GAIA FEASIBILITY: CURRENT RESEARCH ON CRITICAL ASPECTS

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ABSTRACT

ESA is supporting an industrial study aimed at preliminary assessment of some critical aspects of the GAIA mission implementation: hereafter, our study approach is presented. The Fizeau interferometer of GAIA features a strict correlation between the conventional telescope and interferometer concepts and problems. The wide angle measurement concept is based on the stability of the basic angle between two macroscopic structures: the implementation is challenging. An experiment will address feasibility and performance of metrology at sub-nanometer level, over 0.5 m distance, controlling displacement and relative orientation ('tip-tilt') of two platforms, simulating optical elements of GAIA. System definition is based on the scientific rationales of GAIA; however, trade-off among competing requirements, if needed, should neither descope the mission nor push any critical parameter to its limiting values. Most of the critical aspects which arose in the Cambridge 1995 workshop on GAIA are being addressed, and some viable solutions seem to be taking shape: microarcsecond global astrometry is becoming closer to implementation.

Key words: GAIA; interferometry; laser metrology; optics; detectors.

INTRODUCTION

The GAIA mission concept is described in other contributions to this Symposium, and in literature (Lindegren & Perryman 1994, Lindegren & Perryman 1996). Although the scientific possibilities of GAIA are extremely appealing, the implementation problems are very challenging, as discussed in detail in the joint RGO-ESA Workshop held in Cambridge (van Leeuwen & Perryman 1995), in which several critical issues were underlined: (a) optical configuration performance and feasibility, including residual aberrations calibration; (b) opto-mechanical tolerancing for interferometric performance (coherence, cophasing); (c) stability of three interferometers to 10-20 μas during a single scan (for every significant degree of freedom); (d) availability of detectors suitable to Direct Fringe Detection (small pixel size, increased effective focal length); (e) requirements of very low structure distortion and attitude disturbance for the whole interferometer; (f) on-board data processing for compression (telemetry) and system control.

We recall that an angle of 10-20 μas, as from the system accuracy requirements, projected over the $\sim$3 m typical mirror distance, defines an upper limit to linear displacement of the optical components of 150-300 pm, to be preserved over more than 3 hours. More detailed optical design analysis confirmed, as described hereafter, the 20-100 pm range of critical opto-mechanical tolerances.

In order to sustain the required technological development, ESA issued two Invitations To Tender on Active Pointing of Large Telescopes (APLT) and Attitude Measurement Transfer System (AMTS), awarded to a proposal led by Alenia Spazio (Prime Contractor). The study team involves both industrial partners and scientific institutes; the former group is composed by Alenia Spazio, EICAS Automazione, Aerospatiale and Matra Marconi, whereas the latter includes the Osservatorio Astronomico di Torino (OATo) and the Istituto Metrologico 'G. Colonnetti' (IMGC) of the Italian National Research Council (CNR).

Several of the critical aspects from the Cambridge workshop have been included in the study plan: (a) review of the GAIA mission requirements; (b) analysis of performance, tolerancing, and feasibility for current and alternative optical designs; (c) revision of the direct fringe detection option; (d) review of current relevant technologies and analysis of possible solution concepts; (e) tests on sub-nm metrology over 0.5 m distance; (f) preliminary definition of structural configuration, orbit, AMCS and satellite accomodation into launcher.

One of the most relevant parts of our work is the laboratory test of Laser metrology, on an intermediate scale between current laboratory results and the GAIA requirements, will be tested by an experiment in preparation; this will also verify the performance of mechanical analysis and simulation packages, whose accuracy on atomic scale is to be assessed.

The optical configuration is under development, because the basic requirement for fringe imaging is a longer effective focal length, in order to support direct fringe detection over reasonable size devices. Two configuration have been identified, providing the required wide field of view and parameters suitable to DFD and accomodation into the launcher, with a realistic supporting structure.

Attitude measurement and control requirements seem to be compatible with current technologies, requiring small upgrades of Hipparcos-like solutions.

Since the final error is $\sim 10\ \mu$as, the requirement on the individual measures is about one order of magnitude more stringent, ranging between 10 pm and 100 pm. For comparison, the component mechanical variations due to ageing, outgassing and thermal gradients, are expected to be in the range 10 μm–1 mm; even in Hipparcos, a much more compact instrument, the grid regulation for focusing used a 100 μm range along its lifetime.

