Short Report of IVS Working Group 5 (WG5) on Space Science Applications

- An IVS Perspective -

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1. Introduction and Charter of WG5

The IVS Working Group on Space Science Applications (WG5) was established by the IVS Directing Board at its meeting in Bordeaux on 23 March 2009. The mandate of the WG5, its membership, and chairmanship have been reviewed by the IVS Board at its regular meetings.

The current mandate of the WG5 comprises the following tasks (from the charter for WG5):

- *To investigate synergies in scientific and technological areas between the IVS core activities and VLBI experiments in application to planetary and space science missions.*
- *To determine areas of VLBI support of planetary and space science missions where experiments conducted by the IVS (possibly together with other VLBI networks) can be mutually beneficial.*
- *To investigate desirability and feasibility of establishing a mission-specific liaison between IVS and appropriate space agencies and organizations involved in planetary and space science missions.*
- *The WG5 is to be co-chaired by a member of the IVS Directing Board and an external expert. The WG5 is to be composed of up to 16 persons, at least half of which should be affiliated with IVS institutes.*

The mandate of the WG5 was originally approved for the period of one year starting from April 2009. Continuation of the activities of the WG5 beyond March 2010 has been suggested by the IVS Directing Board.

A summary of the studies and discussions within WG5 done so far will be given here.

2. Preamble

Observations of satellites and spacecraft by VLBI radio telescopes in general and the IVS network in particular will be important contributions to several scientific disciplines depending on their general missions and flight paths. The methods of observing these objects are based on either group delay or phase delay measurements, predominantly in differential VLBI (D-VLBI) mode or with the astrometric phase referencing method.

Earth orbiters normally do not require observations by VLBI but these can be used in an ideal fashion to link the dynamical reference frames of the satellites with terrestrial and, most importantly, to the celestial reference frame as defined by the positions of quasars. Spacecraft en-route to the moon and subsequently orbiting the moon and possibly also landing on the moon can be and have been observed by VLBI with great success already (e.g., Goossens et al. 2011). The same applies to various spacecraft and missions to planets and outer space, mainly observed by the NASA Deep Space Network (e.g., Border 2009).

This summary describes the perspectives of future missions, possible implications, and the potential involvement of the IVS. The activities of the IVS in this field are not limited to providing the observations and initial data processing but also contain scientific data analysis and interpretation.

3. Missions

3.1 Artificial Earth Orbiters

A variety of spacecraft is in orbit around the Earth for a multitude of applications. All of them communicate on radio frequency links and may be observable with radio telescopes, thus, also being candidates for VLBI observations. Satellites with dedicated transmitters or even quasar-like beacons are another class of targets to be considered, e.g. GRASP (Nerem et al. 2011) or MicroGEM (Wickert et al. 2008, Brieß et al. 2009).

Observing these satellites with VLBI will provide invaluable information for geodetic and astrometric applications. The geodetic challenges of artificial Earth orbiters are closely related to the establishment and maintenance of reference systems. While in geodetic practice, station coordinates are usually provided in the kinematic International Terrestrial Reference Frame (ITRF) and radio source coordinates in the International Celestial Reference Frame (ICRF), positioning of space probes or the determination of planetary ephemerides rests upon dynamical theories. The link between these systems can only be established and maintained with VLBI observations of the spacecraft and preferably relative to radio sources of the ICRF.

As most of the modern geodetic techniques make use of sensors and targets in extra-terrestrial space, the main challenges for applications on Earth today are to interlink the underlying reference frames to guarantee accuracies at the mm-level with a stability of better than 0.1 mm/y. For example, orbits of GNSS (Global Navigation Satellite Systems) satellites are linked to a certain ITRF realization of observing stations on the Earth's surface. To avoid inconsistencies and errors during measurement and calculation procedures, exact frame ties between quasi-inertial, kinematic, and dynamic reference frames have to be secured. By observing space probes alternately to radio sources with the differential Very Long Baseline Interferometry (D-VLBI) method, the relative positions of the targets to each other on the sky can be determined. As the directions to the radio sources are well known in the ICRF, it is possible with such observational configurations to link the bodies within our solar system with the ICRF. While the Earth orientation parameters (EOP), which are regularly provided by the International Earth

Rotation and Reference Systems Service (IERS), practically link the ICRF to the ITRF, the ties with the dynamic frames will be established by D-VLBI observations.

