VLBI FROM THE MOON

L. I. GURVITS
Joint Institute for VLBI in Europe
P.O.Box 2, 7991 PD, Dwingeloo, The Netherlands
and
Astro Space Center of Lebedev Physical Institute, Moscow, Russia

1. Introduction

Very Long Baseline Interferometry (VLBI) technique occupies a special place among tools for studying the Universe due to its record high angular resolution. The latter is in the inverse proportion to the length of interferometer baseline at any given wavelength. Until recently, the available angular resolution in radio domain of about 1 milliarcsecond at centimeter wavelengths was limited by the diameter of the Earth. However, many astrophysical problems require a higher angular resolution. The only way to achieve this at a given wavelength is to create an interferometer with the baseline larger than the Earth's diameter by placing at least one telescope in space. In February 1997, the first dedicated Space VLBI mission, VLBI Space Observatory Program (VSOP), led by the Institute of Space and Astronautical Sciences (Japan) has been launched (Hirabayashi 1997). The VSOP mission opens a new dimension in the development of radio astronomy of extremely high angular resolution and will be followed by other Space VLBI missions. A review of scientific drives and technological challenges of the next generation Space VLBI mission have been discussed, for example, by Gurvits et al. (1996) and Ulvestad et al. (1997).

The Moon as an inevitable step in Space exploration by the mankind offers several very attractive features for building effective astronomical facilities, a radio telescopes in particular. The advantages of a Moon-based radio astronomy are briefly discussed in the section 3 below and in other presentations at this Joint Discussion. These advantages certainly would lead eventually to constructing a highly sensitive radio telescope on the Moon (possibly, a Moon-based analog of the Square Kilometer Array Interferometer (SKAI, `http://www.nfra.nl/skai/index.htm`). Once such a telescope is becoming a reality, it would be very natural to use it as a part of VLBI system.

2. Scientific case

The scientific case for a Moon-based VLBI radio telescope should be considered along the lines which have been studied for about twenty years as part of the international effort to extend VLBI systems into space (see Gurvits 1997 and references therein). Three major characteristics of a Space VLBI system have impact on its scientific potential:

- the **baseline length** – defines the highest angular resolution;
- the completeness of the *uv*-**coverage** – defines the quality of image reconstruction;
- the **aperture size** of space-borne telescope – defines the sensitivity of the VLBI system.

Three possible geometrical configurations of a VLBI system including a Moon-based telescope could be enviseged. They differ by the main characteristics of an interferometer – the geometry of its baseline(s), thus directly addressing the two former items above.

2.1. EARTH - MOON VLBI

The Earth–Moon configuration is the most immediate VLBI application for a radio telescope on the Moon. This configuration offers an angular resolution ~ 40 times higher than available on the Earth. Such the configuration offers a very limited *uv*-coverage with a duty-cycle of one month.

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Practically, it precludes VLBI imaging. However, such the Earth–Moon VLBI might be effectively used in non-imaging VLBI observations, such as estimate of a source's size directly from uv-data, especially for sources close to the ecliptic plane, for which the variation of a baseline projection during the orbital period is significant. This is of special interest for sources of extremely high brightness temperature in continuum (intraday variable extragalactic radio sources and pulsars) and in spectral lines (maser sources). Images of both continuum and maser sources are expected to be broadened by scattering effects. This would enable to investigate the properties of interstellar, and possibly, intergalactic medium.

A limited uv-coverage of a single baseline Earth – Moon might prove to be useful for astrometric experiments, especially if implemented in the Cluster-Cluster mode (*i.e.* with multiple antennas at each end of the baseline, Sasao et al. 1994 and Rioja et al. 1997). Formally, this technique at a 380 000 km baseline could enable astrometric measurements with a submicroarcsecond accuracy. It has to be noted though, that serious technical and methodological problems must be resolved before this level of accuracy becomes reachable.

Note, that an interferometer of a baseline module B with the observing wavelength of λ has a near-field zone of the size B^2/λ. Thus, the Earth–Moon interferometer will be sensitive to three-dimensional structure of a radio source at a distance up to 100 pc, provided the source is bright enough to be detectable.

2.2. MOON – MOON VLBI

This configuration presumes an existence of more than one radio telescope on the Moon. In terms of angular resolution and uv-coverage this option does not offer any advantages over Earth-based VLBI. However, new radio frequency domains unavailable on the Earth due to the atmosphere opacity (*e.g.* 60 GHz band, including the oxygen spectral line) would be of particular interest for VLBI studies from the Moon. The Moon–Moon baselines could be also considered as an enhancement in many applications for the Earth–Moon configuration described above.

