Phase Centre Determinations at GPS-Satellites with VLBI

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Abstract

The collocation of various geodetic space techniques provides the tie of satellite reference systems into the quasi-inertial reference system of radio sources. The concept of a fundamental station is the ideal realization for collocating instruments on Earth's surface. A challenge is to tie satellite transmitters of navigation systems directly into the International Celestial Reference Frame, the most accurate realization of a quasi-inertial reference system with VLBI measurements. An orbit determination of the phase centre of the satellite transmitters complement existing orbit determinations. For VLBI-type determinations some research and development work needs to done. For this purpose a new type of dual beam radio telescopes will be of advantage. If the method will be successful an *inertial frame service* is possible in the future.

1 Global Reference Systems

In (space) geodesy two kinds of reference systems play an important role:

- celestial reference frame (CRF),
- terrestrial reference frame (TRF).

Reference systems are necessary to describe measurements for the determinations of position and velocity in space. In principle the determined position and velocity can be expressed only relative to the measuring platforms, which are moving themselves. Therefore a strong interest exists in the definition and availability of a globally available inertial reference systems.

Within the solar system the catalogue of fix stars was used for more than a century as an inertial reference system. However with the increase of accuracy and the long time span of observations of the measurements, the proper motion of galactic stars is in contradiction to the realization of an inertial system. The development of radio astronomy and of the Very Long Baseline Interferometry observation method allows the observation of the most remote objects in the universe. Today the very distant extragalactic quasars are providing the most accurate realization of a global inertial system. The proper motion of the very distant quasars is often negligible, but variations of the source structure require continuous monitoring programmes. The small changes of the radio objects themselves request the expression *quasi-inertial system.*

The optical reference frame became obsolete when VLBI demonstrated a higher astrometric accuracy of about two magnitudes in the reference frame of quasars. This was acknowledged by the IAU recommendation [1]:

> *The ICRF will be based on radio sources observed by VLBI and will therefore replace the optical objects of the FK5, beginning from January 1st, 1998.*

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This recommendation is meaningful, since VLBI is now responsible for the primary quasi-inertial reference frame. Any kind of results from non-VLBI space geodetic measurements are comparable only, if they can be expressed relative to the inertial frame ICRF based on radio sources.

The only measurement technique which gives access to the inertial frame of distant radio sources with the best current level of accuracy is the Very Long Baseline Interferometry (VLBI).

2 Tie of Reference Frames

It is possible to generate (periodically) global solutions for each individual geodetic space technique including all the participating measuring platforms. The result are terrestrial reference frames for each single technique. One of the geodetic tasks is to compare these independent results of baselines or station coordinates. The comparison is possible:

- if the individual techniques are collocated at one site and the of the reference points can be provided by a local survey. This is best realized by operating fundamental stations for geodesy.
- if the individual techniques can be collocated in space; e.g. retroreflector for satellite laser ranging (SLR) at GPS satellites.

There exists another option since GPS-satellites and VLBI-techniques are using from the electromagnetic spectrum similar wavelengths: microwaves. The question arises:

> **Why don't we use astrometric VLBI methods to tie the GPS satellite orbits directly into the ICRF?**

3 Astrometry

In astrometry the phase-referencing method is applied to measure weak sources relative to known quasars. If the angular separation between both objects should not exceed about 5° in order to assume the same atmospheric effects on the propagation of the signals. If both sources are observed alternating then the most accurate method of phase-differencing is applicable.

The ICRF is based on about 608 radio sources which are distributed over the entire sky. The statistical distribution on a sphere results in an averaged angular separation of each ICRF reference source of about 9°.

4 GPS

Currently are 27 GPS satellites on an orbit, of which 24 are operating. At one ground location at middle latitudes 7 to 8 GPS satellites are above the horizon for about 4.5 hours each. In this article GPS serves as an example. The idea of monitoring phase centres of GPS-transmitters applies to any other navigation system, like e.g. GLONASS or newer developments.

The orbits of GPS satellites are represented usually by the movements of the centres of mass. But the measurements with GPS refer to the centre of phase at the transmitting and receiving antennae. Since GPS uses two different carrier frequencies there are two different phase centres at the transmitter, which can be assumed to be offset to each other. (For simplicity in following the singular form is used in this article.) The centre of phase and the centre of mass of the extended GPS satellites are minimisation offset by more than one meter. Due to the perturbations of the orbits due to solar wind, Earth shadow and gravitation the orientation of the offset between centre of mass and centre of phase are subject of temporal changes. As result the orientation of the eccentricity vector between the centre of phase as the geodetic reference point and the centre of mass as the dynamical reference point is not fixed in space and requires continuous monitoring and orbit determinations. The International GPS Service computes daily precise orbits of the GPS satellites based on ground stationed GPS permanent receivers. The residuals range typically from 2–20 cm.

