Applications of Very Long Baseline Interferometry (VLBI) to planetary missions

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ABSTRACT Very Long Baseline Interferometry is a radioastronomical technique capable of producing the sharpest image of the Universe. VLBI arrays include telescopes thousands of kilometers apart, operating in coordination to deliver high-precision data with milliarcsecond resolution. These advanced observational techniques have successfully been applied to space mission support as part of the Planetary Radio Interferometry and Doppler Experiment (PRIDE), enabling ultra-precise tracking of spacecraft in the Solar System. We deliver an introductory overview of VLBI and its interdisciplinary application to PRIDE, followed by a step-by-step creation of a future PRIDE observing campaign for two active orbiters around Mars.

KEYWORDS
Radio astronomy
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INTRODUCTION

Precision has always been a determining factor in the successes and failures of space missions. In an industry where costs are measured in billions of Euros and mission opportunities average at ~2 per career lifetime, the margin of error must be absolutely minimal. For obtaining this goal, the space industry has reached for an interdisciplinary alliance with radio astronomy; in particular the method of **Very Long Baseline Interferometry (VLBI)**, an astronomical technique of unprecedented precision with a plethora of applications. The Netherlands-based Joint Institute for VLBI ERIC[1] (JIVE) has created an initiative for radioastronomical enhancement of planetary missions' science return named the **Planetary Radio Interferometry and Doppler Experiment (PRIDE)**, the applications of which to ongoing and future planetary missions shall be discussed in this paper.

[1] "ERIC" stands for European Research Infrastructure Consortium. The principal task of an ERIC is to establish and operate new or existing research infrastructures on a non-economic basis.

Very Long Baseline Interferometry (VLBI)

The first application of interferometry in astronomy dates back to Michelson's stellar interferometer (1890 - 1920), an optical double-slit experiment which enabled an estimation of stellar diameter for several brightest stars. The increase in resolution required to make this experiment possible results from the fact that a single aperture of diameter d has an angular resolution $\theta \sim \lambda/d$, but two such apertures separated by a large distance D form a fringe pattern with improved resolution $\theta \sim \lambda/D$. After Karl Jansky's historic discovery of cosmic radio emission in 1933, astronomers were quick to recognize the applicability of interferometry to the newborn practice of radio astronomy. Considering the large wavelength of radio waves, angular resolution of a single radio telescope dish was quite poor. Applying the learnings from the optical counterpart, the first two-element radio interferometer performed its observations in 1946. A new vocabulary had entered radioastronomical discourse: concepts such as baseline, fringe and geometric delay became crucial for interpreting the new observations.

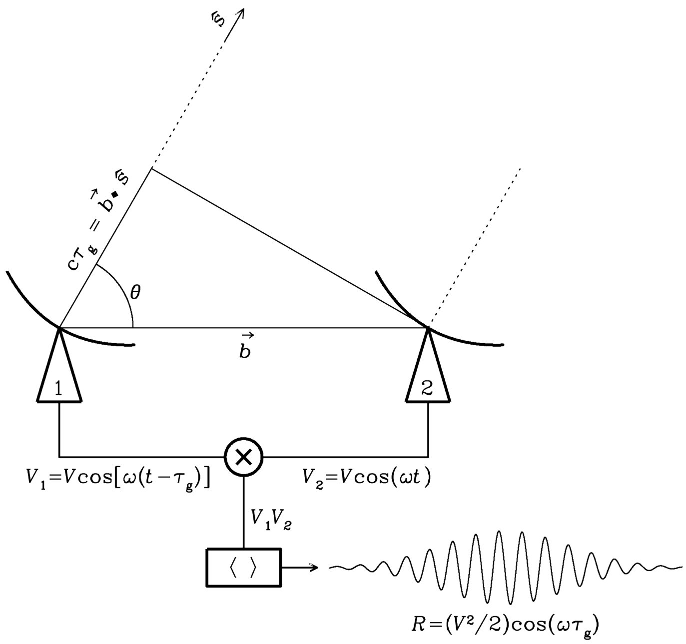

Figure 1 A diagram of the components of a two-element interferometer. Vector $\hat{s}$ points towards the target source, $\vec{b}$ is the baseline. Output voltages V_1 and V_2 are multiplied and averaged by the correlator, creating a time-dependent interferometric fringe. (Source: NRAO)

