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ISAS Optical Design Report

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ABSTRACT

This document describes the first Optical Design of ISAS (Interferometric Stratospheric Astrometry for Solar system). ISAS is a proposed mission that should fly on a balloon with the target of astrometric high precision measures of position and proper motion of solar system bodies. The measure will be homogeneous with reference of external field stars. The precision of astrometric measure will be of the order of 1 milli-arcsec (mas) for fields separated by few degrees around the Sun. It uses abundantly the principle of diluted pupil and try to couple a non traditional optical scheme with a simple layout. The document is oriented to the specification of the parameters needed for a preliminary efficient mechanical design.

Keywords: ISAS, Balloon Instrumentation, Diluted Pupil

1. INTRODUCTION

The Gravitation Astrometric Measurement Experiment (GAME) is the concept of a space mission using high precision astrometry for determination of the γ and β parameters of the Parametrised Post-Newtonian (PPN) formulation of Einstein's General Relativity (GR) and competing gravitation theories. The GAME concept has been previously presented in the form of either a small or medium class mission, aimed at the measurement of the gravitational deflection of the light close to massive objects, in particular the Sun.

The Interferometric Stratospheric Astrometry of Solar system (ISAS) project built on the GAME concepts, and represents an intermediate step toward the space mission, since it defines
(a) a stratospheric balloon payload design, and
(b) a multiple flight campaign
with two main goals: achieve significant scientific results, namely the improvement of the planetary ephemerides, and demonstrate the key technological solutions proposed for GAME.

In particular, we choose to give up the simultaneous observation of Sun-ward and outward fields, requiring just an additional pierced flat mirror, and retain the combination of coronagraphy and Fizeau interferometry which are the unique feature of the proposed instrument.

The orbit of Jupiter is currently not well constrained due to lack of precise data since 2000. It is then crucial for preparation of future space missions as JUICE to improve drastically the accuracy on the Jupiter orbit. Gaia will provide the positions of faint satellites of Jupiter, but from these positions we will not be able to deduce position and motion of the center of mass of the jovian system with an accuracy better than 10 *mas*. By using only 2 positions obtained each year, over a total project lifetime of 3 years, with an individual accuracy below 5 *mas*, the ephemerides of Jupiter will be improved by at least a factor 2.

The ISAS experiment will provide such positions of outer planets before the release of the complete Gaia catalogue, before arrival of the JUNO mission to Jupiter (planned in July 2016) and before the launch of the JUICE mission if selected. The positions observed by ISAS during a 2-years period (from 2014 to 2016) will then help to optimize the approaches of these missions.

For Uranus and Neptune, the ISAS experiment will be the only tool for improving their orbits drastically as no spacecraft will fly to these planets for the next ten years. A better knowledge of these orbits is an interesting tool for testing gravity as alternative gravity models foresee deviations to general relativity at long distances from the sun, mainly beyond the Saturn orbit.

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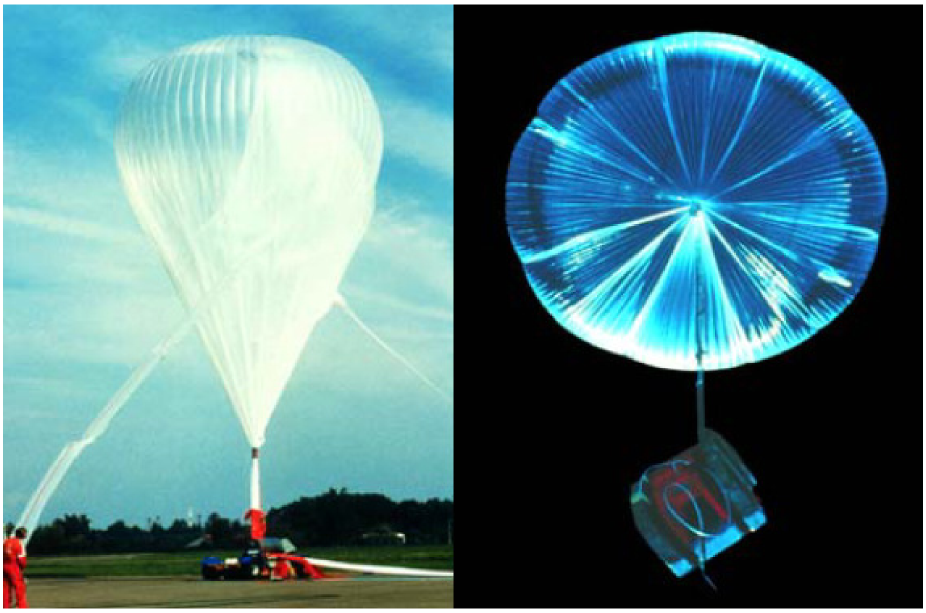


Figure 1. ZERO-PRESSURE STRATOSPHERIC BALLOONS (ZSB - BSO).

