Precise Astrometry: Earth Analogs and Beyond

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Introduction

The GAIA mission has demonstrated the value of high-precision astrometric data. ESA is encouraged to build on this success. A uas-level astrometry mission should be the next step. For the first time, this will allow the detection of temperate Terrestrial worlds circling nearby sun-like stars. It will also provide insight into the physics of black holes, galactic motions and the nature of quasars.

This can be accomplished by means of a long-baseline Michelson Interferometer. The instrument is capable of providing 1 uas measurements during individual observations. More importantly, over a series of "looks," a precision of 0.3 uas can be attained. During NASA's Space Interferometry Mission (SIM) project, an Astrometric Beam Combiner was built and validated to a TRL-6 readiness level. This hardware still exists. It is proposed that a joint project to utilize this technology should be pursued by ESA and NASA.

Star Watch is the title given to this new effort. It benefits not only from NASA's investment of 600 million Euros and 10 years of engineering development, but also from the March of Progress since 2010.

Star watch will allow ESA to follow up the Gaia mission with an even more capable astrometry probe. There are several ways in which this can be pursued. One is a cooperative mission with NASA in which ESA would contribute the equivalent of an M-class mission. European industry has demonstrated its expertise in manufacturing space-based laser metrology hardware in the LISA Pathfinder and GRACE Follow-On missions.

Figure 1: Beta Coma Berenices

SCIENCE CASE

A key scientific goal is to directly image, and obtain spectra, of Earth-like planets. The challenge for Direct Imaging missions is the combination of the extreme contrast between the star and planet, the small angular separations, and the sheer faintness of the planet. Rocky planets orbiting 1 AU from star 10 parsecs away will have a magnitude of V = 28, separated by only 100 mas from a 5^{th} magnitude star. Astrometry is optimized to discover such low-mass planets around the nearest stars and, in the process, provide the best targets for later missions that can directly image those worlds.

An example of the utility of astrometry is the case of the Chara (beta CVn) star system. It is relatively close (8.5 parsecs) G0 star and radial velocity searches have detected no planets. Another example is the beta Coma Berenices system, a G0 star at a distance of 9 parsecs, with no Doppler planet detections. These are prime targets for Star Watch as these Solar Twins may have "hidden" planetary systems. If the invariable plane of these systems is highly inclined to our line-of-sight, then high precision astrometry is the best avenue by which such systems can be discovered and charted.

The star Muphrid (eta Bootis), at a distance of 11 parsecs presents an interesting case. It is a G0 subgiant, evolving away from the Main Sequence, with a mass of 1.7 Msun. Star Watch will be able to discover its planetary system and confirm whether Muphrid is a spectroscopic binary.

Another example of the strength of astrometry is the case of Aldeberan b. This exoplanet candidate orbits a K5 giant star (distance = 20 parsecs). Radial Velocity data have indicated that a Super Jupiter, Aldeberan b, orbits the host star at a distance of 2 A.U. Recent analysis has determined that the existence of this planet is doubtful. Star Watch will determine whether there is such a planet orbiting this Giant star, and will be able to do the same for other Red Giants.

Earth Analog Characterization

Splitting the discovery and characterization of other Earths between two sequential missions (an easier, indirect astrometry mission and a later Direct Imaging mission) allows for technology to be developed for the latter mission with specific detection thresholds. Such a two-step approach offers complementary information about Earth Analogs. Star Watch will provide detection of temperate, rocky planets, their masses and their three-dimensional orbits for the first time. In combination with Doppler observations, this will produce an inventory of Terrestrial and Giant planets around individual nearby stars. In turn, this census will offer valuable constraints on the formation and dynamical evolution of planetary systems in general.