2.3. MOON-BASED TELESCOPE AS AN ELEMENT OF SPACE VLBI SYSTEM

An inclusion of a Moon-based radio telescope into a VLBI system which unifies telescopes on the Earth and one or more telescopes onboard free-flying spacecraft would be the most advantageous. The choice of orbit for the next generation Space VLBI radio telescope is likely to be within the range of apogee heights of tens to several hundred thousand kilometers, which correspond to orbital periods from several hours to several days (*e.g.*, ARISE mission, Ulvestad and Linfield, 1997). The tripartial VLBI system with Earth-, Moon- and orbit-based radio telescopes would combine the high angular resolution of the Earth–Moon baseline with a high degree of completeness of uv-coverage. Such the system would be superior in high quality imaging at an angular scale 10 – 100 μas at centimeter wavelengths. It is important to note though, that the free-flying radio telescope, not the Moon-based one, is a key element of the system.

3. Technical aspects

From the technical perspective, a radio telescope on the Moon surface represents a synthesis of technical elements typical for a "standard" ground-based antenna (*e.g.* mechanical parts) and a space-borne antenna (*e.g.*, RF and digital electronics, thermal systems). The present technology is sufficient to design and build such the telescope. The following environmental properties on the Moon should be considered as advantages for radio astronomy:

- **Low gravity** would allow construction of a lighter mechanical structure than for an Earth-based telescope of the same size. It would also result in smaller structural deformations which are of crucial importance for short-wavelength antennas.
- An absence of **atmosphere** opens for radio astronomy new windows (as the mentioned above 60 GHz band) as well as eliminating propagation effects at short centimeter and millimeter wavelengths, which limit capabilities of present ground-based VLBI systems. An absence of atmosphere also eliminates another problem, especially serious for large ground-based radio telescopes – aerodynamic load.

- **Deep natural cooling** during nights (and in the under-surface thermostats) could be effectively used for achieving temperatures below 100 K relatively easy.
- **Low magnetic field** and less prominent than the terrestrial ionosphere substantially decrease phase instabilities due to propagation effects, especially significant at frequencies below 500 MHz.
- Finally, perhaps the most attractive opportunity of the Moon-based radio astronomy is an **interference-free radio environment**, especially on the farside of the Moon. This issue is increasingly tense for ground-based and low-orbit radio astronomy in spite of all the attempts to preserve "radio windows" into the Universe, which are legally protected. In some bands, the legal protection is absent, impossible or inefficient. The former is the case, for example, for extragalactic OH giga- and megamasers at redshift $z \sim 1$. Their emission falls into a band of 500 - 1000 MHz extensively used for telecommunications and other purposes. It would not be surprising, that at some stage a project similar to SKAI with the emphasis on operations at frequencies $\nu \leq 5$ GHz will be put on the agenda as a Moon-based facility. Such the telescope definitely could operate as a useful element of a VLBI system.

All the advantages above, of course, come at the expense of much higher construction and operational cost of the Moon-based radio telescope compared to an Earth-based counterpart of similar characteristics. At present, this expense hardly could be justified considering solely VLBI use of the Moon-based radio telescope. However, since a single telescope radio astronomy from the Moon has many reasons to be considered on its own right, the use of such the facility in VLBI regime would come at negligible incremental cost. Furthermore, as repeatedly stated at this Joint Discussion, sharing expenses between various users of a lunar base would result in achieving higher scientific output per investment unit (McLaughlin 1997). It has to be also noted, that a sensitive radio telescope on the Moon could serve as a facility for deep space communications with future interplanetary missions and be useful for non-astronomy applications of VLBI technique (selenology, spacecraft navigation), further increasing the overall efficiency of the investment.

4. Conclusion

VLBI could not and should not be considered as a primary drive for a radio astronomy base on the Moon. However, VLBI would be a very valuable addition to the scientific ammunition of such the base, which would allow a significant increase in scientific return of the mission at negligible incremental cost. The conclusion might seem too pessimistic for the Moon exploration enthusiasts, and too optimistic for those who believe that the topic is too exotic to be taken seriously. It is nevertheless for the sake of the science to consider this case well before it is imposed on the scientific community as a matter for budgetary consideration.

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