GAMES: Gamma Astrometric Measurement Experiment Study

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Gamma Astrometric Measurement Experiment Study

GAMES

Cover Page:

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- **Host Institution:** **Istituto Nazionale di Astrofisica - Osservatorio Astronomico di Torino (INAF-OATo)**
- **Proposal full title:** **Gamma Astrometric Measurement Experiment Study**
- **Proposal short name:** **GAMES**
- **Proposal duration in months:** **36**

Proposal summary (half page, possibly copy/paste of abstract from administrative part A1)

GAME is the concept of a space based experiment for measurement of the gravitational deflection of light by the Sun, with a targeted precision on the γ parameter of the Parametrised Post-Newtonian formulation of General Relativity in the range 10^{-6} to 10^{-8}, i.e. one to three orders of magnitude better than the best currently available results.
The implementation is based on a small mission, observing repeatedly selected sky regions close to the ecliptic, with an optimised instrument, for a period of two years; simulation results are compatible with the goal precision.
GAME adopts a fully differential scheme optimised for determination of the light deflection, and in particular of γ. It also builds on astrometric measurement principles well established in the framework of the ESA missions HIPPARCOS and Gaia.

The proposed investigation of the GAME concept aims at defining the practical feasibility and realistic performance, in terms of implementation on a small mission targeting the precision level 10^{-6} to 10^{-7}; the intrinsic physical limitations of the technique (e.g. for a possible larger scale mission with the precision goal 10^{-8}); the additional astrophysical information achievable on Solar system objects and selected sky sources. The activity includes verification of the science case; definition of a realistic payload design and mission profile; assessment of critical instrument aspects; identification of detailed design parameters for subsequent development stages.
Crucial lab experiments planned in this proposals concern design and verification of:
- telescope optical configuration;
- baffling for rejection of solar radiation;
- internal metrology system.
The results will be used to build scientific consensus toward the implementation of GAME, and will be used for preparation of a proposal for GAME mission development by the European Space Agency or a consortium of national space agencies.

1. State-of-the-art and objectives

The bending of the light path due to the gravitational pull of massive bodies is one of the best known effects introduced by the General Theory of Relativity. In the language of this theory, the effect is interpreted in terms of the curvature induced on the space-time geometry by the mass of the bodies. The PPN formalism (Will, 2006) identified a whole class of metric theories of gravity each characterized by the values of a given set of parameters. In this framework, the γ parameter quantifies the effect on space time curvature and it is unity in General Relativity.

GAME is a novel implementation, a century later and with modern technologies, of the previous experiment of Dyson, Eddington and Davidson, which gave in 1919 the first confirmation of Einstein's General Relativity theory. The original experiment was based on the measurement of the relative positions of a small number of stars, both close to the solar limb (during an eclipse) and quite away from the Sun (in night time, with a suitable time elapse); the position variation between the asterisms provided the measurement of light deflection to an accuracy which, in terms of the γ parameter, was limited to 10%. The shortcomings were due to the short eclipse duration, the high background flux from the solar corona, the atmospheric disturbances and the limited number of bright sources imposed by the field available for a given eclipse. The method was used several times in the following decades (Vecchiato et al., 2006), but its accuracy could not be further improved. ***A space experiment is able to overcome such experimental limitations.***

GAME (Vecchiato et al., 2006) is a space based experiment for the measurement of the gravitational deflection of light by the Sun (Figure 1), with a targeted precision on the PPN γ parameter in the range 10^{-6} to 10^{-8}, i.e. one to three orders of magnitude better than the best currently available results by alternative techniques: 10^{-4} to 10^{-5} from the Viking, VLBI and Cassini data (Bertotti et al., 2003). *The measurement principle of GAME is fully differential*, and based on the astrometric signature on the stellar positions, i.e. it is based on the spatial component of the effect rather than the temporal component as in the most recent experiments using radio link delay timing. Therefore *the measurement conditions of the two experiment classes are independent*, providing a convenient framework for mutual verification of the results in the common measurement range. Some of the shortcomings of radio experiments (e.g. propagation in the dispersive medium of interplanetary plasma) are expected to be negligible in the wavelength range of GAME; a thorough verification of the environment effects is anyway planned within this research proposal.

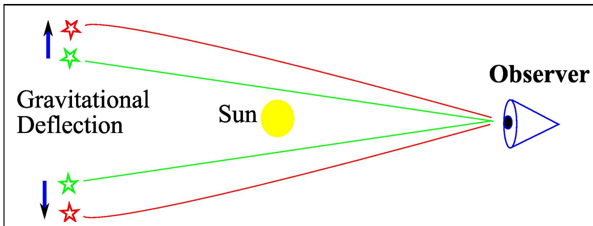

Figure 1 – Representation of the apparent effect of light deflection by the Solar gravitational field on the light rays from stars. The apparent star position is displaced from the Sun because of the photon path bending.

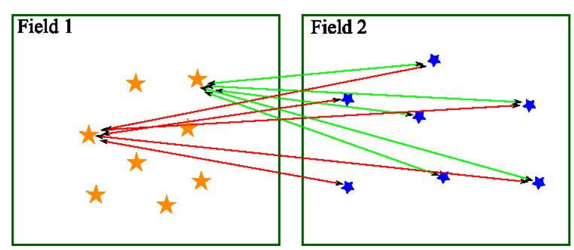

Figure 2 – The Game observable: arcs between stars from each field, superposed onto the detector by the beam combiner. Arc length changes with time, depending on pointing position vs. the Sun.