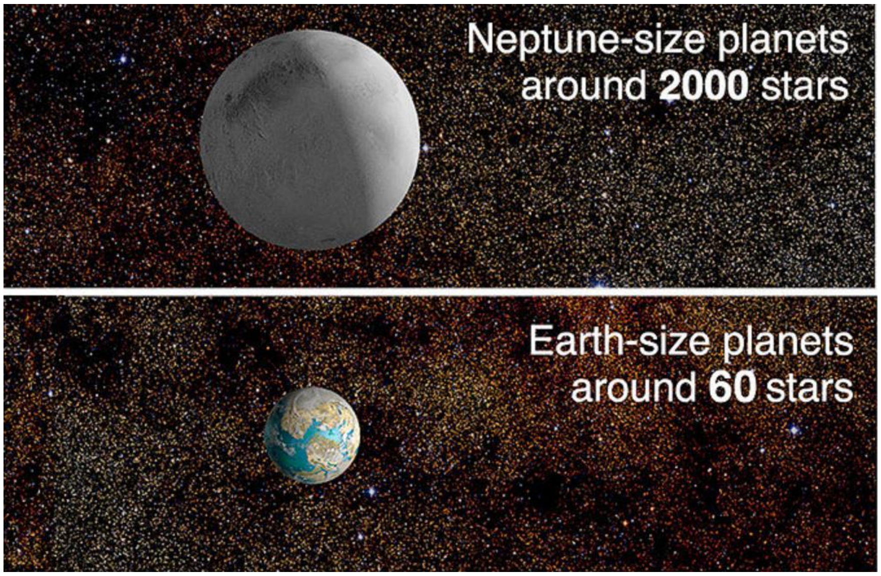

Figure 2: Star Watch planet yields

Mass

Because mass is a fundamental property of planets, the science return of a Direct Imaging mission would suffer significant ambiguities. A dot presents a number of cases. The uncertain albedos of rocky planets will prevent secure mapping of reflected fluxes to planet radius, leaving the planet mass even less secure. Also measuring a planet's mass is crucial for interpreting any spectrum of a planet's atmosphere.

A precise measurement of the planet mass is necessary for understanding the formation and dynamical evolution of a planetary system. In addition, the mass of a planet having peculiar properties can help in the understanding of the nature of that world.

DI Optimization

An Earth-like planet will be positioned at a mere 100 mas from its host star at maximum elongation. For a typical inclination of 45 degrees, the planet is located within 0.1 as for most of its orbit, only briefly appearing outside of that separation. Without prior Star Watch observations, there will be no way to know when those moments of favorable elongation occur.

In addition, Star Watch's astrometry data will establish the orientation of the planet's orbit in space. This will allow a Direct Imaging mission to efficiently time its observations so that it achieves its highest contrast for a limited range of angles and orientations. This will, in turn, maximize the SNR of spectra.

The data from an astrometry mission will allow lower-cost, lower-complexity, space telescopes. Knowledge beforehand of planet orbits, and their existence, will remove the necessity of including a Coronagraph on those future telescopes. With the use of Star Shades to provide imaging and spectra, demands of ultra-precise mirror shape that come with a Coronagraph can be reduced. An example of such a mission is HabEx-Lite which uses only a Star Shade. Since a star shade's light suppression occurs before the photons enter a telescope, HabEx-Lite can use a segmented mirror design with relaxed shape requirements.

Formation Models

Successful theories will need to determine the orbital stability of all planets over long periods of time, including orbital resonances and interactions in multi-planet systems. An understanding planet formation mechanisms, over a range of planet masses, is necessary in order to place exoplanet discoveries in context. Terrestrial planet formation is strongly influenced by Giant planet formation and migration.

One example comes from the astrometry data produced by ESA's Gaia mission. This has shown that there have been a number of Stellar Flybys of the Solar System in a short period of geological time. Star Watch's survey of planetary system architectures may provide evidence of the effects of these close stellar encounters over several billion years.

By detecting both Terrestrial and Giant planets across a wide range of orbital separations, Star Watch will characterize the typical architectures of planetary systems.

Observation Plan

Star Watch will discover Rocky worlds and Ice Giants orbiting within a few AU of nearby stars. A set of 60 stars, within 20 parsecs, will be surveyed by this astrometry probe. This will provide a meaningful census of typical architectures of planetary systems.

Theories of planet formation and subsequent evolution are desperately in need of new empirical constraints. Star Watch can characterize the long-term evolution of the eccentricities and inclinations of planet orbits. These data will permit tests of theories of the origins of multi-planet systems, including migration and gravitational interactions.

Young Planets

Despite the discovery of many planets around mature stars, almost nothing is known about planets orbiting young stars. This is a consequence of the rapid rotation and active photospheres of such stars. Detection by means of transits, direct imaging, or radial velocity monitoring is precluded. As a result, essentially nothing is known about the incidence of planets around young stars. Theories of formation and evolution require such data. Astrometry with Star Watch offers the best opportunity to find Gas Giant, Ice Giant and Super Earths orbiting young (2-100 Myr) stars.

