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Gravitational astrometry from within the solar system

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Mission like Gaia (ESA, launched in 2013) requires to treat gravity properly when compiling microsecond stellar catalogues. This will open the opportunity to put in practice methods of Relativistic Astrometry mainly devoted to model the celestial sphere with the percepts of General Relativity (GR) and promotes the use of highly accurate astrometry to test locally fundamental physics. Gaia will be able to carry out general relativistic tests by means of both global and differential astrometric measurements. Global tests will be done through the full astrometric reconstruction of the celestial sphere, while the differential experiments will be implemented in the form of repeated Eddington-like measurements. After one century, Gaia will perform the largest experiment in GR ever made with astrometric methods (since 1919): a relativistic all-sky reconstruction which includes also QSO at different redshifts. Moreover, at zero redshift, dealing with local cosmology, accurate absolute motions of stars within our Galaxy will provide tests on current cosmological models via the detections of cosmological signatures in the disk and halo.

Keywords: General relativity (GR); solar system; GR measurements in weak gravitational fields; fundamental physics; relativistic astrometry.

1. Introduction

The extraordinary advancement in astronomical observations and instrumentation brought about by space mission requires coding light propagation at an unprecedented level of precision, whenever the accuracy of the measurements are comparable to the curvature due to the gravity source background geometry. As far as a Gaia-like mission is concerned, this implies a relativistic rendition of the astronomical observables and it may open a new detection window of many subtle relativistic effects naturally enfolded in the light while it propagates through the geometry of space-time up to the local observer.

The "observer" is a fundamental ingredient in any definition of the measurement process, especially when one considers the theory of General Relativity. In this regard a Relativistic Astrometric MODel (RAMOD) has been conceived and developed (Crosta et al., Ref. 1 and references therein) providing a fully general-relativistic analysis of the inverse ray-tracing problem, from the observational data back to the position of the light-emitting star.

In the case of Gaia, the satellite acts as a celestial compass, measuring arcs among stars with the main goal to construct a three-dimensional map of the Milky Way and unravel its structure, dynamics, and evolutional history. This task is accomplished through a complete census, to a given brightness limit, of about one billion individual stellar objects. Gaia performs simultaneous observations of large angles then it observes at the same time two different star light directions. Gaia will not point at individual specific objects, but it will scan for at least 5 years repeatedly the sky observing all objects that will pass away in its two fields of view.

Since a Gaia-like observer is positioned inside the Solar System, the measurements are performed in a weak gravitational regime which can be regarded as "strong" when one has to be properly taken into account the measurement protocol in General Relativity, i.e. RAMOD.

2. The RAMOD tool

RAMOD stands originally for Relativistic Astrometric MODel, conceived to solve the inverse ray-tracing problem in a general relativistic framework not constrained by a priori approximation. RAMOD is, actually, a family of models of increasing intrinsic accuracy all based on the geometry of curved manifolds where light propagation is expressed in a general relativistic context, not necessarily applied only to astrometry.

RAMOD uses a 3+1 description of space-time in order to measure physical effects along the proper time and in the rest-space of a set of fiducial observers according to the measurement protocol (see de Felice and Bini, Ref. 2, and Crosta et al.'s contribution in session PT2 of MG14).

The main procedure of the RAMOD approach is to express the null geodesic in terms of the physical quantities which enter the process of measurement, in order to entangle the entire light trajectory with the background geometry to the required approximations. The main unknown is the observed direction as projected on the rest space of the local barycentric observer and represents *locally* what the observer measures of the incoming photons in his/her gravitational environment. This aspect transforms the geodesic equation into a set of nonlinear coupled differential equations which comprises also that for the time component. The first integration of RAMOD equations gives the estimates of the deflection effects (Crosta et al., Ref. 1); in the astrometric case these quantities are needed to solve the astrometric problem, namely the sphere reconstruction by the cosine of the observed angle between the local light direction and the spatial axes of the observer's tetrad (a relativistic tetrad solution suitable for Gaia is published in Bini et al., Ref. 3). The second integration solves the ray tracing for the photon emitted by a star and intercepted at the observer's location, thus obtaining the four spatial-distance at the different approximation levels. This quantity is needed, for example, to address the problem of a relativistic consistent astrometric parameters, including also the definition of a proper distance.

The RAMOD analytical solutions based upon a measurement protocol for the light trajectory naturally include, in a curved space-time, all the individual effects; the latters are somewhat hidden in the covariant formalism of such an approach. Finally, the solution should be adapted to the relevant IAU resolutions considered in the Solar System.