The goal of GAME may be achieved by accurately measuring the relative positions of many stars in two different fields in the vicinity of the Sun, as in Figure 2, thanks to a suitable beam combiner folding the telescope line of sight in the two required directions and therefore generating an artificial eclipse towards the Sun. The resulting image superposing the two fields is shown in Figure 3. By looking at differences in relative position when the same fields are observed far away from the Sun, one can estimate the deflection of the starlight due to the presence of the Sun's gravitational field, mainly related to γ. Deviations are associated to generalised Einstein models for gravitation, e.g. scalar-tensor theories leading toward quantisation of gravity, or the *f(R)* theories (in the range 10^{-5} to 10^{-7}) with potentially huge impacts on the cosmological distribution of dark matter and dark energy, which might be replaced, partially or totally, by space-time curvature effects justifying the same observed effects (Capozziello and Troisi, 2005). GAME also builds on astrometric measurement principles well established in the framework of the ESA missions HIPPARCOS and Gaia, also supported by this team. However, ***GAME adopts a <u>fully differential</u> scheme optimised for determination of the light deflection (Figure 2 and 3), and in particular of γ*** Preliminary evaluations by the proposing group (Vecchiato et al. 2007), suggest that a small mission, observing repeatedly selected sky regions close to the ecliptic, with an optimised instrument, for a period of about two years, could provide the desired precision.

The proposed investigation of the GAME concept aims at defining:

- the practical feasibility and realistic performance of implementation on a small mission aiming at the precision level 10^{-6} to 10^{-7}, i.e. much better than the state of the art;
- the intrinsic physical limitations of the technique (e.g. for a possible larger scale mission with precision goal to 10^{-8});
- the additional astrophysical information achievable on Solar system objects and selected sky sources.

The success of the GAME study will enhance the capability of fundamental physics understanding by astrophysical measurements, in particular high angular precision methods. ***Besides, the technology for high angular precision measurements, and the original optical concept proposed, may offer solutions for other scientific or technological applications.***

The results will be used to build scientific consensus toward the implementation of GAME, and for preparation of a proposal for mission development by the European Space Agency or a consortium of national space agencies.

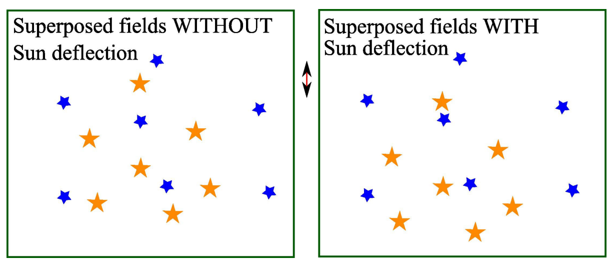

Figure 3 – Focal plane images of the two combined fields in the two measurement epochs, respectively with the Sun between the two lines of sight (right) and with a large angular distance from the Sun (left).

1.1 GAME sensitivity to light deflection effects due to oblate and moving planets

Observations close to Jupiter's limb (or giants planet's, i.e. Saturn) will provide an estimate of the light deflection induced by its gravitational field, namely by its mass-monopole and mass quadrupole, at least in the post-Newtonian or post-Minkowskian approximations of General Relativity. The light deflection, produced by an oblate planet on grazing photons, has been simulated for a Gaia-like mission for the first time in Crosta and Mignard (2006).

In the case of a static gravitational field of Jupiter, the magnitude of the monopole deflection for a grazing ray is ~16 milli-arcsecond (mas), to which a component from the quadrupole moment is superimposed with an amplitude of ~240 micro-arcsecond (μas). This study was the initial part of a wider project called GAia Relativistic EXperiment (GAREX), which aims at putting in practice all the possibilities to test GR with highly accurate astrometric differential measurements. In that paper the quadrupole deflection has been parameterized by introducing a new parameter ε, equal to one if GR predictions are true. This secondary deflection, called q-effect, has a very specific pattern as a function of (i) the position of the star with respect to the oblate deflector and (ii) the orientation of its spin axis. The concept, discussed in GAREX with reference to the Gaia mission, is applicable to GAME with significant advantages in the observing flexibility, which will surely allow to assess the detection of the q-effect by including all the gravito-dynamical relativistic effects due to the orbital velocity of the planet and to build a tool for comparisons with the fully general relativistic astrometric model, namely RAMOD (de Felice et al., 2006) and the post-Minkowskian models by Kopeikin and Makarov (2006) or Le Poncin-Lafitte et al. (2004).

Moreover, as suggested in the paper by Souchay et al. (2007), a significant number of convenient close encounters between Jupiter and selected quasars and stars can be scheduled, but still with reference to the Gaia mission. This can be utilized in GAME to perform again the experiment made by Kopeikin and Fomalont on 8 September 2002 in order to measure the speed of gravity, related to the gravitational field induced by the motion of Jupiter. Of course the measurements of GAME can also provide, with the same procedure proposed in Souchay et al., a link between the dynamical reference system and the ICRF.

1.2 Other scientific applications

GAME will also be able to provide high precision astrometric and photometric measurements for a number of astrophysical goals, from orbital analysis of known exo-planets, to monitoring of comets and near-Earth asteroids in the most internal part of their orbit. In particular, the subject of mass of planets and brown dwarfs, and that of timing of exo-planet transit by photometric monitoring, is discussed in more detail below. Besides, observations at high angular resolution at few radii from the Sun limb can provide valuable information on transient phenomena in the corona, complementary to the monitoring provided by dedicated solar observing missions. ***The definition of instrument specifications will give the highest priority to the main mission goal, and in case of conflicts the additional science goals will be descoped or discarded.***

1.2.1 Actual / upper limits on masses of massive planets and brown dwarfs

Mass is among the most important physical properties of exo-planets because it is the one parameter that can establish a star's companion as an actual planet rather than a brown dwarf or low-mass star. Our understanding of planet formation and evolution can thus be furthered by comparing model predictions with the observed physical and orbital properties of exo-planets with measured masses. Unfortunately, the most successful technique for detecting candidate exo-planets, the radial-velocity (RV) method, cannot be used to remove the degeneracy between the mass and orbital inclination for most of the known exo-planet candidates.

As an important by-product of its purely differential astrometry, GAME is well-poised to carry out selected measurements of a significant number of nearby ($d < 30$-50 pc), bright ($4 < V < 9$) stars known (through long-term high-precision RV monitoring) to host companions with minimum masses in the planetary/brown dwarf regime, and orbital radii in the 3-7 AU range. These targets are too bright to be observable with Gaia (Casertano, Lattanzi, Sozzetti et al. 2008, and references therein).