Dynamic reference frames are typically realized for each individual satellite or satellite constellation by numerical orbit integration. When it comes to the combination of various missions or follow-on satellites (e.g., the various altimetry missions), precise ties between the various frames are essential for correct and reliable results over long time periods, needed, for instance, for monitoring global change and climate variation. A typical example for such a need of consistency is the derivation of sea level heights from the altimetry missions Topex/Poseidon, Jason-1, and Jason-2, which contain a bias for each satellite that has to be removed before trends of global sea level can be determined. Today, altimeter satellites are tracked by Satellite Laser Ranging (SLR) ground stations and D-VLBI observations can provide complementary information.

3.1.1 Low Height Earth Orbiters

From a VLBI observational point of view, near-Earth orbiters are rather challenging since mutual visibility depends on the altitude of the satellite and the separation of the radio telescopes. Furthermore the satellites travel through the field of view very fast requiring radio telescopes with sufficient speed, which will, however, be guaranteed by usage of radio telescopes of the VLBI2010 class. For these satellites, continental-size VLBI observing networks are essential.

3.1.2 Medium Height Earth Orbiters

Global Navigation Satellite Systems (GNSS) are the overall representatives of medium height Earth orbiters. They have been observed with VLBI successfully in recent years (Tornatore and Haas 2009, Tornatore et al. 2011) and will permit a direct link between the terrestrial, the dynamical, and the celestial reference frames. The common field of view of two or more radio telescopes is extended for medium height Earth orbiters.

3.1.3 Geostationary Orbiters

Normally, geostationary orbiters do not have noteworthy importance in geodetic applications. However, in terms of reference frames, these satellites also deserve a closer look and some efforts to evaluate their importance in reference frame studies and time transfer applications. Observations and analysis of geostationary orbiters are hampered by frequent maneuvers to keep the orbiter in its preset box in the sky. Thus, the orbits themselves cannot be considered as being smooth over time.

3.2 Missions to the Moon

VLBI observations of orbiters of the moon have contributed important information for the determination of orbits and trajectories of spacecraft in the vicinity of the moon. In the future, VLBI will also help to position landers on the moon. As for Earth orbiters, these observations will be used to map the Moon into the known hierarchy of the established reference systems. All the lunar missions mentioned below may have valuable VLBI observation components.

SMART-1 was ESA's first mission to the moon. The purpose of tracking this satellite with VLBI methods was a demonstration of its capabilities in space applications during critical events, like the precise timing and location determination of the impact on September 3, 2006 (JIVE , 2008).

KAGUYA/SELENE. A significant milestone in lunar geodesy has been reached with the successful implementation of the Japanese SELENE (SELenological and ENgineering Explorer) mission, launched on September 14, 2007. SELENE consists of three satellites: a main satellite (MS), a relay satellite (RS), and a VLBI sub-satellite (VS), all three inserted in a coplanar orbit with an inclination near 90°. The MS had an initial 100-km-altitude circular orbit controlled by attitude maneuvers, while the RS and VS are free flyers on highly eccentric orbits with 100/880 km and 100/2400 km perigee and apogee, respectively. Besides other observing methods, same-beam differential VLBI tracking (projected accuracy 1 mm integrated over 100 sec) between RS and VS was used to precisely determine the RS orbit, which serves as the reference for the four-way Doppler measurements.

The overall goal of Kaguya/Selene is to derive an improved version of the lunar gravity field. After successfully orbiting the moon for 1 year and 8 months, the main orbiter was intentionally crashed onto the lunar surface on June 10, 2009. Data analysis is still continuing to this day (e.g., Ando et al. 2012).

For the future, a so-called inverse VLBI experiment is proposed (where artificial radio sources are located either in two landers or in one lander and the orbiter) for the lunar landing mission SELENE-2 (Kikuchi et al., 2010).