A purely passive approach does not seem to be sufficient to meet the stability requirements of GAIA; at least accurate measure of a large number of parameters is required, and most likely a complex, high accuracy control system is called for.

1. A SYSTEM APPROACH

The GAIA concept, based on 3 interferometric units, with wide angle observations provided by correlation between pairs of interferometers, involves serious implementation problems, in spite of its simplicity. As for the case of Hipparcos, global measures on a scanning satellite require a deep design interaction between the instrument and its carrier, concerning both configuration and operations. Therefore, a 'system view', taking into account the relevance of each parameter with respect to the mission goals, and their mutual interaction, is required, in order to achieve a feasible design.

For example, the transverse size of the field of view and the precession angle between subsequent great circles are linked by the need of providing sufficient superposition along all of the two sky strips scanned, in order to achieve sufficient closure conditions; besides, precession angle and spin rate together must provide full-sky coverage over few weeks, in order to provide the several measures per year (in different directions) required by the parallaxes. Further on, spin rate defines the detectors read-out rate. Therefore, a smaller field reduces the logical format of the focal plane assembly, but it requires a smaller precession angle: this, in turn, asks for faster spin rate (because reducing the precession rate would yield less observations), resulting in a reduced exposure time per passage (decreasing the astrometric accuracy) and more stringent requirements on the readout electronics speed.

Concerning the optical configuration, the base angle stability issue is critical; besides, in the baseline design, the operational description of such quantity is complex, since it is the angle on the sky between the two lines of sight of distinct interferometric units. The line of sight, considered as coincident with the optical axis, i.e. the axis of symmetry of the optical configuration, is defined by the tridimensional position of all of the optical elements involved, 6 in the baseline configuration; in principle, all rotational and translational movements must be considered, resulting in 36 degrees of freedom per each interferometric unit (still neglecting the focal plane assembly). The measure of the base angle is thus based on measuring 72 quantities, from two stacked interferometers, with respect to a common reference mechanical frame, and merging them by the complex expressions defining their relative geometry.

2. OPTICAL CONFIGURATION

Direct fringe detection, in the baseline configuration, seemed to be extremely difficult to implement because of the very large gap between the geometry of available CCD pixels and the optical scale. Assuming to sample the Young fringe period ($\lambda/B = 46$ mas at $\lambda_{\rm eff} = 550$ nm) over 4 pixels, the focal length of 11.5 m required vertical size of about 0.6 μm, about one order of magnitude below known commercial devices.

Reports on CCD prototyping with pixel size in the range 2–3 μm have been provided by some manufacturer (Philips, private communication), and ongoing simulations show that a reasonable performance penalty is involved in sampling the fringe period over about 3 pixels. Therefore, the feasibility of direct fringe detection is strictly related to the definition of an optical design with effective focal lenght in the range 25–30 m.

Two configurations featuring such extended focal lenght and a reasonably large coherent field of view have been identified: the former, proposed by OATo, is a 4 mirrors/4 reflections scheme similar to the baseline design, whereas the later, proposed by Aerospatiale, is a Korsch configuration. An opto-mechanical analysis, including mechanical toleracing, of the baseline and 4 mirrors/4 reflections configurations have been presented in this Symposium (Cecconi et al. 1997, Cecconi et al. 1997).

A distinction is due, here, between the interferometer and telescope constraints. For Michelson type interferometers, the key performance figure is visibility; the GAIA instrument requires visibility only to take advantage of the superior resolution of the interferometer, but its main requirement is the stability of the mapping between focal plane and sky coordinates. Whichever the configuration, the mapping must be preserved, in order to allow global position determination by great circle solution. This defines constraints on the optical component degrees of freedom, since any optics perturbation introduces distortions, which can be solved in data reduction only if they are stable along the whole scan period, preserving the closure conditions. An interferometer features more degrees of freedom than the underlying telescope: for example, the individual primary mirrors can suffer a tilt either corresponding to a monolithic movement (i.e. correlated), or independent, with one of them tilted with respect to an arbitrary vertex (e.g. its centre or its edge), and the other unperturbed. Independent mirror perturbations must be explicitly evaluated and it can be shown that they provide relevant distortion, comparable with the monolithic degrees of fredoms, or larger.