The expectation from the error-budget analysis in the bright-magnitude regime is that a typical accuracy of 30-50 μas could be achieved per measurement. For most of these systems, expected minimum astrometric signatures are on the order of a few milli-arcsec (thus the true signal will often be larger, and sometimes much larger).

During the two-year expected mission lifetime, it would be possible to optimally select the times of observations for such systems so that the largest variation along the orbit can be detected. A combined astrometric-spectroscopic orbital solution will then provide the opportunity to fully characterize the orbits, and derive actual companion mass estimates. Even in the case of non-detections, useful upper limits will be placed on the companion masses. The GAME results will thus allow us to improve on the modelling of the actual shape of the mass distribution of massive sub-stellar companions within 5-10 AU, helping to improve on the characterization of the 'brown-dwarf desert' at intermediate separations (radii shorter than 3 AUs and larger than 30-50 AUs having been thoroughly screened by RV and AO imaging surveys, respectively).

1.2.2 Searching for timing variations in transiting exo-planet systems

When extrasolar planets are observed to transit their parent stars, we are granted unprecedented access to their physical properties. Among the host of follow-up studies that can be carried out for transiting systems, the measurement of variations on the order of 0.1 - 100 minutes in the time interval between successive transits affords the opportunity to detect additional planets in the system (not necessarily transiting), via their gravitational interaction with the transiting planet (e.g., Holman & Murray 2005). GAME has the potential to carry out high-cadence (~1 min), high-precision (milli-mag) photometry on a sample brighter than that of

COROT. Depending on transit duration, planet to star radius ratio, and photon count rate, we estimate that GAME could achieve an error on the time of transit centre of a few seconds for a star of V = 11.

A targeted photometric search for transit timing variations in a representative sample of bright transiting systems with GAME would thus be a valuable complement to and significantly extend the time baseline of ground-based spectro-photometric monitoring for these objects, that usually become lower priority targets for this type of studies soon after discovery.

As a minimum by-product of these measurements, important constraints will be put on the existence of additional companions of given mass, period, and eccentricity. If variations are detected, thanks to the flexible scheduling of the satellite's observations it will be possible to re-prioritize the target list to accommodate intensified monitoring of more the most promising ones.

1.3 GAME vs. Gaia

The measurement of γ through astrometric measurements is also a result expected from the Gaia mission, with a photon-limited precision close to the goals of GAME (Vecchiato et al., 2003). In that work, we assumed just an overall envelope of systematic and calibration errors. However, for Gaia γ is just one parameter among the several million astrophysical ones, and the many thousand instrumental ones, derived from the whole set of observations through the five year mission lifetime. In the case of GAME, for similar simulations (Vecchiato et al. 2007), the same result is achieved with about 1.5 months of observations, with nearly simultaneous calibration. The result over the whole mission lifetime can be further improved by averaging down the measurements. *The GAME measurement method is fully differential*, thus reducing significantly the sensitivity to instrument parameters, and the source classification, position and motion are mainly irrelevant. Moreover, Gaia performs its measurements at a minimum distance of 40° from the Sun, where the deflection is at the milli-arcsec level, whereas GAME observations are at ±2° from the Sun, corresponding to ±0.2 arcsec deflection.

Therefore, we expect that GAME results on γ will be more precise, and more reliable, than Gaia's, in spite of the comparable photon limit (in different conditions) quoted in our papers.

2. Implementation Concept

2.1 The GAME Idea

GAME could be implemented by a space mission launched in low Earth orbit on a small class satellite, with a payload based on an optimised telescope observing simultaneously two fields of view with few degree separation, in the visible. The instrument concept is based on a dual field, multiple aperture Fizeau interferometer, with line of sight split and folded simultaneously over two sky regions by a beam combiner with two flat mirrors set at a fixed angle. The measurement sequence requires repeated observation of selected sky regions, in two conditions: (a) with the Sun between the two fields (maximum deflection observed close to the Solar limb), and (b) with a significant displacement of the Sun (minimum deflection).

The Fizeau interferometer is built by aperture masking, with suitable geometry, of a conventional telescope. The diluted optics approach is selected to ease the setup aimed at an efficient rejection of the scattered solar radiation, while retaining a convenient angular resolution on the science targets. The crucial measurement of GAME of the arc between stars is translated into determination of the relative phase of their fringe patterns. The beam combiner implementing the gauge repeatedly set on the sky represents therefore a critical element, which nonetheless does not have to retain a specific selected value, but whose stability has to be ensured with the utmost care. Adoption of a common optical system, thus ensuring that most perturbations act in common mode and are thus most effectively rejected, is a critical contribution to the robustness of the experiment, with respect to disturbance mitigation. Calibration and metrology are the twin factors supporting the measurement goal.

2.2 Telescope Optical Configuration

The telescope optical design does not appear to have critical requirements. Further optimisation is crucial to achieve not only good image quality over the field of view, but also to improve the overall instrument robustness with respect to optical component manufacturing, tolerancing and alignment errors; baffling efficiency; convenient payload allocation in terms of geometry, mass budget, and stability. A set of individual apertures on the pupil of a conventional telescope produces interferometric images. Such approach has been used in past experiments, and has been investigated also by the proposing team both at design and lab test level. ***Each sub-aperture can be individually baffled***, even on the short length available within a reasonable payload envelope. They all contribute to a coherent diffraction image with resolution comparable to the full edge to edge size of the underlying telescope. Conventional alignment techniques ensure the relative phasing of the sub-apertures; therefore, a real time hardware cophasing system is not required. Time evolution of the phase among sub-aperture can be identified by means of an appropriate set of calibration measurements on reference sky regions, and by continuous monitoring of the image profile characteristics.

A preliminary optical configuration of the Ritchey-Chrétien type (Loreggia et al., 2007) has been implemented and analysed with the ray tracing package Code V; the parameters used (individual aperture 40×220 mm, focal length 21 m, aperture diameter 0.66 m) are representative of the GAME design requirements, although not coincident with a flight ready layout and the most current values used in the performance evaluation below. The geometry is shown in Figure 4, and an indication of the image quality through the spot diagrams is shown in Figure 5.