VLBI has the potential to verify these GPS orbit determinations.

5 Phase Centre Determination of GPS-Transmitter with VLBI

The VLBI-method of phase-referencing would allow to observe GPS-transmitters during apparent approaches to radio sources. GPS-transmitters are very strong sources compared with quasars, but phase-referencing method will enable high accuracy for the orbit determination due to the of atmospheric effects (fig. 1).

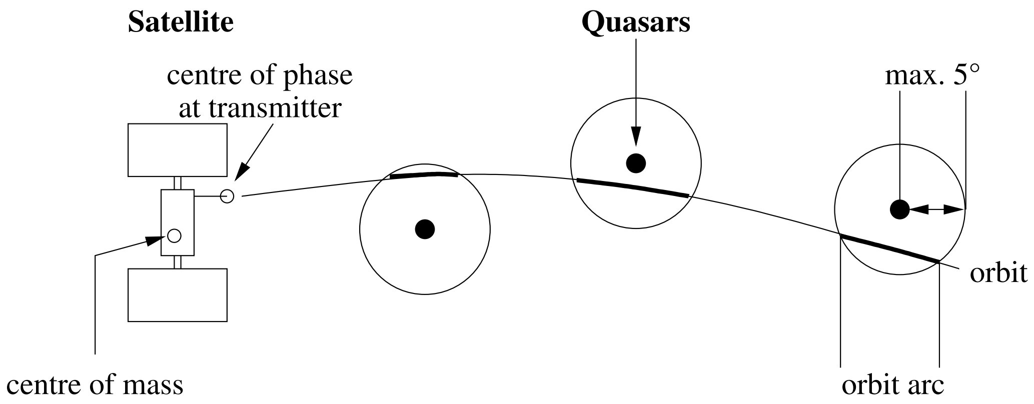

Fig. 1: Apparent approaches of satellite to ICRF radio sources. Phase-referencing astrometry can be carried out within a range of about 5 degree of angular separation.

Assuming that 608 sources and 24 GPS transmitters are observable, there should be statistically always globally six apparent approaches and at each site one apparent approach with less than 5° angular separation observable. The orbit of the phase centre would be determined in arcs which need to be interpolated when no radio source is available.

For those kind of observations some *research and development* problems have to be solved:

- Phase referencing on quasar pairs is static, while phase referencing on quasar and GPS-transmitter is kinematic. Interferometry models will need to include velocities of transmitters relative to Earth rotation.
- Phase referencing with quasar pairs is done in same spectrum for each source, while GPS frequencies are in L-band and the ICRF is based mainly on S/X-band observations. Astrometric determined positions of quasars show sometimes dependency on the observed frequencies. Is it possible to translate the phases between different spectra? If this is not possible, then the quasars must be observed in L-band or future navigation satellite projects should be equipped with S- and X-band transmitters.
- Method of the interpolation of orbit arcs achieved from phase-referencing method must be investigated.

- Introduction of satellite tracking routines to the antenna control units and PC Field System for alternating observations between quasar and transmitter.
- Method of simultaneous observation of two objects requires a new observing instrument: Dual beam radio telescope with movable eccentric second feed. The advantage is the continuous simultaneous observation of both objects relating to the same reference point at the antenna. The large reflector would observe the weak quasar, while the eccentric feed would observe strong satellite transmitter. The main reflector tracks by compensating the Earth rotation, while the ex-centric feed compensates for the satellite orbit in the inertial frame (fig. 2).
- GPS-transmitters seen in an altitude of 20000 km with a VLBI baseline of about 6000 km would allow to make a three-dimensional orbit determination (near-field). The 3-D position needs to be transformed in to the unit-sphere ICRF (far-field).

