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Probing interferometric parallax with interplanetary spacecraft

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Abstract

We describe an experimental scenario for testing a novel method to measure distance and proper motion of astronomical sources. The method is based on multi-epoch observations of amplitude or intensity correlations between separate receiving systems. This technique is called Interferometric Parallax, and efficiently exploits phase information that has traditionally been overlooked. The test case we discuss combines amplitude correlations of signals from deep space interplanetary spacecraft with those from distant galactic and extragalactic radio sources with the goal of estimating the interplanetary spacecraft distance. Interferometric parallax relies on the detection of wavefront curvature effects in signals collected by pairs of separate receiving systems. The method shows promising potentialities over current techniques when the target is unresolved from the background reference sources. Developments in this field might lead to the construction of an independent, geometrical cosmic distance ladder using a dedicated project and future generation instruments. We present a conceptual overview supported by numerical estimates of its performances applied to a spacecraft orbiting the Solar System. Simulations support the feasibility of measurements with a simple and time-saving observational scheme using current facilities.

Keywords: Distance; Interferometric parallax phase; Interferometry; Spacecraft

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1. Introduction

The direct estimate of distances in Astronomy has always been one of the most difficult measurements to perform. Although many indirect methods based on photometric and spectroscopic observations already exist, the methods providing direct, geometric distance of the celestial bodies, independent of any additional parameter, is limited to our own Galaxy. At optical wavelengths, the method of the trigonometric parallax (TP) probed distances to the order of kpc with the Hipparcos satellite for more than 100.000 stars in the solar neighborhood (Perryman et al., 1997) and the GAIA mission aims to extend this measurement to ~1 billion stars (de Bruijne, 2012). At radio frequencies, examples of TP measurement are provided by Hachisuka et al. (2006), Reid et al. (2009) and van Langevelde et al. (1999) that estimated the distances and proper motions of galactic masers by

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means of the Very Long Baseline Array (VLBA) and Japanese Very Long Baseline Interferometry (VLBI), exploring the nearby interstellar medium until ~10 kpc. However the TP technique requires extreme instrumental stability to produce images of the quality to obtain precise astrometric analyses.

A new method to estimate distances and proper motions called *interferometric parallax* (IP) has been proposed by Jain and Ralston (2008). This method differs substantially from TP and it does not require a precise measurement of the object's angular position, neither by making an image nor resolving the object under study. The IP method entirely bypasses the step of image production/acquisition, while concentrating on the raw signals collected by pairs of receivers. The measurements can be performed either with the amplitude interferometry at radio frequencies or by using the optical intensity interferometry, subject of revived interest thanks to the upcoming Cherenkov Telescope Array (CTA) (Dravins et al., 2012).

While interferometers work in the Fraunhofer far field hypothesis, IP relies on an extension of the Van Cittert-Zernike (VCZ) theorem that assumes a plane wave approximation. The extension includes effects from the curvature of the wavefronts from a source at finite distance, which contributes an observable phase difference. The basic use of IP assumes the observation of a foreground object (target) and one background object (reference) that are angularly close and point-like sources; by studying the equal time correlated signals retrieved from a pair of separate receivers as a function of time over a suitable period that ranges from days up to six months, the distance of the foreground object is measured.

As a pathfinder experiment for IP verification we seek to measure the distance of an object orbiting the Solar System and producing a fairly detectable IP effect over a short time period. The test case we describe exploits amplitude correlations of signals from deep space spacecraft in conjunction with distant galactic and extragalactic radio sources (Fig. 1). The target bodies envisaged for this pilot experiment are Cassini, Juno, Dawn and New Horizons spacecraft. VLBA astrometric observations of the Cassini spacecraft were carried out by Jones et al. (2011) to improve the Saturn planetary ephemerides. The Cassini spacecraft was used as a bright artificial radio source and its precise astrometry was retrieved. We suggest to observe spacecraft signals with a similar approach that includes significant new features, to estimate the average distance and proper motion coordinates of the spacecraft at some suitable times when we can conveniently extract the parallax phase.

Once the reliability of the method is assessed within the Solar System scale, a direct cosmic distance ladder could be established by comparing objects at progressively greater distances provided that a dedicated project and future technological developments will be achieved. In this perspective, the amplitude correlations between wavefronts from a galactic maser or a pulsar and those of a radio galaxy can be studied to probe a galaxy-size distance scale. In the case of intensity interferometry (II), the distances that could be probed are limited at a galactic scale due to the intrinsic lower signal to noise ratio of this observation mode. Although with this limitation, II could lead to measure the distance of foreground galactic stars angularly close to stellar objects belonging to a background star cluster, or vice versa, i.e. when a member of a foreground star cluster is angularly close to a background star field. In addition, the galactic stars distance could be measured exploiting a transient bright background object as a nova or a supernova. The existence of wave curvature corrections has been recognized in precise VLBI time delays calculation within the Solar System (Kopeikin and Schäfer, 1999). The novelty of the proposed approach consists in detecting this corrective term by interferometry, and then using it as a tool for direct distance and proper motion estimation overcoming the limitations of image-based analysis.

In this paper the mathematical derivation of the method and the differences between the trigonometric parallax are first described (Section 2). Then the motivation for the use of a spacecraft for the verification of the technique is presented (Section 3). The simulations on the observing scenario and the technical aspects of the observations are discussed in Section 4. Finally, the possible applications to the observation of some astrophysical sources and the perspectives with the next generation of ground-based large telescopes are briefly presented.

2. Experimental overview

The method requires a source nearby (the spacecraft) and a very distant astronomical source (the background radio source). Fig. 1 shows the orbit of Cassini projected on the sky plane along with a number of background radio sources for the year 2016. The simulation can be easily extended to any epoch of interest. There are many near conjunctions of Cassini with the radio sources in the NRAO VLA Sky Survey (NVSS) (Condon et al., 1998). These radio sources are our reference objects for the interferometric parallax measurement. As we will show, each radio source provides an independent opportunity for the direct determination of the distance between the telescope receiver and the spacecraft. The Cassini spacecraft is assumed as an example candidate, but the derivation is valid for all other spacecraft in general. The description of the method and the mathematics reported in Sections 2.1 and 2.2 are entirely based on the formalisms assumed and used in Jain and Ralston (2008).

2.1. Background and definitions

Consider an array of two receivers, labeled 1 and 2, with vector coordinates $\mathbf{x}_1$ and $\mathbf{x}_2$ relative to a given origin. It will be convenient to represent the coordinates in terms of their separation $\Delta\mathbf{x}_{12} = \mathbf{x}_2 - \mathbf{x}_1$ and a center of mass vector $\mathbf{X}_{12} = (\mathbf{x}_1 + \mathbf{x}_2)/2$. Each receiver observes the signal