The Fizeau interferometer is derived from the underlying telescope by aperture masking. The set of apertures corresponding to each line of sight (LOS1, LOS2) is shown in Figure 6, where red and green areas are fed respectively by each of the two fields of view in the sky, using a suitable beam combiner. The diffraction limited PSF at λ=650 nm (which can be derived e.g. by the array theorem mostly used for description of diffraction gratings) is shown in Figure 7. The fringe visibility remains above 95% over a field of 7×7 arcminutes, significantly larger than the CCD detector size. The distortion is very low, corresponding to a relative scale variation below 10^{-4}.

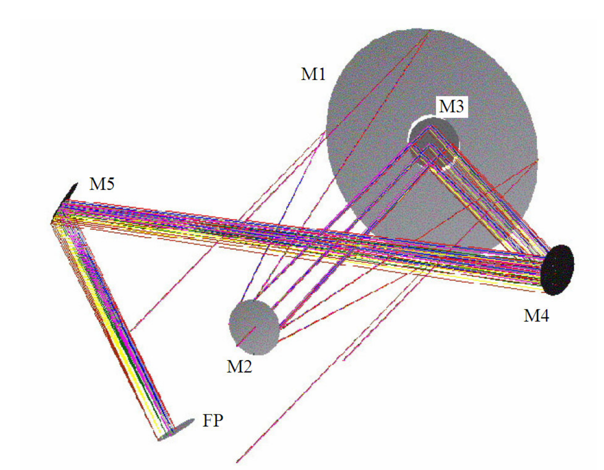

Figure 4 – Preliminary Ritchey-Chrétien optical configuration for optical quality assessment.

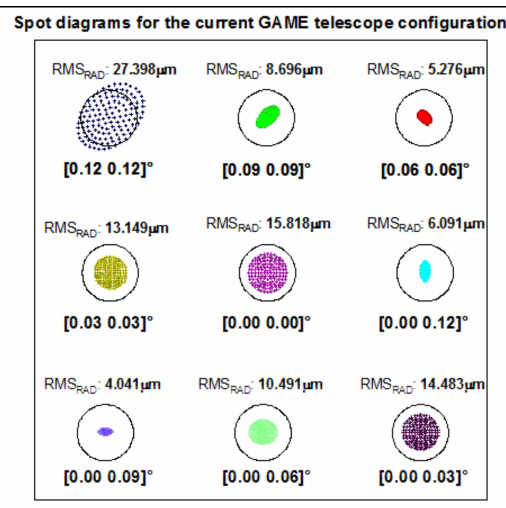

Figure 5 – Spot diagram of the preliminary configuration over a 7×7 arcmin field.

Tests of a representative instrument prototype are planned, both in the lab and on the sky, for validation of the optical configuration on realistic stellar distributions. Observations will be performed close to the full Moon, which generates an high diffused background (although not coincident with the case of the Sun observed from low orbit), for optimisation of some data reduction and calibration procedures.

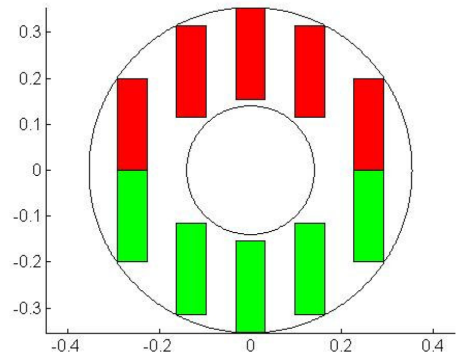

Figure 6 – Pupil mask of the telescope for the Fizeau interferometer; red and green sets observe each one different field on the sky.

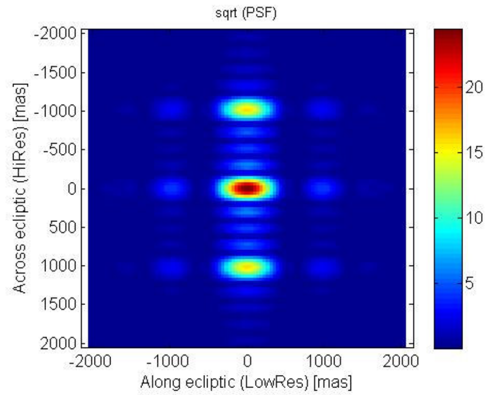

Figure 7 - Monochromatic diffraction limited aperture corresponding to the pupil geometry. Intensity is represented on a square root scale.

2.3 Spectral bandwidth of observation

The spectral band of observation is part of the trade-off for performance optimisation, weighting the opposite requirements of increasing the photometric signal level from sources, and of reducing as far as possible the solar diffused background. The option of a filter wheel is considered, in order to ease calibration and to allow flexibility against possible degradation of real performance with respect to the design case. The baseline assumes a 120 nm spectral bandwidth around the wavelength 650 nm.

Since solar background is expected to decrease at increasing wavelength, the capability of tuning the observing band to the measurement conditions is a potential asset which is not discarded at the current design level. Filter-less, full-bandwidth exposures, if compatible with the background level, would increase the instrument throughput and therefore sensitivity and precision.

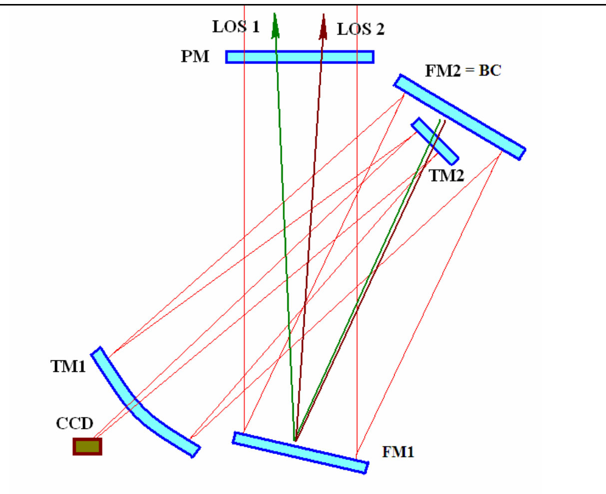

Figure 8 – Optical train representation, flattened in two dimensions; the beam combiner is in front of the primary.