The interferometric conditions on the Optical Path Difference (coherence, OPD ¡¡ $\lambda^2/\Delta\lambda$, and cophasing, OPD ¡¡ λ/n, n = 60–100) result in comparably relaxed requirements, of the order of 10–50 nm (still challenging from an engineering point of view, with respect to ageing and thermal gradients).

The focal plane/sky mapping stability conditions, however, impose opto-mechanical constraints evaluated in current optical analysis of the baseline configuration (Cecconi et al. 1997, Cecconi et al. 1997) and of some of the parameters of the two long-focal configurations, providing constraints on the mechanical position and orientation of the mirrors of 20–100 pm. The proposed configurations are roughly equivalent in performance: both have baseline $B \simeq 2.5$ m, aperture $D \simeq 0.6$ m, large effective focal lenght – $F = 25$ m (OATo) and $F = 30$ m (Aerospatiale)–, and a coherent field of view diameter $> 1°$. Optical configuration selection requires further in-depth analysis and trade-off.

3. FOCAL PLANE AND DETECTION SYSTEM

Current simulations provide acceptable accuracy of the location process for sampling resolution of the order of 3 pixels per fringe period; this, together with the increased effective focal length of the optical configurations under development, results in pixel size requirements of the order of $2 - 3$ μm, which are within a factor 2 from commercial devices. The across scan pixel size can be as large as 70 μm, since the Airy disk does not require to be resolved, in the simplest detection schemes.

Private communications from CCD manufacturers (Philips) are encouraging with respect to the feasibility of large area CCDs with the required high resolution. The problem still to be assessed is the improvement of the quantum efficiency, which at the moment seems to be potentially limited to rather low values, ~ 20 per cent.

A field of view of $\sim 0.8°$ per side, with the new configurations, will occupy 40-45 cm, with a logical format of the order of 7000×180.000 pixels. The field of view actually covered by a scan is defined only by the across scan size of the focal plane assembly; the along scan dimension, fixed the scan speed ($V_s = 10$ arcsec/s on a $T_r = 3$ hours period), provides the on-target exposure time per passage, in this case 24 s. We recall that this value can not be used directly for evaluation of the limiting magnitude: the elementary integration for each object has been assumed to be limited to about 0.2 s, therefore the whole passage provides about 120 independent measures. This limitation is due to system reasons: the integration time must be small with respect to the period of typical system disturbances (e.g. jitter), which are expected to take place on the time scale of 1 s. Moreover, since the optical system suffers distortion and residual aberration, the exposure must be limited to comparably small regions, with small local variation of the focal plane to sky mapping.

In this framework, and assuming read-out and electronic noise comparable with current state-of-the-art scientific instrumentation, essentially photon-limited performance is achieved up to magnitude $V \sim 16$; in case satellite and structure stability, on one side, and optical quality, on the other side, will allow for longer integration time, corresponding improvements on the faint limiting magnitude would be achieved. Extending the elementary exposure time to about 2 s, photon-limited accuracy up to magnitude $V \sim 18$ should be attainable.

4. MULTIDIMENSIONAL CONTROL PROBLEMS

As from the Hipparcos experience, global astrometry measurement based on a scanning instrument, with a large field of view, requires stability of the mathematical transformation linking each point on the focal plane to a corresponding direction on the sky. If the parameter variation is sufficiently 'smooth' (i.e. slow versus the scan period and small in amplitude), then the mapping can be calibrated to remove systematic errors from the data. This corresponds to an instrument *stiffness* requirement, to be achieved by passive and/or active means.

The relevant perturbations can be identified by their frequency range:

high frequency noise (> 5 Hz) is mainly due to satellite jitter and optical system vibrations, providing random fluctuation of the shape and position of the istantaneous image with respect to the expected values during the integration; the global effect is a reduction of the fringe contrast, i.e. of visibility, but the photo-center position is not modified significantly. For limited visibility degradation, the location process efficiency is not severely compromised; the single measure accuracy suffers acceptable degradation up to several milliarcsec cumulative perturbation effects.

very low frequency instrument parameter variations, acting on a time scale slower than the 3 hour scan period, are generated by long-term structure settling, ageing, outgassing, and other effects. They can be modelled and estimated from the data on ground, from the data, taking advantage of the closure conditions. The configuration variations require control to preserve the instrument optical quality; the variations, including launch stress, can reach the millimetric range, and the required resolution is of the order of a few nm.