The second implication of the ISAS experiment is in testing gravity by two possible approaches.

A first approach is related directly to the observations of outer planets and of the improvement of planetary ephemerides. As proposed by Hees et al. (2012), it is now possible to test alternative metrics of gravity by comparisons to spacecraft tracking data but also to very accurate optical observations of planets, mainly VLBI. With the ISAS experiment, it will be possible to compare the very accurate positions of outer planets with alternative metrics by the use of modified version of the INPOP ephemerides.

A second approach is the determination of the PPN parameter γ by the deflection of light, testing the feasibility and performance of the GAME concept. From a phenomenological point of view the γ parameter is associated to the light deflection, and it is easy to demonstrate (Vecchiato, A. et al. 2009) that the accuracy estimation of the γ parameter is proportional to that of the light deflection, which is directly related to the precision of the angular separation measurements.

2. OPERATING PARAMETERS

ISAS mission is designed in order to fly onboard an aerostat. It is conceived as a scientific mission but it can become a validation for future space missions.

In order to have a reliable optical and mechanical design, we will outline some representative operative conditions. We will refer to the CNES call "2012 CALL FOR SCIENTIFIC RESEARCH PROPOSALS USING BALLOONS", "REF. CNES/DSP/ARP 2012.0001265". Within this call, one of the aerostats proposed is the "ZERO-PRESSURE STRATOSPHERIC BALLOONS (ZSB - BSO)". We report here some of the known features of this balloon. It has a variable volume that ranges from 3 000 to 800 000 m^3 with a payload mass up to 1000 kg. The ZSB-BSO balloon will fly at an altitude between 20 and 40 km, and offers the recoverability of the payload. From NASA sources (see Figure 2) the typical temperature variation of the 20 to 40 km altitude, ranges from 220 to 250 K. Typical mission flight ranges from hours to some days (around 5).

In this concept the payload is composed by two stages: the gondola and the telescope. The gondola can point the telescope with a relatively low precision, while the telescope role is that of fine pointing and focusing the light. Since at present the gondola parameters can not be precisely defined yet, this issue will be treated in a future work.

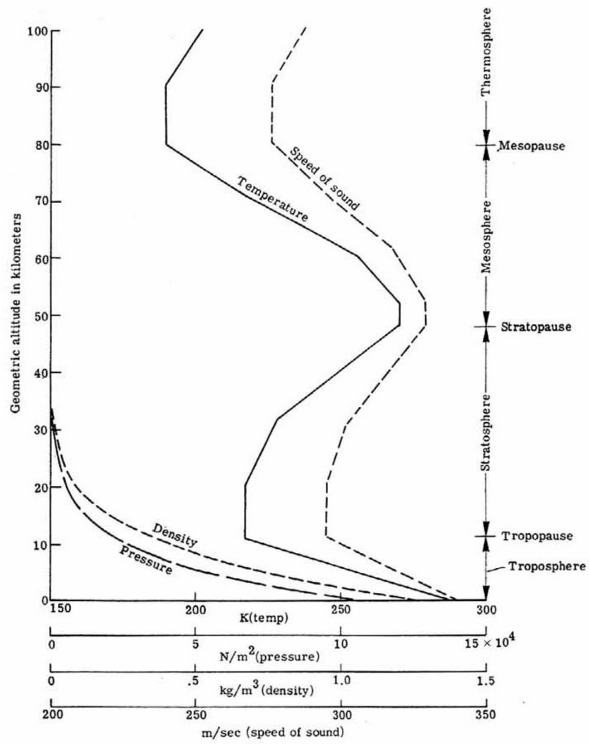


Figure 2. Geometric altitude vs. temperature, pressure, density, and the speed of sound derived from the 1962 U.S. Standard Atmosphere. (Credits - NASA)

The designed telescope is based on the hypothesis that it will operate in an alt-az configuration The instrument will operate pointing to the Sun with an estimated elevation range between -20 and +20 degrees from the horizontal position.