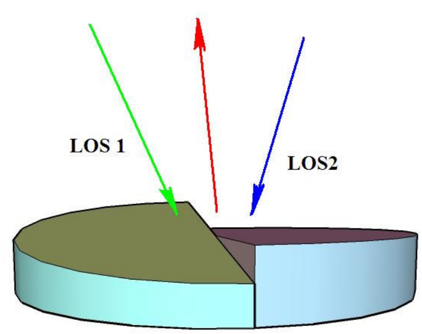

Figure 9 – A possible beam combiner implementation geometry (not to scale). Red and green areas fold the telescope viewing direction each to one field on the sky, with given separation.

2.4 Beam Combiner

The combination on the telescope line of sight of the fields from two directions on the sky is performed by the assembly of a pair of mirrors set at a suitable fixed angle with respect to the observing direction. The optical train, in which only two mirrors (TM1, TM2) represent the telescope optics, is shown in Figure 8; the beam combiner is the first flat folding mirror in front of the telescope primary, whereas the additional folding mirror and the pupil mask are used for the baffling. The beam combiner may be implemented by manufacturing the two relevant surfaces on a common optical mirror blank, to improve the relative stability.

2.5 Baffling

Observing very close to the Sun, high efficiency rejection of solar photons is required. The space mission COROT specifies a rejection factor 10^{-12}, which is already challenging, and GAME requires a further improvement by two-three orders of magnitude. To accommodate such requirement, the beam path from the entrance window to the telescope pupil is increased by folding mirrors, and the additional length is used for shielding of the diffracted and diffused sunlight. Baffling is extremely sensitive to geometry, surface roughness and reflectivity; thus, standard design techniques are affected by comparably large errors, so that lab verification of design geometry and of component quality is mandatory.

The proposed diluted optics solution makes easier the baffling of each individual aperture of the overall Fizeau interferometer. The basic concept is shown in Figure 10: the regions between optical surfaces not used by the beam envelope corresponding to each line of sight are used to host the baffles (geometry details not included).

2.6 Detector

The current design is based on a $2k^2$ CCD with 15 µm square pixels, covering an area of 3.5×3.5 arcminutes on the sky. The optical design is compatible with a 2×2 CCD mosaic, and the parameters can be adapted easily. The flight device may be selected among many existing CCDs, e.g. E2V CCD42-80 (2k×4k, 13.5 µm pixels), or Kodak KAF-09000 (3k×3k, 12 µm pixels). The data rate is reduced by selection of small regions around the brightest stars; taking advantage of a preliminary exposure of each field for pointing verification, the star positions can be identified for windowed readout of the science exposures, thus optimising the noise performance. With respect to tolerance to radiation damage, it can be noted that the operational orbit is sufficiently low to be efficiently protected against a fraction of the ionising radiation by the natural Earth magnetic field; the CCD mosaic is comparably small, so that it can be shielded by an equivalent metal thickness with acceptable impact on the satellite mass budget; finally, observations with a high optical diffused background provide a significant charge density over the device, filling part of the traps and reducing the variation of charge transfer inefficiency.

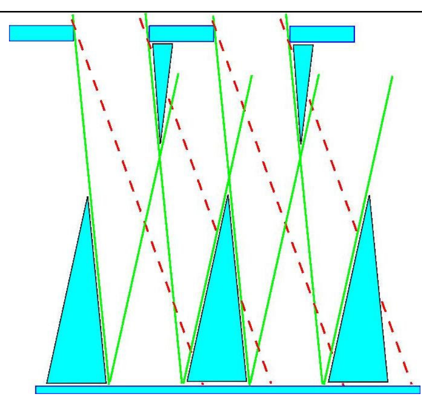

Figure 10 – Baffling concept – a set of directions (solid green) is transmitted among active regions of subsequent mirrors, whereas others (dashed red) are blocked.

Figure 11 – Possible detector for GAME: E2V CCD42-80 back illuminated high performance CCD sensor, 2k×4k, 13.5 µm pixels. Two devices required for the 7×7 arcmin field.

2.7 Astrometric Performance

The precision on the GAME measurable, i.e. the separation between stars in the field, derives from composition of the results from the location process applied on each individual source.

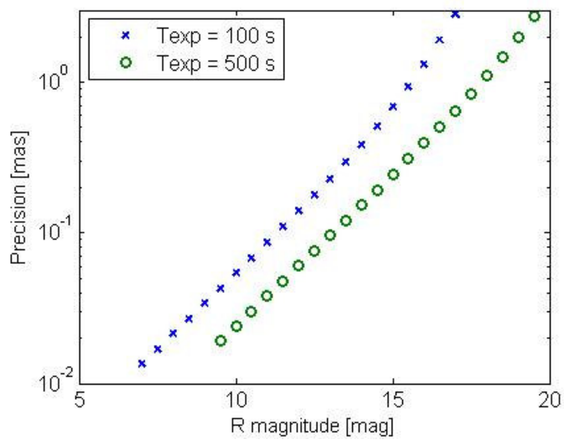

Figure 12 – Astrometric precision on an individual unresolved source, as a function of the source magnitude. Case 1 (crosses): near-Sun observation, with higher diffused background; Case 2 (circles): 20° away from the Sun, lower background, longer exposures feasible for some scientific applications.