Intermediate frequency disturbances deserve in-depth study, because of the several sources and of the potentially dangerous systematic errors accumulated on the data. They come from the thermo-elastic properties of the materials and structures, or from attitude perturbations; the effects can be reduced by statistics in the higher frequency range, as for noise acting during the elementary exposure, or estimated by modelling on several time scales. In principle, these perturbations must be either measured or controlled to within the mission accuracy limits, providing the most stringent requirements.

The measurement concept, as described below, will rely on laser interferometers monitoring the mirror-to-mirror displacement; either absolute or relative measure will be implemented, because actual ranging can be useful for initial and periodic alignment and cophasing operations, but several parameters (as the baseline) do not need actual tuning to a specific value, but only stabilization within given accuracy to an unknown value, which will be derived during data reduction. Two distinct actuation concepts are under evaluation: displacement of optical components with respect to the supporting structure; and mirror-to-mirror connection by means of *active struts* featuring, by design, the required visco-elastic properties in the operating temperature range.

In the former case, the component controls interact with each other in a complex and non-linear way, through the supporting structure, although mutual interaction could be reduced by reaction balance; this, in turn, would add to the mass and power budget because of the extra mechanisms. Besides, active struts, which would simplify the control problem by *implicit* stability of several critical distances, and provide a stiff, lightweight instrument truss by integration with conventional passive struts, are to be fully investigated. In both cases, the actuators of choice are piezo-translators.

A critical study task is a laboratory experiment addressing feasibility and performance of sub-nm metrology. The objective of a metrological system on GAIA is both measure and control, which can not be separated on this scale, of the optical component spacing to within 100 pm over distances of a few meters. Laser interferometry seems to be the only measurement technology potentially providing such performance.

However, in order to actually achieve the required resolution, every environmental disturbance must be suppressed or reduced to a minimum. Therefore, the testbed plates will be placed in a vacuum vessel, resting on a table supported by three pneumatic isolators, because thermal and acoustic effects would change the local refraction index, and consequently inducing variations of the optical path, from DC to hundreds of Hz, leading to unacceptable and uncontrolled measure degradation (Figure 1).

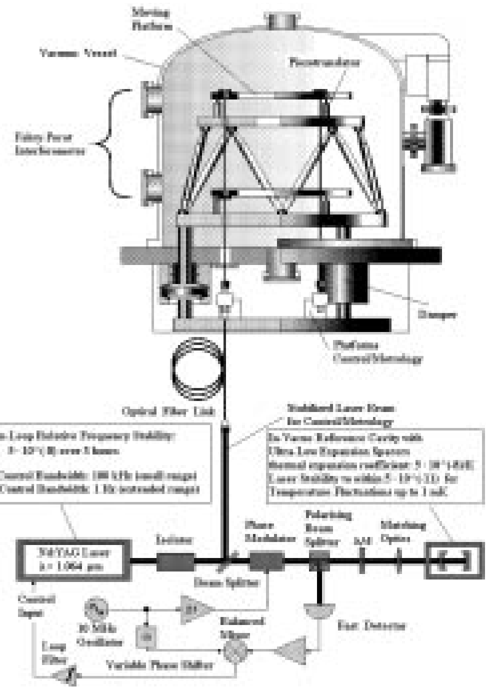

Figure 1. The metrology testbed layout.

CONCLUSIONS

Although the technological requirements of GAIA are very challenging, just as its scientific yield promises to be impressive, they do not seem to be beyond reach of appropriate development in the next few years. The studies currently in progress are focused on several critical aspects, and the chances of identifying viable system solutions seem to be reasonably good. Development is still required on optical configurations, detection system, metrology, structure and operations; however, at the moment, none of them constitutes an apparently impossible obstacle. GAIA appears to be technically within reach.

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