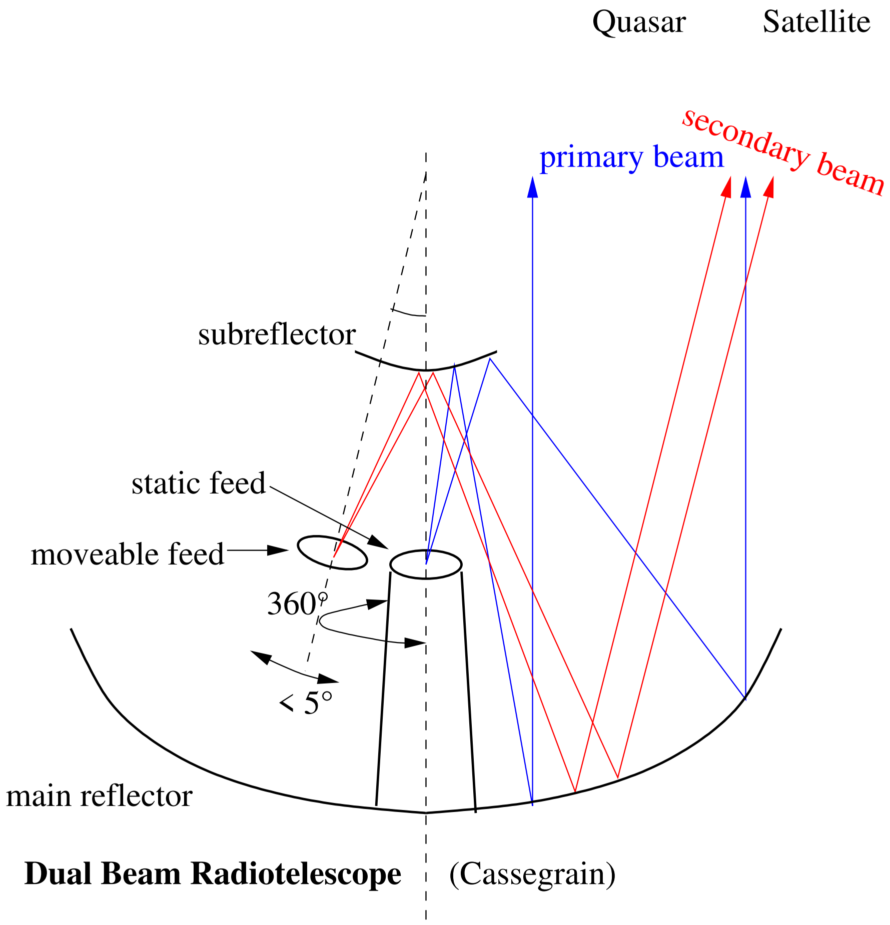

Fig. 2: Dual beam radio telescope for simultaneous phase-referencing VLBI observations. The primary beam tracks the quasar by compensating Earth rotation while the secondary beam tracks the satellite by compensating in a given range of maximum 5° angular separation the satellite movement. The result is a very precise orbit arc of the transmitter relative to the position of a quasar.

The advantages of *simultaneous* observations of quasar and transmitter with the dual beam radio telescope are:

- Direct continuous phase comparisons.
- Intersection of radio telescope axes is the ground based geodetic reference point for quasar and transmitter observations without eccentricity. This is of importance for the tie of ground based geodetic networks.

The observation schedule will contain pointings to GPS-transmitter whenever an apparent approach is observable and to quasars in between. The quasars will be selected due to the apparent approaches and due to the optimisation for the determination of Earth orientation parameters. The benefits of such observation schedules are:

- It will be possible to **decorrelate the orbital errors from earth orientation variations**.
- Orbits of the phase centre of the GPS-transmitter should be derived with about **3-6 cm accuracy in an inertial frame**.
- If orbits of transmitters are determined in the ICRF in return the observation of nutation and earth rotation can be performed with the much denser global GPS permanent network.

6 Outlook

Let us assume, that a new instrumental generation consisting of dual beam radio telescopes with real-time-VLBI infrastructure will be available in a global network. Applying dual beam VLBI techniques with simultaneous observations to the existing (or a new generation of) navigation satellites would allow the orbit determination on the level of a few centimetres directly tied in the ICRF. New navigation satellite programmes could be designed VLBI friendly by choosing frequencies which are also in the S/X-band regime and by higher altitudes for the transmitters for new space navigation purposes. The centimetre-level in accuracy of orbits obtained by VLBI-methods should reflect higher accuracy by positioning on the ground as well, since less hypothesis about the orbits themselves and the signal propagation through atmosphere are involved.

If the navigation satellites can be directly measured in the quasi-inertial frame of the ICRF, the deep space navigation can use the strong signals of the navigation satellites. Tied into the ICRF they provide stable reference points for high precision space navigation manoeuvres. While the remote space vehicle could navigate with the relatively strong signals from the navigation satellites rather than those weak signals from quasars, it will be also possible to include the remote space vehicle in the VLBI observation programme. VLBI phase referencing method will allow precise orbit determination also at larger distances of any transmitter.

The extension of the quasi-inertial reference frame of quasars with directly tied navigation satellites could be used as a backbone for an *inertial frame service*.

References

[1] Ma, C., Arias, E.F., Eubanks, T.M., Fey, A.L., Gontier, A.-M., Jacobs, C.S., Sovers, O.J., Archinal, B.A., Charlot, P.: The International Celestial Reference Frame as Realized by Very Long Baseline Interferometry, The Astronomical Journal, 116, S. 516-546, July 1998