The location estimate of an unresolved source image can be derived e.g. by least square methods (Gai et al. 1998, Gai et al. 2001), taking advantage of the peculiar signal distribution (Figure 7). The performance vs. source magnitude has been derived in a band centred on λ_0=650 nm, with FWHM $\cong$ 120 nm, considering a diffused background corresponding to 15.5 mag and 19.75 mag per square arcsecond, respectively with an exposure time of 100 s and 500 s, and the elementary measurement precision is shown in Figure 12. The former case corresponds to expected background level close to the Sun, whereas the latter refers to measurements at a significant angular separation with respect to the Sun, e.g. for calibration or low deflection condition. The longer exposure time is considered for the additional science cases (e.g. deflection close to Jupiter's limb). For the detector, the quantum efficiency considered is 70%. Even with the shorter exposure time, the precision is below 1 mas for sources brighter than magnitude 15.5, and the photon limit scales with magnitude below 0.1 mas for sources brighter than 11 mag.

Simulations (Vecchiato et al. 2006) show that, using the average star counts from the GSCII catalogue, and assuming that all stars down to 16 mag are observed on the Sun path along the ecliptic, for a period of 20 days, the achievable precision on γ is 3×10^{-6}. Longer observing sequences, set in high stellar density regions, will further improve the precision to the 10^{-7} level. Accuracy must be guaranteed by calibration, monitoring the possible evolution of the optical scale and of the base angle throughout the observations.

2.7 Metrology

The base angle is used to set a known offset between the two fields simultaneously observed by GAME. Its variation is, in principle, indistinguishable from the goal measurable of image displacement induced by the gravitational deflection. The possible sources of noise are from dimensional variation of the optical device implementing the beam combiner, or changes in the optical aberrations of the telescope acting in differential way over the two sets of beams from the two fields. The latter can, to some extent, be identified by monitoring of the signal profile for each arm, since aberrations change the phase relationship among the sub-apertures as well as that between the two fields. On the contrary, the former can only be identified by external measurements, taking advantage of a physical reference. The base angle of GAME must be either intrinsically stable or known by measurement, in the period including elementary deflection and calibration measurements, to a level compatible with the astrometric noise on bright stars, i.e. 10 μarcsec, corresponding to about 50 prad.

Suitable calibration on the sky will be included in the observing sequence, e.g. on regions with constantly low deflection and bright sources, but the effectiveness of such technique resorts on measurements faster than the expected typical rate of variation of the base angle. Besides, a metrology sub-system in the payload may provide a robust, independent constraint to the stellar measurements. The project will address the feasibility, cost and implications of development of a flight ready metrology system, to be considered for the subsequent proposal for implementation of GAME. *The GAME metrology study and the lab demonstration will be performed by the colleagues in the National Institute for Metrology Research (INRIM, Turin, Italy), included in the INAF-OATo team for efficiency of project management.*

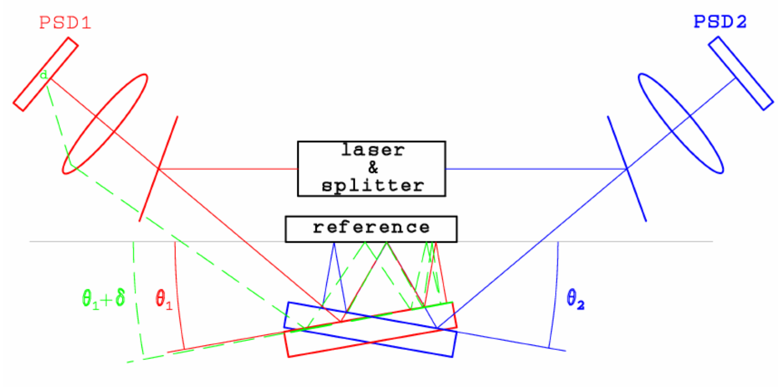

Figure 13 – Metrology concept. Multiple reflections between a common reference optical surface and each of the two monitored flat mirrors are used to amplify the displacement associated to the base angle variations.

The proposed laboratory experiment, concept shown in Figure 13, uses a reference flat surface (optical quality $\lambda/20$) facing the two mirror assembly representative of the beam combiner.

A fibred laser beam is split in two equal intensity components, each sent to one of the mirrors. The multiple reflections on the common reference surface amplify the tilt angle generating a different beam path, then projected on a Position Sensitive Device. Common mode displacements are rejected, and the zero position is set at the nominal (or initial) position. The desired base angle variation measurement is associated to the differential beam displacement. An intrinsic resolution better than 1 nrad has been demonstrated in a previous experiment (Pisani and Astrua, 2006), and extrapolation to the desired 50 prad precision, with appropriate design of the optical configuration, seems to be challenging but feasible.

A detailed analysis of the in-flight configuration, and metrology lab tests on optical devices representative of the beam combiner, are fundamental to identify the expected stability level and therefore the requirements of astronomical calibration. In turn, this will allow optimisation of the overall observing strategy of GAME, including the calibration frequency.

2.8 Mission Profile

The orbital elevation is subject to a trade-off between low (easing launcher and telemetry requirements) and high values (lower sensitivity to Earth gravity and irradiation and above all lower air drag). The option of a polar, Sun-synchronous orbit with proper inclination increases the visibility of the desired fields around the Sun, and an elevation above 1500 km avoids eclipses. Thus, observing time is maximised and stable solar power and thermal environment are ensured. The Vega launcher may insert into such orbit a load of order of 100 kg. A preliminary satellite definition based on a previous spacecraft, adapted for allocation of the GAME payload, provides a compatible mass budget, with margins. A representation of the GAME satellite, respectively stowed into the launcher fairing and deployed for operation, is shown in Figures 14 and 15. The estimated telemetry rate (average 256 kbps) is compatible with a single ground station (Fucino or Kiruna).

This assessment has been provided by Thales Alenia Space (TAS-I, Turin, Italy) for a quotation of an industrial mission study contract, including mission profile analysis, satellite and payload preliminary design; in particular, space engineering expertise is required for a realistic instrument design, including optical, thermal and structural analysis. The opto-mechanical model will be adapted for tests on sky at INAF-OATO.