A sketch of this simple two-element interferometer is seen in Fig. 1. A point source in the direction of unit vector $\hat{s}$ is emitting monochromatic radiation of frequency $\nu = \omega/(2\pi)$. The vector pointing from antenna 1 to antenna 2 is the **baseline** vector. The length of the baseline will determine the angular resolution of this configuration. Incident radiation will produce output voltages at the two receivers, retarded by the **geometric delay** $\tau_g = \vec{b} \cdot \hat{s}/c$. These voltages are amplified, multiplied ($\times$), and time averaged ($\langle\rangle$) by a device called the **correlator** (because the time average of the product of two signals is proportional to their cross-correlation), generating an output **fringe** which varies as

$$R = \frac{V^2}{2}\cos(\omega\tau_g) = \frac{V^2}{2}\cos\left(\frac{b}{c}\cos\theta\right). \quad (1)$$

The amplitude of this response is proportional to the flux density of the point source, and the phase depends on the position of the source in the sky. The broad Gaussian envelope of the fringe shown in Fig. 1 shows how the quasi-sinusoidal signal is attenuated as the source passes through the beam of the dishes as their pointing remains fixed.

Evidently, a small shift $\mathrm{d}\theta$ in the position of the source registers as a fringe phase shift

$$\mathrm{d}\phi = \frac{b}{c}\sin\theta\,\mathrm{d}\theta. \quad (2)$$

The fringe phase is thus an exquisitely sensitive measure of source position if the projection of the baseline $b\sin\theta$ is many wavelengths long. By using highly precise atomic clocks in measuring the fringe phase, we can obtain sub-arcsecond precision in our measurements despite small pointing offsets in the individual antennas. This realization prompted the first fully successful VLBI experiment to be conducted a little over 50 years ago, in 1967. It included stations at the Algonquin Radio Observatory near Ottawa, Ontario, and the Dominion Radio Astrophysical Observatory near Penticton, British Columbia, a baseline of incredible 3,074 kilometers (Broten et al. 1967). What set VLBI apart from conventional radiointerferometry is nonexistence of physical connection between interferometer elements, rendering real-time data processing impossible. Observations had to be recorded on tape and timestamped with utmost precision, then transported to a facility which would correlate and process the data.

The next development in interferometry was adding multiple telescopes to an interferometer, thus creating $N(N-1)/2$ simultaneously observing baselines (resulting in a wider range of observed spatial scales), and increasing the total collecting area (resulting in higher sensitivity). Furthermore, if the observing times were made to be very long, rotation of the Earth would cause baseline projection lengths to vary with respect to the source, increasing the range of possible baseline lengths even further. However, with the creation of increasingly complex multi-element interferometric arrays, imaging also became more complicated. New methods had to be developed using Fourier analysis, which are now known as **aperture synthesis** (Ryle 1961). Essentially, this procedure allows us to reconstruct the image produced by any given telescope aperture by only sampling the cross-correlation of the radiation field at a given set of points on the aperture. If we now consider our array as one giant aperture with radius corresponding to the longest baseline, we can synthesize an image as seen by this imaginary giant telescope just from the output of individual pairs of telescopes. The quality of this image depends on the number and variation of baselines.

(For a more comprehensive overview of the history of radio interferometry and the mathematics behind aperture synthesis, see textbooks by Thompson et al. (2001) or Wilson et al. (2009).)

