust requirements, mass and reliable operational time. We require one primary engine for the SC80 orbit injection and several secondary engines, on both spacecraft, for attitude control and SCE orbit corrections. We have investigated several possible propulsion systems, including ones with a low Technology Readiness Level, but due to a lack of drivers we choose to utilize a standard chemical bi-propellant.

All engines use monomethylhydrazine (MMH) as fuel, oxidized with dinitrogen tetroxide (N_2O_4). Both are stored into different volume Astrium OST 01/X tanks (for SC80º) and OST 31/0 (for SCE). The volume ratio between the fuel and oxidizer is 1.65. The system consists of eight pairs of Astrium Model S10-21 thrusters (12 + 4) for redundancy. Added to these are 4x10N thrusters for the SCE system, respectively a single Astrium Apogee Model S400-15 for SC80 satellite.

5.4. ACS

The attitude control system (ACS) consists of sensors that determine the attitude and actuators that correct it in order to keep the pointing accuracy within the payload requirement's threshold.

The sensors consist of a HAST system (High accuracy star tracker) that includes two Star Sensor Heads (SSH) and one Star Sensor Electronics Unit (SSEU), an IRU (inertial reference unit gyro-pack) and two Sun Sensors (SS).

The actuators consist of 4 Reaction Wheels (RW) and a set of 16 Hydrazine Thrusters.

In our case, the main driver for the ACS requirements is the Magnetic Imager that requires an accuracy of 0.5'' and an exposure time of 4 s during science mode.

These requirements can be met combining HAST and IRU systems, with the first one giving a 0.1'' pointing accuracy before exposure and the second giving the rate errors to interpret the data with a bias drift of 0.0005'' per second that gives a total drift well within 0.1'' during exposure time.

The main ACS control modes are the following:

Coarse Sun Acquisistion: right after injection into orbit and orbit maintenance operations, the SS's will provide the attitude, and the RW will slew the vehicle to the Sun. In case of saturation of the wheels we will use thrusters to unload the stored momentum.

Fine Sun Acquisition: the ST in the HAST system will provide information to the RW in order to put boresight within 0.5'' from the target.

Science Mode: ST will provide pitch and yaw errors while IRU will provide rate errors for data handling. The RW will maintain the required pointing and store the daily momentum build up from environmental torques.

Safe Mode: only SS and IRU will provide attitude determination to maintain a low power usage but also ensure a coarse pointing for thermal safekeeping.

In order to have a rough estimation of the fuel usage for ACS we calculated the total torque given by external perturbations, in particular magnetic torque and Solar Radiation pressure torque, since for our sun pointing requirement these kinds of perturbations are not cyclic and build up in time.

Assuming the presence of a magnetic field of 1 µT (WCS), a dipolar charging for the spacecraft of 1 A/m^2, a reflectivity of 0.6 mm and a displacement of 0.5 m between the centre of mass and the centre of radiation pressure we find a value of 31.7 µNm (with a 50% margin).

Taking this torque into account and knowing the moments of inertia we estimated that in order to keep our pointing within the accuracy threshold of 0.5'' we'll need to use RW for adjustments only after 10 s.

Having an exposure time of 4s the accuracy is guaranteed.

Considering a thrusters torque of 7.5 Nm we can derive the amount of fuel for corrections with:

and considering a 100% margin we find a value of **1.12 Kg (per year).**

5.5. Power

In respect to on-board average/peak electrical power consumption and the orbital profile the power subsystem has been sized in order to provide, store and distribute the necessary power.

For 1 AU average distance to Sun, the solar arrays have been identified as the best solution of power generation. The solar arrays have been dimensioned with their end of life performance according to the average electrical power needed for the solar flux provided at 1 AU. The power storage system supports each spacecraft in the worst case of control loss for up to 12 hours. The overall power consumption for both spacecraft has been identified as non-critical.

Communication can be pointed out in Table 7 as the main power consumer at SC80 while Payload is for SCE.

5.6. Thermal

The main requirement of thermal subsystem is to keep the general temperature of the spacecraft at normal room temperature 20°C. Furthermore some instruments have cooling requirements but these are assumed to be solved in the relevant payload design. The temporal requirement is fulfilled by sizing radiators based on the spacecraft hottest orbital position and supplying an extra heating power based on their coldest orbital position. The satellite is assumed to have one constantly sun-facing side and the thermal radiation as well as the solar reflection from the Earth is considered negligible. The cases for both satellites are presented in Table 5.

Spacecraft	SC80	SCE
Hot case	1 AU from Sun	1 AU from Sun
Radiator size	1.6 m^2	1.6 m^2
Cold case	1.15 AU from Sun	Same as hot case
Heating power	110 W	0 W

Table 6: Thermal subsystem design

5.7. The Communication Subsystem

The scientific objectives of the PAC²MAN mission impose high demands onto the communication subsystem regarding necessary data rate and distances. In order to design a communication system which meets these requirements, a link-budget has been calculated for each satellite independently. Besides the demands introduced by the mission profile, the link-budget considers the communication attributes as follows:

Both satellites will operate at a **frequency** of 8500 MHz (X-Band). Even though Ka-Band provides larger antenna gains, X-Band transmissions are less demanding onto ground stations regarding, for instance, elevation angle or phase shift compensation. Furthermore, the majority of ESA tracking stations do not provide Ka-Band capability.