Lunar Reconnaissance Orbiter Mission. NASA’s Lunar Reconnaissance Orbiter (LRO) was launched on June 18, 2009, and began its nominal mission on September 15. The spacecraft is orbiting the moon in a circular polar orbit at a mean altitude of 50 km through its one-year “primary mission”, followed by a multi-year “science mission” in a modified elliptic orbit. Accurate lunar 3D-orbits of such orbiters are a prerequisite for the processing of imaging or altimetry data. Although techniques exist to improve lunar orbits from camera data and altimetry crossovers, in general the quality of the orbits plays a significant role in the realization of the lunar reference frame (http://lro.gsfc.nasa.gov/).

GRAIL. The US-mission GRAIL (Gravity Recovery and Interior Laboratory), launched on September 10, 2011, realizes the concept of inter-satellite, high-precision ranging in a planetary orbit for the first time. GRAIL’s science objectives include the mapping of the gravity field for studies of lunar interior, thermal evolution, and tidal dynamics (Zuber et al., 2008). GRAIL consists of two spacecraft in lunar orbit, tracked by S-band from Earth and connected by Ka-band ranging derived from the GRACE concept.

LEO, Lunar version of GRACE. In 2007, DLR (German Aerospace Center) suggested to establish the German lunar-orbiting mission LEO (Lunar Explorations Orbiter, Jaumann et al., 2007) for comprehensive studies of the Moon, including for mapping of lunar magnetic and gravity fields. Flechtner et al. (2007, 2008) proposed to include a GRACE-type experiment with LEO, consisting of two sub-satellites to be released from LEO in lunar orbit and to be tracked from Earth by the two-way, two-frequency (X/S-band) precise range and range-rate (PRARE-L) system. Moreover, Ka-band ranging was chosen to realize a high-precision (projected accuracy 2.5 μm/s) link between the sub-satellites. Aside from the lunar gravity field, the science objectives of this experiment included geophysical parameters like crustal density, Love numbers and contributions to the reference system. The LEO mission has not been realized yet.

Remark: The US-German twin-satellite mission GRACE (Gravity Recovery and Climate Experiment) may be used as a predecessor for lunar and planetary missions applying similar concepts. GRACE (Tapley and Reigber, 2001) has two identical spacecraft using an intersatellite K-band ranging link with μm-accuracy. It was primarily designed to map the static and time-variable gravity field and has provided excellent results allowing the determination of mass transport within system Earth. The GRACE Follow-on satellites have been approved and according to present schedule will be launched in 2017.

3.3 Missions to Planets, Comets, and Other Bodies

Since the 1980s the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and recently also the Japan Aerospace Exploration Agency (JAXA) have performed D-VLBI observations during their (deep) space missions, generating data that can also be used to establish precise frame ties to major celestial frames (e.g. Hildebrand et al., 1994). Another potential network to carry out D-VLBI and suitable for spacecraft navigation is the Very Long Baseline Array (VLBA); see Lanyi et al. (2005). An interesting development is the plan of the Deep Space Network to move to the 32 GHz band for spacecraft tracking (which provides higher telemetry rates) while the astrometric community is also considering to adopt higher observing frequencies (up to 43 GHz) yielding better accuracies due to reduced source structure effects (Lanyi et al. 2010, Charlot et al. 2010, García-Miró et al. 2012). Some efforts in the development and application of phase-connection techniques are also of interest (Marti-Vidal et al., 2008).

The term D-VLBI comprises the determination of a relative position using differential observations in order to minimize common error sources like atmospheric propagation delays, antenna-specific delays, and station position inaccuracies. The configuration of the character of the spacecraft tone, the observed frequency, the antenna size, the observation network, and the achieved accuracy vary between different realizations of D-VLBI, as described by Lanyi et al. (2007). A very well developed technique performed routinely by NASA and ESA is the so-called Delta Differential One-way Ranging (ΔDOR) employing antennas of the Deep Space Network (DSN). Mainly used to support precise spacecraft navigation at the level of some nrad (e.g., Martin-Mur et al., 2006), Mars spacecraft VLBI measurements (Mars Global Surveyor, Mars Odyssey, Mars Reconnaissance Orbiter) tie the planetary ephemerides to the ICRF with an accuracy better than 1 mas (= 5 nrad) (Folkner, 2008). The reliance on special DOR-tones transmitted by the spacecraft, the need of big antennas with special receiving units, and an accuracy regulated by the group delay measurement disqualifies ΔDOR for many observations other than to deep space probes. Recent successful D-VLBI observations using the phase referencing technique of, for instance, ESA’s Huygens probe landing on Titan (van ’t Klooster, 2005) or within JAXA’s lunar gravity mission SELENE (Liu et al., 2010) managed to overcome those restrictions. This opened up a wide range of new applications and initiated further research in D-VLBI. With the Planetary Radio Interferometry and Doppler Experiment (PRIDE), an initiative by the Joint Institute for VLBI in Europe (JIVE), Duev et al. (2012) present the VLBI spacecraft technique which has been successfully tested observing ESA’s Venus Express Spacecraft. Working with almost any phase-stable radio signal from a spacecraft, observed in phase referencing mode, the PRIDE approach is applicable to virtually any deep space mission, as well as to planetary science missions and near-Earth targets (Duev et al., 2012).