3. OPTICAL DESIGN

In this section we will describe the optical design and its main features. The optical train can be subdivided into two main logical stages, which are devoted to the combination of the two lines of sight, and to the focusing of each incoming combined beam respectively. In following two sections we will describe separately the two stages.

3.1 Beam combination

The beam combination is performed by two main elements, the pupil mask and the beam combiner. The two elements will be depicted in the optical train later in Section 3.2, and in Figure 6. The core of the system is the Beam Combiner, represented in Figure 3, using two suitably tilted surfaces, which combine two fields of view into a common beam to be processed by the telescope.

Both elements are characterized by the dilution of the pupil, that translates into the multi-holes features clearly visible in Figure 4. Since the light that has to be combined must cross the primary mirror, another set of holes has to be done onto this surface.

3.2 Focusing the beams

Once the beams are combined, the next step is to focus the light onto the focal plane. This can be performed through a single telescope that accepts the combined light.

In order to allow for tolerances which do not stress on the telescope requirements and to reduce at maximum the complexity of the optical train we decided to have a first focus camera. The scheme adopted is with a

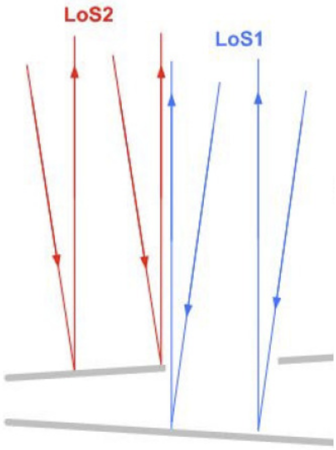


Figure 3. Beam Combiner Principle.

Table 1. Table of the most important parameters of the Optical Path. All values are expressed in [mm].

Optical element	Material	Curvature	Distance to next element
M1	Aluminium or Sic	4000.552	1550.000
M2	Aluminium or Sic	flat	280.002
Camera	BK7 & SF2	various	296.134*

*This number takes into account two distances: 281.020 mm is the thickness of the camera, while 15.114 mm is the distance of the camera to the focal plane (FP).

spherical primary reflective mirror and a relatively complex refractive camera. The reader may notice that the camera presented later is not possible to build. The philosophy of this design phase regarding the diffractive elements is to overload the train and leave to the glass machining all the camera tolerances. In other words the refractive train will carry its tolerances as a single element. Since the camera will likely be mounted into a single barrel and can be treated as an unique piece.

In Figure 5 the 3D optical layout of the telescope stage is shown.

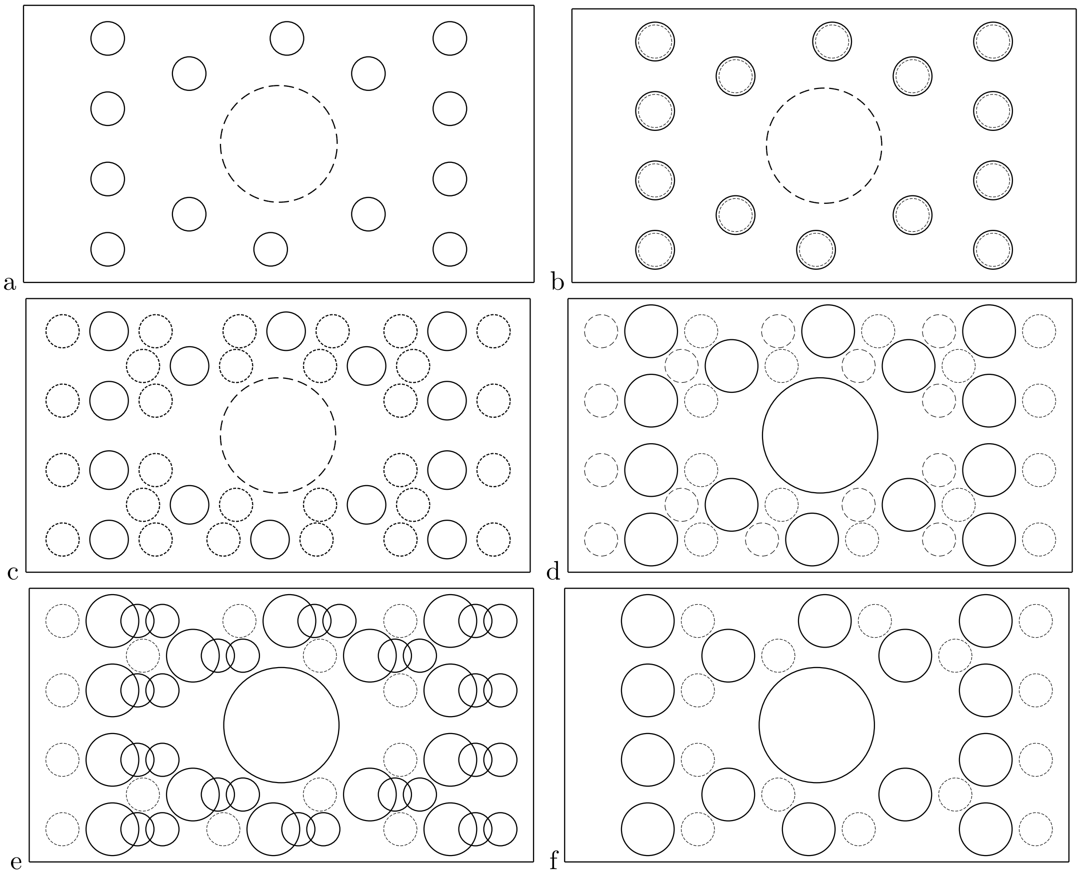
The telescope stage (focusing stage) receives the light from the beam combiner. It has been designed with an Effective Focal Length (Equivalent of Zemax EFFL) equal to 22 m. Looking at Figure 6 it is possible to see all the optical elements of the instrument.