The usage of the common 15m, X-Band ESTRACK **ground stations** allows a continuous communication by using three ground stations with an approximate relative alignment of 120°. A continuous communication also reduces the necessary down-link bit rate.

In order to achieve a reliable communication a code rate of ½ will be used. Even though this doubles the necessary data rate (-3dB), it leads to an additional **coding gain** of 6 dB. Furthermore, BPSK **modulation** will be used in order to minimize the bit energy to noise ratio demand to the least possible value (9.6dB for a max. bit error rate of 10^{-5}).

Both satellites will utilize high gain, narrow beam, parabolic antennas for scientific and operational data. The **antenna gain** of the transmitting and the receiving antenna is given by the diameter of the antenna and the operational frequency. As these antennas need to be pointed at the earth, they will be steerable. For every unit of freedom an additional **steering loss** of 1 dB is assumed. Furthermore, low gain, omnidirectional antennas are used in case of a failure causing a link breakage. The noise at the receiving antenna for X-Band frequency causes an additional link degradation of 15.2 dBK.

The **path loss** is estimated using the free space path loss formula by Friis. It depends on the transmission frequency and the distance between the satellite and the ground station. Furthermore, additional **on-board losses** are estimated with 1 dB.

The communication system of the SCE has to provide a down-link capable of transmitting scientific data of up to 43.2 GB per day. Combined with operational data, 10% overhead and additional redundancy to achieve the coding gain, an overall data rate of 10485 kbit/s is necessary. With a distance of 1.5 million kilometres, a RF power of 15 W and an antenna diameter of 0.5 m the link margin can be calculated to 4.6 dB. The backup communication uses the same transponder and amplifier. The omni-directional antenna provides a gain of 4.5 dBi. Therefore, a link-margin of 4 dB remains for a communication at 50 kbit/s.

The SC80 needs to deliver 910 MByte per day. This corresponds to 200.6 kbit/s, including operational data, overhead and redundancy. With a transmission power of 160 W, an antenna diameter of 2.3 m and a distance of 193 million kilometres, a link-margin of 3.2 dB remains. The backup communication is capable of 200 bit/s at a remaining link margin of 3.4 dB.

5.8. Control Subsystem

The control subsystem consists of dedicated control units for each module. A Satellite Control Unit (SCU) handles the housekeeping as well as Failure Detection, Isolation and Recovery (FDIR) based on the derived information from other sub-control units. The SCU interprets and executes commands which are forwarded by the communication-control subsystem. Furthermore, it handles the data which should be stored or buffered before it is send to the earth ground station. The data is recorded on a solid state mass memory which can store up to 70 GB.

Two separate modules for the Service (SVM) and the Payload (PLM) report back to the SCU. The PLM consists of a payload controller, a data processing unit and thermal controlling subsystem.

The SVM consists of an attitude and orbit controller, a propulsion controlling unit, a communication controller as well as a controlling unit for the thermal system. Furthermore, the control of the power source as well as the power storage and power distribution control will be handled by dedicated power control unit.

The control units belonging to the PLM will be attached to a high speed SpaceWire network while the controllers of the service module will use a CAN-Bus in order to communicate within the satellite

Subsystem	SCE [W]	SC80 [W]
Payload	226	101
Propulsion	21	24
AOCS	42	47
TT&C	60	350
OBDH	21	24
Thermal	21	24
Power	63	71
Total consumption	436	549
With 20 % margin	523	658
Total power available after 11y	654	823

Table 7: Power budget

6. Budgets

	SCE		SC80	
Subsystem	Mass [kg]	Mass w/ safety margin [kg]	Mass [kg]	Mass w/ safety margin [kg]
Payload	172.3	206.7	164.0	196.8
Propulsion	13.7	14.4	105.0	110.3
AOCS	86.0	90.3	86.0	90.3
TT&C	50.0	52.5	80.0	88.0
OBDH	20.0	22.0	30.0	33.0
Thermal	36.4	42.4	51.1	56.2
Power	59.3	62.2	125.4	75.0
Structure	120.1	127.2	153.2	168.5
System margin (including harness)		154.2		204.2
S/C Dry Mass		770.9		1021.0
Propellent		86.1		541.1
S/C Wet Mass		857.0		1562.1
Adaptor		150.0		150.0
Launched Mass		1007.0		1712.1
Launcher potential		2150.0		2100.0
Launch margin		1143.0		387.9

Table 8: Mass budget

7. Launchers

Since the planned satellite lifetime is 6 operational years we want to time our scientific measurements with a solar maximum to get as much data about the solar events as possible. We plan for a final orbit spacecraft arrival 3 years before the predicted solar maximum of solar cycle 26. This puts the arrival in early 2034, see Figure6 for launch details. If the launch is delayed too much we risk operating in a solar minimum, but even during the solar minimum there are 0.5 CMEs/day [Gopalswamy et al., 2003]. Based on the required transfer orbits from the Earth and the wet mass of the spacecraft we have chosen to use two Soyuz launchers launched from Kourou, French Guiana. The first launcher shall inject SC80 into an elliptic transfer orbit through an Earth escape orbit with c^3=1.15 km^2/s^2 and the second launcher shall inject SCE into its Lissajous orbit through an Earth escape orbit with c^3=0.08 km^2/s^2. The Soyuz launcher has the capability to deliver 2100kg respectively 2150kg into the required orbits [Soyuz-User-Manual-2012].