3. The Gaia case, the dawn of Gravitational Astrometry

There exist different ways to model an astronomical observable in the context of weak gravitational regime in GR (Ref. 4, Ref. 5, Ref. 6). Their availability is needed in order to consolidate the future experimental results, especially if one needs to implement gravitational source velocities and retarded time effects in the Solar System. From the experimental point of view, in fact, relativistic astrometry opens a largely unknown territory (Ref. 7). Moreover, high-precision measurements, which demand suitable relativistic modeling, need to be validated. In this regard, it is of capital importance to allow the existences of different and cross-checked models which exploit different solutions to interpret the same experimental data. For the reason above, inside the Consortium constituted for the Gaia data reduction (Gaia CU3, Core Processing, DPAC), two models were considered: i) GREM (Gaia RElativistic Model, Ref. 4) baselined for the Astrometric Global Iterative Solution for Gaia (AGIS), and ii) RAMOD implemented in the Global Sphere Reconstruction (GSR, Ref. 8) of the Astrometric Verification Unit at the Italian data center (DPCT, Ref. 9, the only center, together with the DPC of Madrid, able to perform the calibration of positions, parallaxes and proper motions of the Gaia data). Since both models are used for the Gaia data reduction, any inconsistency in the relativistic model(s) would invalidate the quality and reliability of the estimates, indeed all the relevant scientific outputs. Indeed, the main Solar System curvature perturbation amounts approximately to 100 micro-arsecond, which will cause the individual parallaxes to fast degrade beyond 1 kpc, while completely invalidating the most accurate calibration of, e.g., the primary distance calibrators. This alone is sufficient reason for making a theoretical comparison of the existing approaches a necessity and set the scientific case for further developments and applications.

By providing an homogenous all-sky survey of high precision parallaxes, space motion (proper motions and radial velocities) and astrophysical characterization for more than one billion stars throughout the Galaxy and thanks to the depth of the volume achievable, Gaia will deliver a huge amount of astrometric, spectroscopic, and photometric data. Gaia will contribute also to the determination of an optical reference frame by observing many thousands of quasars. In doing so Gaia will have a huge impact across many fields, including many branches of stellar astrophysics (details of the structure and stellar evolutionary phases), exoplanets, solar system objects, the cosmic distance ladder (through a model independent of the primary calibrators) and fundamental physics (see http://www.cosmos.esa.int/web/gaia/science). New “accurate” distances and motions of the stars within our Galaxy will provide access to the cosmological signatures left in the disk and halo offering independent, direct and detailed comparisons the predictions of the most advanced cosmological simulations.

Nevertheless, all the above results will not be achieved without the correct characterization and exploitation of the “relativistic”, i.e. very high accuracy, astrometric data. Once a relativistic model for the data reduction has been implemented, any subsequent scientific exploitations should be consistent with the precepts of the theory underlying such a model. A mission like Gaia, repeatedly observing over 5 years a million or so of bright and stable stars uniformly scattered across the sky to a precision of 10-20 micro-arcsecond, will constitute by far the largest and most thorough astronomical experiment in testing GR ever attempted since its formulation (one century ago), possibly with the sensitivity for testing the dilaton-runaway scenario (Ref. 10). Gravity theories alternative to GR require the existence of this scalar field and predict it fades with time, so that this residue would manifest itself through very small deviations from Einsteins GR in the weak field regime. In fact, very accurate global astrometry is a very powerful and independent tool to unveil the presence of the scalar field. This outcome can be regarded as an independent verification of other proposed missions and also for testing gravity theories inside the Solar System providing available scenarios without dark components.

While global tests will be done toward mission's end, when most of the observations will be collected, differential experiments, exploiting the precision of the elementary measurements, can be implemented also in the form of repeated Eddington-like experiments by comparing the evolution of angular distances in bright stellar asterisms consecutively observed by the satellite within a few planet's radii from the limb of a giant planet like Jupiter (Ref. 11). Results based on simulated observations of actual star fields near Jupiter's orbit prove Gaia's ability to detect the light deflection due to Jupiter's quadrupole (Ref. 12), predicted by GR and yet to be detected, with opportunities quite early into the mission in 2017 (in the case of a differential scenario). Any further tests on GR, even if performed in the well tested weak field regime, will constitute a new constraint for the alternative theories to GR.

RAMOD high precision astrometry is very suitable to be applied also to exoplanet and brown dwarf mass detection and characterization (centroid shift accurate corrections, Ref. 13, proper radial velocity via General Relativistic Doppler formula, Ref. 14).

Finally, the fact that the RAMOD main observable, i.e. the *local-line-of sight*, is developed as a physical measurement allows to apply the inverse problem which consists of using the actual result of some measurements to infer the values of the parameter that characterize the system under study. Furthermore, a "physical local-line-of sight" will guarantee the appropriate consistency of the measured physical effects to the intrinsic accuracy of the space-time (Ref. 15) thus avoiding misinterpretations of parallel but different quantities.

4. Conclusion

In tracing back light rays we need to keep consistency, at any level of approximations, with General Relativity. In this process the weak gravitational fields of the Solar System can be regarded strong for Gaia-like observers. As far as RAMOD is concerned, rigorous relativistic modeling of Gaia observables consistently with the precepts of GR and the theory of measurements are being completely assessed and relativistic consistency of the whole data processing chain are indispensable prerequisites for having the physical correct determination of distances, parallaxes and proper motions. Any discrepancy between different approaches, if it can not be attributed to errors of different entity, will mean either a limit in the modeling/interpretation - that a correct application of GR should fix - and therefore a validation of GR, or a violation of GR. The realization of the celestial sphere with RAMOD is not only a scientific validation of the absolute parallax and absolute proper motions in Gaia, but is, by number of celestial objects (up to 100 million "references") and directions involved (the whole celestial sphere!), the largest experiment in General Relativity ever made with astrometric methods (since 1919); a relativistic all-sky includes also QSO at different redshifts. Thank to Gaia, we will assist at the revival of Astrometry after almost one century of the formulation of the General Theory of Relativity, a direct legacy to 1919 experiment.

The method of measurements in GR introduced so far by RAMOD extends beyond the scope of Gaia: now Astrometry is part of fundamental physics and, in particular, in that of gravitation (Ref. 16).

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