The first surface encountered by the beam is the Mirror M1. It is a sphere with a radius of 4000.55 mm, and a rectangular aperture of 920 mm by 450 mm. The light beam then is folded by 45 degrees through the Mirror M2, which is a flat mirror with a rectangular aperture of of 300 mm by 200 mm. This mirror can be used as a fine pointer stage with a tip tilt regulation. After the folding mirror the light beam goes into the camera stage. For the purposes of such level of development the elements of the camera are purely ideal and should be considered not affected by alignment errors. The camera is designed using 10 refractive elements with alternating SF2 and BK7 common glasses in order to have the coupling of "crown" and "flint" glass. The purpose of the design of this stage is to overload the train with elements in order to be conservative in a mass budget estimation. At this level of detail, it is possible to suppose that the lens train will be incapsulated into a barrel, that can be considered as a rigid element.

Table 1 reports the principal values for the optical train of the telescope.

4. TOLERANCES

In this section we report on the values of the tolerances for the operative payload. Since our knowledge of the gondola is unclear at present, at this stage we assume it as ideal.



a b c d e f

Figure 4. Beam combination. Sketch of single surfaces holes dispositions. The upper left (a) is the hole disposition of the pupil mask, the upper right (b) shows the arrangement of the hole to be drilled in the primary mirror. Center left (c) shows the footprint of the beams related to the holes again on the primary mirror. Center right (d) shows the disposition of the hole and footprint maps on the beam combiner. Lower left and right (e) and (f) show the configuration of holes for each folder of the beam combiner.

In Table 2 a positioning tolerances set of values is reported.

The table reports the Beam Combiner as composed by two separate elements. If it is built as a single element, the respective tolerances are those of the "*Beam Combiner front*" row. On the other hand, if the Beam Combiner will be carried out with two separate elements, the key tolerance is the stability of the angle between the two slabs.

Regarding to the surface stability tolerances, the requirements has to be applied to the Spheric Mirror M1, to the Fold Mirror M2 and to the Front Beam Combiner. The tolerance value for all these surfaces is 0.5 lambda RMS and 1 lambda PTV.

A final consideration must be done on the flexibility of the values mentioned above. All values can be reconsidered if they requires high mass or high budget solutions. A close interaction between the Optical subsystem and Mechanical subsystem is strongly recommended.

4.1 Mass Budget

The payload values for the mass budget are those relative to the CNES call. We assume as maximum allowed mass for the payload the value 1000 kg. The fraction of the budget that should be allocated for the "gondola" stage is not known, therefore a conservative treatment of the telescope is suggested.