8. Operations & Ground Control

The communication is established using at least three 15m, ground-based antennas provided by ESTRACK. The usage of three ground stations will allow a continuous communication which will be necessary in order to deliver forecasting data in the first project phase and pre-event forecasting data in the second project phase with a minimum delay. These ground stations are operated by the European Space Operations Centre (ESOC).

A mission operations centre (MOC) located at ESOC is responsible for maintaining the satellites operability as well as mission planning, execution, monitoring and control. It is also responsible for archiving the received raw telemetry data.

A Science Operations Centre (SOC) located at the European Space Astronomy Centre (ESAC) will be in charge of the scientific operations. These operations include merging payload operation requests, data archiving and data analyses support. The SOC will be mainly concerned with calibrating scientific instruments at the beginning of the mission. Until the second project phase the payload operations mode will not change. At the beginning of the second project phase some payload operation changes will be necessary in order to achieve a reliable space weather pre-event forecasting application. The SOC will merge operational adaption requests, plan the adapted scientific operation and submit it to the MOC. For long-term archived scientific data at ESAC and data distribution to the scientific community the SOC project teams will provide reformatted and calibrated data. The scientific data will be processed on ground and alerts are produced based on forecasting. In the second project phase additional on-board data processing is required in order to achieve pre-event forecasting and decrease alert times. Alerts are provided to the ESA Space Weather department.

9. Cost estimation

The cost is a major mission driver for any space mission and this is also true for our mission. Using two spacecraft puts the ROM budget on a similar level as two M-class missions. We achieve some cost reduction due to platform heritage from Planck/Herschel, similarities between the two spacecraft and a possible shared launch for the SCE. De-scoping is also possible, but is not recommended. A six year mission extension with more operational Space Weather focus will add an extra € 100 million to the cost.

Activity	Cost/M€
Launchers	120
SCE platform	250
SC80 platform	200

SCE operations	40
SC80 operations	50
Ground segment	100
ESA cost	760
Payload instruments and scientific data processing	420
Total cost	1180
Agency/management (included in the above figure)	130

Table 9: The ROM Cost Estimation

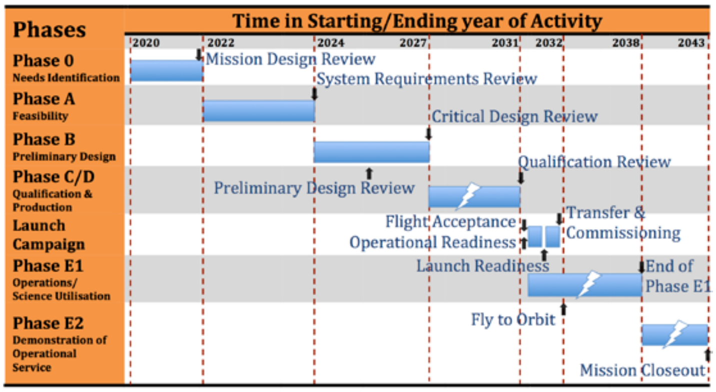

Figure 6: Project plan

10. Risk assessment

During mission design we evaluated several scenarios that could represent possible risks for our mission. We considered their likelihood and the severity of their impact on the mission objectives. The most important ones are:

- Unavailability of scientific instruments close to launch time (B3). The IR/UVP and MMI for which we evaluated a TRL degree of 3, are to be considered. Possible mitigation for this risk could be a close monitoring of instrument's development or a mission delay
- Degradation of instruments due to constant solar exposure (B3). Especially a degradation of the Polarimeter's filters. A possible mitigation could be the implementation of spare filters in filter wheels.
- Loss of C80 spacecraft (A4). Even if this is a critical risk cause without SC80 we won't meet most of our objectives, SCE could still represent a perfect substitute for the ACE spacecraft
- Loss of attitude control (C1). We can mitigate this by creating a customized Safe Mode and adding redundant sensors and actuators
- Loss of SCE spacecraft (A3). In this scenario we could consider using already existing satellites in L1 to cover some measurements of SCE. SC80 can still provide Space Weather forecasting by measuring CMEs from Sun to Earth.

11. Conclusion

The PAC^{2}MAN mission will help improve our knowledge of the atmospheric conditions of our star. The detailed tracking of solar events will also be used as a Space Weather forecasting tool that can monitor the interplanetary space between the Sun and the Earth from a privileged location.

An early warning system that can evaluate the likelihood of solar events would help to predict their effects on the Earth environment. Some of the economical sectors that would benefit from this early warning system include the telecommunications networks, the Galileo/GPS positioning systems and the electric generation industry, all of which directly affects the lives of all the people in the world.

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