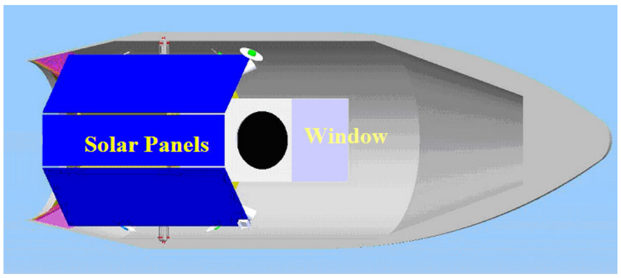

Figure 14 – Representation of the GAME satellite stowed in the Vega launcher fairing.

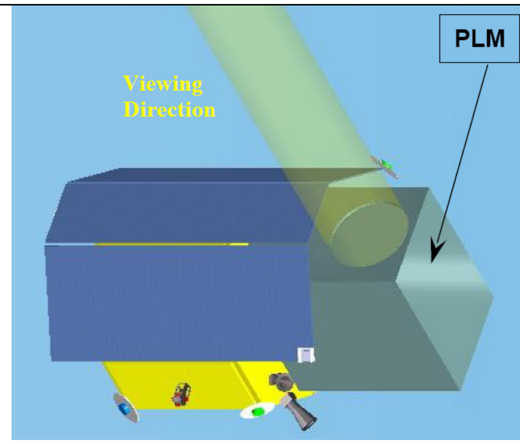

Figure 15 – GAME deployed for operation.

2.9 Dissemination and collaborations

The scientific and technological results will be presented to international conferences and published in the appropriate forms for maximum dissemination, including the preparation of a public web site containing the project related information, with possible exceptions concerning industry sensitive data where appropriate.

Expressions of interest have been received from Italian universities, and a collaboration with the Shanghai Observatory (Shanghai, China) is under definition, following the presentation of the GAME concept at the IAU Symposium 248.

2.10 Development Plan

The science case verification will address the known physical limitations of the space environment with respect to the proposed experiment, including the contributors to noise on the photon propagation and to local space-time curvature (e.g. quadrupole). Also, the additional science goals will be investigated, evaluating the performance of GAME and the observation requirements. The science case will be used to define the baseline operation, i.e. observing and calibration strategy, detector requirements, and expected data rate.

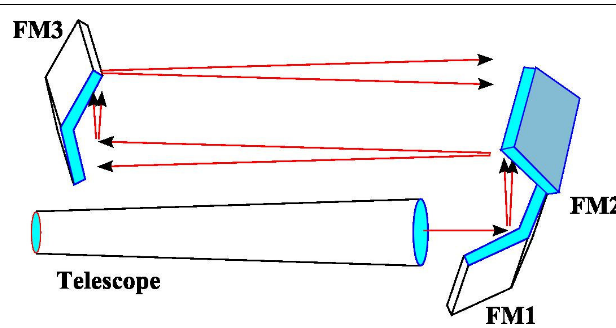

Figure 16 – Concept of validation of GAME operating principle by a mock-up with a small telescope observing close to the Moon's limb. The mock-up will be replaced in a subsequent stage by the opto-mechanical model of GAME delivered by TAS-I.

The optical configuration will be optimised by design, with a trade-off among collecting area, field of view, optical quality, payload allocation, stability and mass budget. A representative prototype will be implemented in the lab to verify the consistence with the design predictions, and used for observations on the sky to optimise observing and data reduction strategies. Pointing close to the Lunar limb provides realistic constraints on geometry and stellar fluxes, and also a diffused background with acceptable level, albeit variable and not exactly equivalent to the Solar one. The test instrument concept is shown in Figure 16.

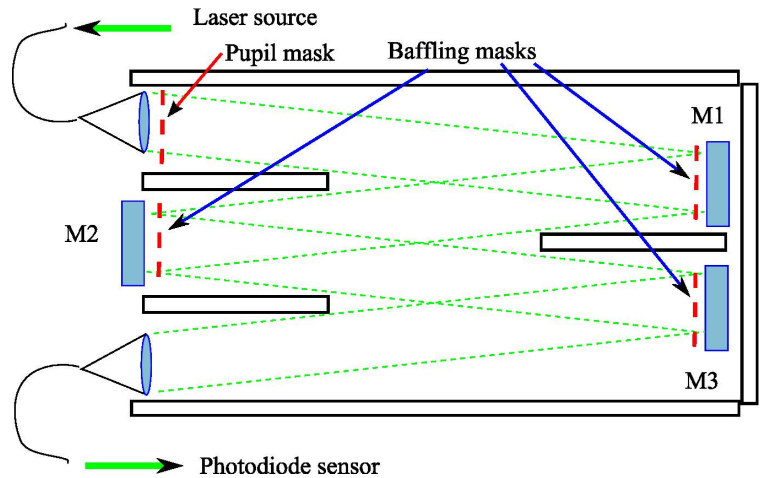

Figure 17 – Concept of a lab setup for measurement of photon diffusion for test of component geometry and surface characteristics, aimed at optimisation of the baffling design.

The baffling development plan is based on careful analysis according to guidelines from similar instruments; lab tests of photon scattering on reference cases of geometry and surface finishing; definition and analysis of a preliminary implementation design. In Figure 17 a conceptual setup for the planned tests on photon diffusion and baffling component is shown. Several tests can be performed on INAF-OATO's premises for optimisation of baffling geometry and comparison of materials; however, quantitative assessment of straylight and definition of strict design specifications of the flight instrument require the space optics characterisation facility OPSYS of INAF-OATO installed at a nearby space industry, Altec (Turin, Italy), supported by their engineering expertise. An industrial contract to Altec is included in this research proposal, for integration of the test setup into OPSYS, and for Altec support to the tests and the flight instrument design.

The metrology verification will proceed by design analysis of the payload and lab test of the stability of a device representative of the GAME beam combiner. Also, it will define the feasibility and development plan for a flight ready metrology system.

The results on operation, optical configuration, baffling and metrology will be used for a preliminary definition of the GAME satellite, including spacecraft and payload, defining the feasibility and the development plan for implementation.