Synthesis Imaging

The successful demonstration of synthesis imaging at optical wavelengths with Star Watch is expected to have a significant impact on the design of future space-based instruments for astronomical imaging.

SIM imaging will also offer new capabilities for the study of the structure of targets presently only barely resolved by HST, or otherwise confused by the inability to adequately remove diffraction spikes and scattered light from nearby bright stars.

General Astrophysics

Star Watch's uas-level measurements will benefit many areas of astronomy. For example, it will measure parallax distances to 2% accuracy out to 3 Kpc. It will achieve 5% accuracy out to a distance of 6 Kpc, past the galactic center. Star Watch will be able to determine both the solar distance to the Galactic Center (Ro) and the solar angular velocity around the Center (Wo).

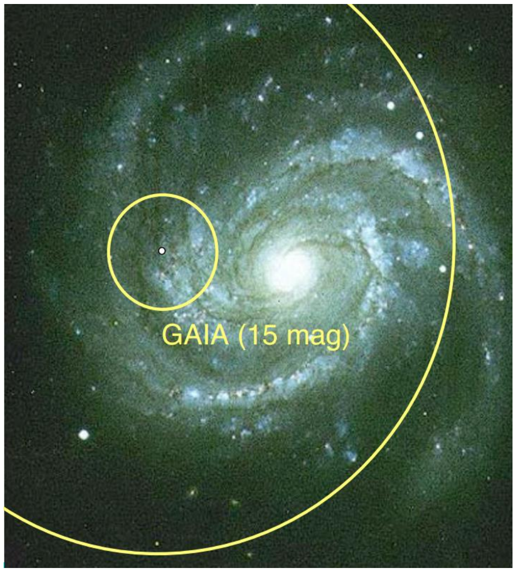

Figure 3: The "reach" of Gaia vs. Star Watch

Star Watch will be able to map the orbit of the Cygnus X-1 binary system. It will determine the mass of the Black Hole thought to reside there, allowing firm data for analyses of these objects.

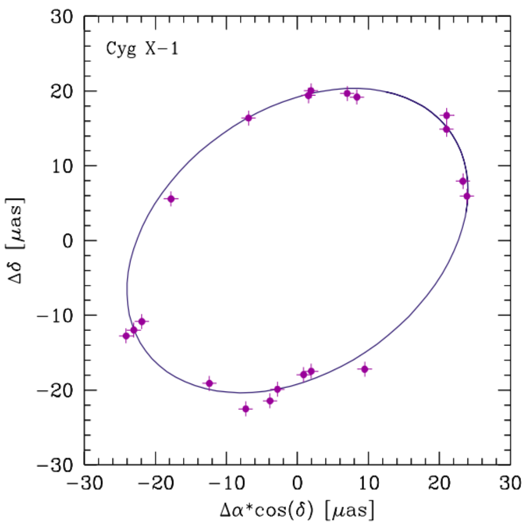

Figure 4: Orbit diagram of Cygnus X-1 orbit

Star Watch will search for planets around White Dwarfs, both survivors from the Main Sequence progenitors, as well as newly formed objects.

Attempts will be made to observe the orbit of SS 433, as well as the proper motion of the visible clumps in its relativistic jets.

Star Watch synthesis imaging will be useful on crowded fields which contain many targets. These include the central regions of galaxies as far as the Virgo cluster, which include active nuclei and jets. This mission will obtain proper motions for up to 27 galaxies in the Local Group.

Star Watch will be able to monitor Quasars beyond 1 Gpc. Motion of their photocenters may result from a variable nucleus or from interaction with a host galaxy.

In addition, it will be able to detect the astrometric signature of Binary massive black holes in several Active Galactic Nuclei (AGN). These may result when two galactic nuclei merge.