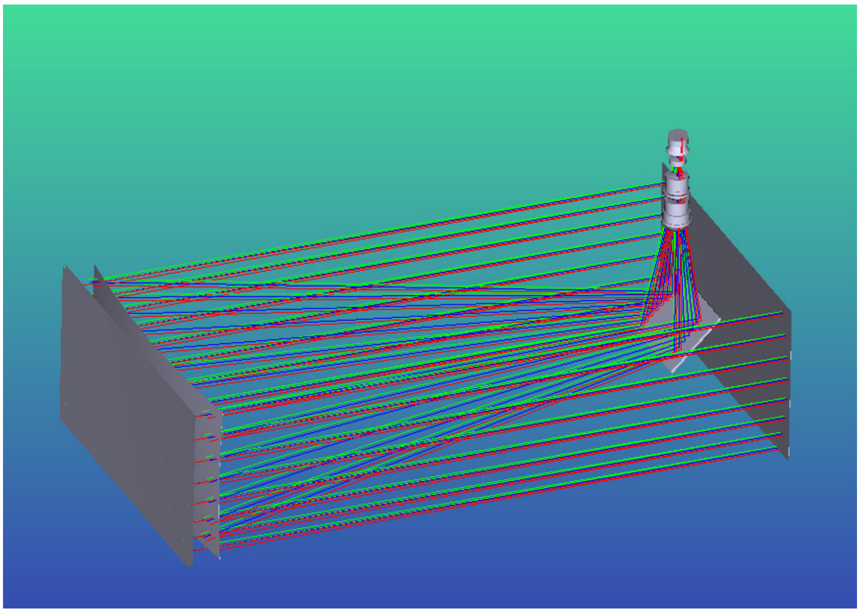


Figure 5. 3D Optical Layout of the ISAS telescope focusing stage.

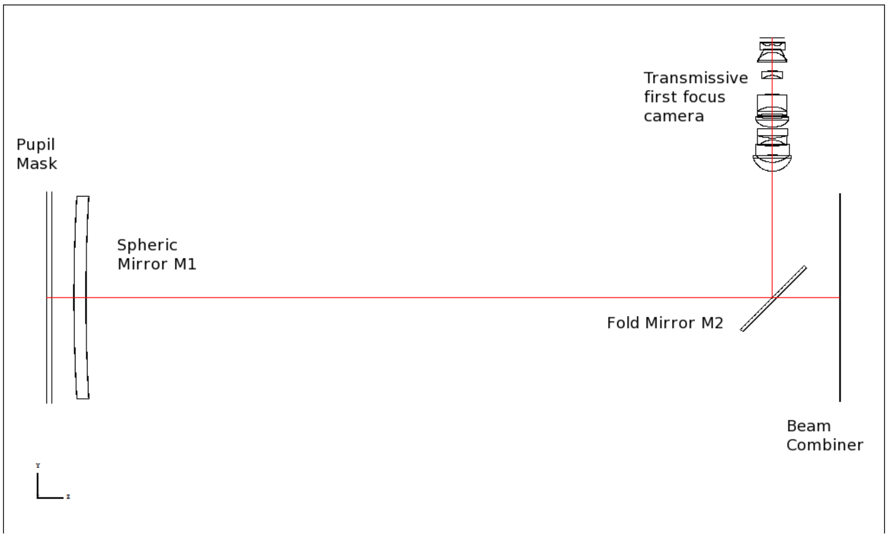


Figure 6. 2D Optical Layout of the ISAS telescope focusing stage.

Table 2. Table of the tolerances for the positioning of the ISAS optical elements. Values are [mm] for translations (Tx Ty Tz) and [°] for rotations (R_α R_β R_γ). All values must be intended as +/−.

Optical element	Tx	Ty	Tz	R_α	R_β	R_γ
Spherical Mirror	0.01	0.01	0.10	0.10	0.10	180.00*
Pupil Mask	0.10	0.10	0.01	0.10	0.10	0.10
Beam Combiner front	0.10	0.10	0.10	0.10	0.10	0.10
Beam Combiner rear	0.10	0.10	0.10	0.10	0.10	0.10
Camera	0.01	0.01	0.10	0.10	0.01	180.00*
Focal Plane	0.01	0.01	0.10	0.01	0.01	0.01

*This number means that the item is substantially not affected by any variation of such degree of freedom

5. CONCLUSIONS

The present Technical Note summarizes a possible Optical Design for a balloon mission to be eventually submitted to the proper calls. The optical design here proposed refers to the ISAS mission, whose main goal is the measure of positions and proper motions of Solar System bodies. It is designed through the diluted pupil concept and beam combining of two fields separated by few degrees around the Sun. The technical note is oriented to the initial interface for a high performance mechanical design, with an initial estimation of the possible tolerances and operating conditions.

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