VLBI tracking of Cassini, VenusExpress or MarsExpress have been already successfully used for the orbit reconstruction of the spacecraft during their flyby or orbital phases. As demonstrated by Folkner et al. (1994), the relative positions of the spacecraft observed in the projected vicinity of an extragalactic radio source with its position defined in the ICRF provide strong angular constraints for the spacecraft orbit but also for the planetary ephemerides. VLBI S/C observations are used in the adjustment of the planetary ephemerides. Even if very few VLBI data are used so far (about 0.25% of the total amount), they are the only accurate link between the orbits of the planets and the ICRF. Because of this, they are absolutely crucial for the construction of planetary ephemerides in the ICRF as required by the International Astronomical Union.

3.4 Spacecraft in Transit to Outer Space

Flybys of planets by spacecraft in transit to outer space are also a good source of information. Owing to the vicinity of the probe and its accurate tracking during this crucial phase of the mission, together with VLBI tracking, it is possible to deduce very accurate positions of the planet as the probe passes by. For gas planets, this type of observations puts a major constraint on their orbits (flybys of Jupiter and Saturn, mainly). Even if they are not numerous (less than 0.5% of the data sample), they impose 50% of the constraints brought to the Jupiter and Saturn orbits. As an example, the New Horizons mission flew by Jupiter at a distance closer than that achieved by Cassini from which the positions of Jupiter have been deduced in late 2000 by JPL. The analysis of the New Horizons radio science data during its flyby of Jupiter with an accuracy below 10 meters in geocentric distances and 5 mas in right ascension and declination give new very accurate constraints for the Jupiter orbit.

Precise ephemerides of the planets have been computed at various different institutions (Development Ephemeris (DE), JPL, see Folkner et al. 2008, Ephemerides of Planets and the Moon (EPM), IAA, see Pitjeva 2005, Integration Numerique Planetaire de l'Observatoire de Paris (INPOP), see Fienga et al. 2008) and are updated in current projects using tracking or navigation data from orbiting spacecraft or from flybys. These observations are also essential tools for monitoring the gravitational and non-gravitational forces affecting the spacecraft trajectory. These data enable the determination of planetary gravity fields with their time variations and the interpretation of the results in terms of geophysics and dynamics of solar system objects.

4. Involvement of the IVS in Space Missions

The operation of the IVS observing network and the distribution of the correlator load are controlled by the IVS Observing Program Committee (OPC). The OPC decides on observing proposals on the basis of scientific and operational merit according to the general rules of the IVS as set forth in the IVS Terms of Reference. Furthermore, the OPC discusses with the observatories and correlators involved whether observations can be carried out for the specific purpose of the proposal.

It is expected that proposals for future VLBI observing campaigns related to space science applications which require the involvement of one or more of the IVS components will be handled in the same objective resource-responsible manner. The benefits of scientific or possibly also economic developments which may help to maintain the IVS's infrastructure will remain the driving force behind any decision.

5. Concluding Remarks

The application of the VLBI technique for observing spacecraft is a valuable contribution to support space science applications as has been demonstrated by completed and ongoing projects. In the future, forthcoming missions will also draw from the strengths of the VLBI technique in general and from the expertise of VLBI scientists in particular. Geodetic and astrometric VLBI bears good chances for further developments in the area of space sciences and will provide ample opportunities for synergies. On the other hand, VLBI itself will benefit from space science applications due to external demand for technical progress and due to increased visibility in the science community.

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