Star Watch Spacecraft

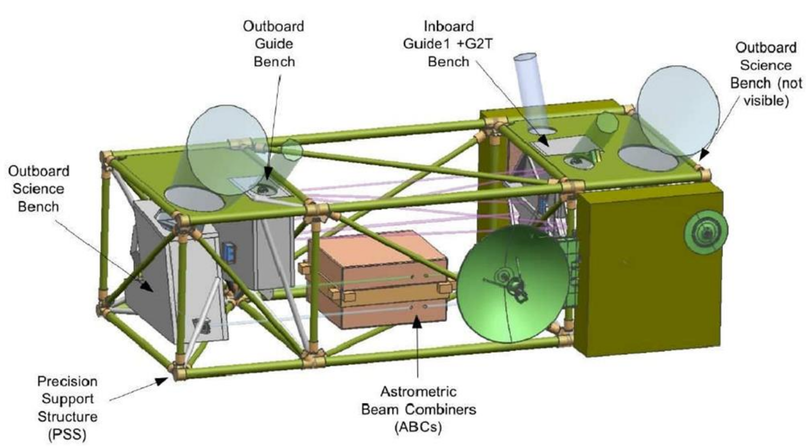

Figure 5: Star Watch Michelson Interferometer

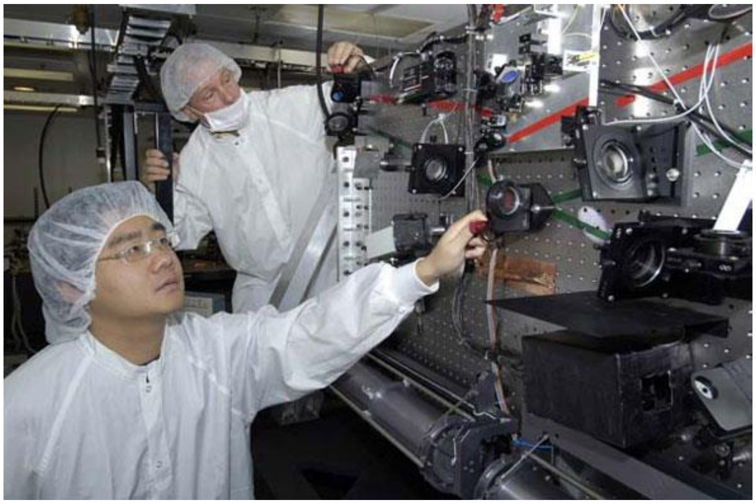

Figure 6: Astrometry Optical Metrology Hardware; JPL

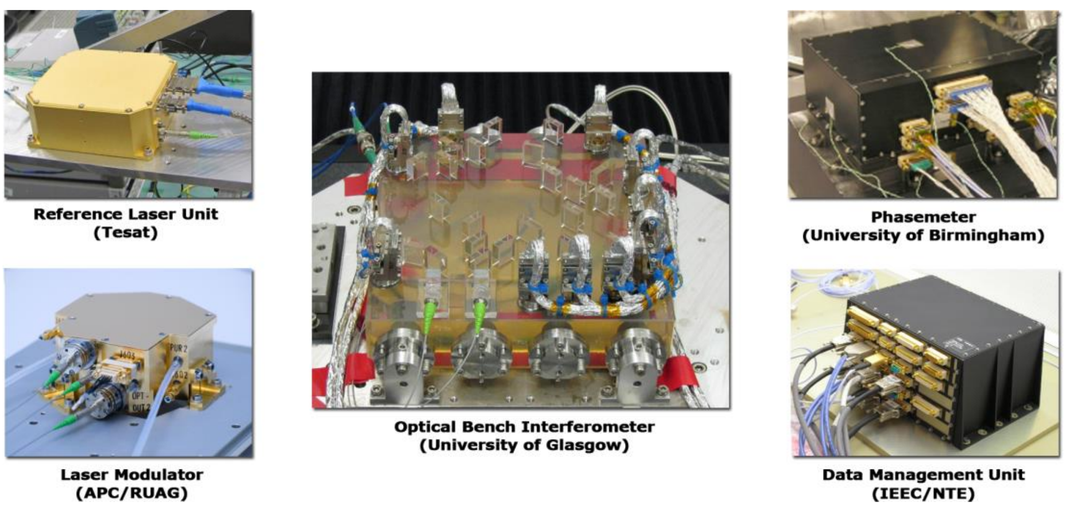

Figure 7: LISA Pathfinder Optical Metrology Hardware

Conclusions

Star Watch will open a new window onto the Universe. The contribution from ESA would be equivalent to an M-class mission. Hardware to begin such a mission already exists, in storage at JPL. Also, European industry has demonstrated recent expertise in Laser Metrology in the LISA Pathfinder mission.

References

"Star Watch Astrometry Probe," 2019; Horzempa, P.; Astro 2020 APC White Paper

"Science with Space Interferometry Mission," 2002; edited by Unwin and Turyshev