3. Activity breakdown

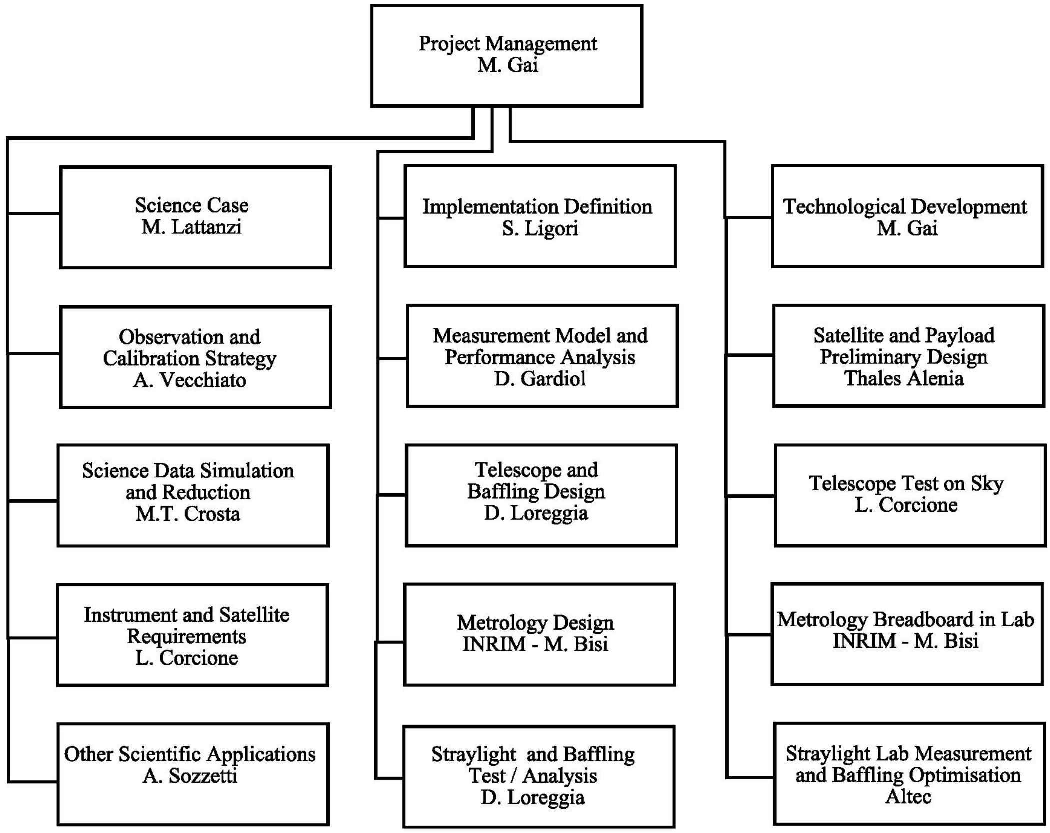

Figure 18 – Activity breakdown of the research project.

4 References

Bertotti B., Iess L., Tortora P. - A test of general relativity using radio links with the Cassini spacecraft
Nature 425, 374 (2003)

Capozziello S.; Troisi A. - Parametrized post-Newtonian limit of fourth order gravity inspired by scalar-tensor gravity
2005, Physical Review D, vol. 72, Issue 4, id. 044022

Crosta M.T.; Mignard F. - Micro-arcsecond light bending by Jupiter
2006, Class. Quantum grav., 23, 4853

De Felice, F., Vecchiato A., Crosta MT. , Lattanzi MG, Bucciarelli B.
ApJ, 653, 1552-1565 (2006)

Fomalont E.B., Kopeikin S.
ApJ, 598, 704 (2003)

Gai M., Casertano S., Carollo D., Lattanzi M.G. - Location estimators for interferometric fringes
Publ. Astron. Soc. Pac., 110, 848-862 (1998).

Gai M., Carollo D., Delbò M., Lattanzi M.G., Massone G., Bertinetto F., Mana G., Cesare S. - Location accuracy limitations for CCD cameras
A&A 367, 362-370 (2001)

Holman M.J., Murray N.W. - The Use of Transit Timing to Detect Terrestrial-Mass Extrasolar Planets
Science, 307, 1288 (2005)

Kopeikin S., Makarov V. - Gravitational bending of light by planetary multipoles and its measurement with microarcsecond astronomical interferometers
Phys. Rev. D 75, 062002 (2007)

Le Poncin-Lafitte C., Linet B., Teyssandier P.
Class. Quant. Gravity, 21, 18, 4463 (2004)

Loreggia D., Gai M., Vecchiato A., Lattanzi M.G., Gardiol D. - Design of a high precision, compact astrometric instrument for the GAME Mission
Proc. IAU Symp. 248, Shanghai (China), Oct 15-19, 2007, eds. Jin W.-J., Platais I. & Perryman M., in press

Pisani M., Astrua M. - Angle amplification for nanoradian measurements
Appl. Opt. 45, pp. 1725-1729 (2006)

Souchay J., Le Poncin-Lafitte C., Andrei A. H. - Close approaches between Jupiter and quasars with possible application to the scheduled GAIA mission
A&A 471, 335–343 (2007)

Vecchiato A., Lattanzi M.G., Bucciarelli B., Crosta M., De Felice F., Gai M. - Testing General Relativity by Micro-arcsecond Global Astrometry
A&A 399, 337-342 (2003)

Vecchiato A., Gai M., Lattanzi M.G., Morbidelli R. - Measurement of the PPN-\gamma parameter with a space-born Dyson-Eddington-like experiment
Proc. of the Eleventh Marcel Grossmann Meeting, Berlin, July 23 - 29, 2006, in press.

Vecchiato A., Lattanzi M.G., Gai M., Morbidelli R. - A spaceborn Dyson-Eddington-like Experiment for the astrometric measurement of the PPN gamma parameter
Proc. IAU Symp. 248, Shanghai (China), Oct 15-19, 2007, eds. Jin W.-J., Platais I. & Perryman M., in press

Will C.M. – The confrontation between General Relativity and experiment
Living Rev. Relativity, 9, 3 (2006). URL (cited on 20/02/2008): http://www.livingreviews.org/lrr-2006-3

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