In the case of modern VLBI, this synthesized aperture can have the diameter of the Earth, or even larger if radio observing satellites are included. Institutes like JIVE are tasked with coordinating observations using a network of international, globally distributed individual telescopes, most notably the **European VLBI Network (EVN)**. The EVN is a network of radio telescopes located primarily in Europe and Asia, with additional antennas in South Africa and Puerto Rico, which has the ability to perform high angular resolution observations of cosmic radio sources. (See map in Fig. 2.) For reference, the milliarcsecond resolution obtainable by the EVN is a thousand times better than the resolution of the optical Hubble telescope. It is the most sensitive VLBI array in the world, thanks to the collection of extremely large telescopes that contribute to the network. Global VLBI observations are also often conducted in conjunction with the Very Long Baseline Array in the USA and the Russian RadioAstron satellite in Earth orbit.

The data processing for the EVN is also done at JIVE; observations are recorded on high capacity magnetic tapes at individual telescopes, and these are later replayed and combined at a special purpose data processor - the "Correlator" - a supercomputer located at the JIVE headquarters in Dwingeloo, the Netherlands. Advances in optical fibre technology have recently inspired the development of **e-VLBI** (Garrett 2004), a novel technique in which VLBI streams are transmitted to the JIVE Correlator in real time even from the most remote stations across the world, paving the way for the next generation of radio astronomy free of the need for physical delivery of magnetic tapes.

Planetary Radio Interferometry and Doppler Experiment (PRIDE)

This research applies the methods of VLBI somewhat unconventionally. Instead of observing radio signals of distant galaxies and quasars, we observe the transmissions of spacecraft within the Solar System.

PRIDE: the Planetary Radio Interferometry and Doppler Experiment (Duev et al. 2012) is an initiative by the Joint Institute for VLBI ERIC (JIVE) providing **ultra-precise estimates of spacecraft state vectors** (spatial coordinates and velocities) as a function of time utilizing phase-referenced[2] VLBI tracking and radial Doppler measurements. This method is applicable to any radio-emitting spacecraft, and the results can be used in a plethora of disciplines from planetary science to high-precision celestial mechanics, gravimetry and fundamental physics. Although PRIDE shares some similarities with traditional astrometric applications of the VLBI technique, additional modifications are required in the data processing stage to account for the spacecraft emitting in the near-field regime of the VLBI-synthesized aperture. These are not simple corrections, as the incoming radiation can no longer be treated in the plane-wave approximation. For this purpose, a dedicated software toolkit has been developed at JIVE. In addition to the VLBI observables, PRIDE can also produce open-loop radial Doppler observables for the spacecraft by processing data from individual telescopes separately.

The accuracy of the PRIDE method was first demonstrated by Duev et al. (2012) by tracking ESA's Venus Express spacecraft under the EVN observing project EM081. Despite unfavourable observing conditions (low target declination, high separation with calibrator), the orbit accuracy estimate was at a 3-sigma level of 200-300 m across the VEX track and 500-600 m along the track. A significant sharpening of the PRIDE technique was achieved by tracking MEX during its closest fly-by of Phobos under the EVN experiment GR035 (Duev et al. 2016), enabling the measurement of the lateral position and radial Doppler of the MEX spacecraft with a **precision of about 50 m and 30 μm/s**, respectively. These results are comparable to closed-loop Doppler data obtained by dedicated deep space tracking systems like NASA's Deep Space Network and ESA's Estrack (Bocanegra-Bahamón et al. 2017), proving that PRIDE data could enhance the science return of missions not initially designed for radio science experiments. As such, PRIDE has been selected by ESA to provide high-precision tracking for the JUpiter ICy moons Explorer mission (JUICE) launching in 2022.

Many other opportunities for the application of PRIDE are possible both in existing and future missions. However, the precision of PRIDE depends heavily on the availability of a nearby phase calibrator source; that is, a compact unresolved radio source of known spectral properties (most commonly a quasar) which is observed by the telescopes to calibrate the

[2] *Phase referencing* is the practice of observing nearby calibrator sources of known properties to correct for atmospheric effects during observation of a target.

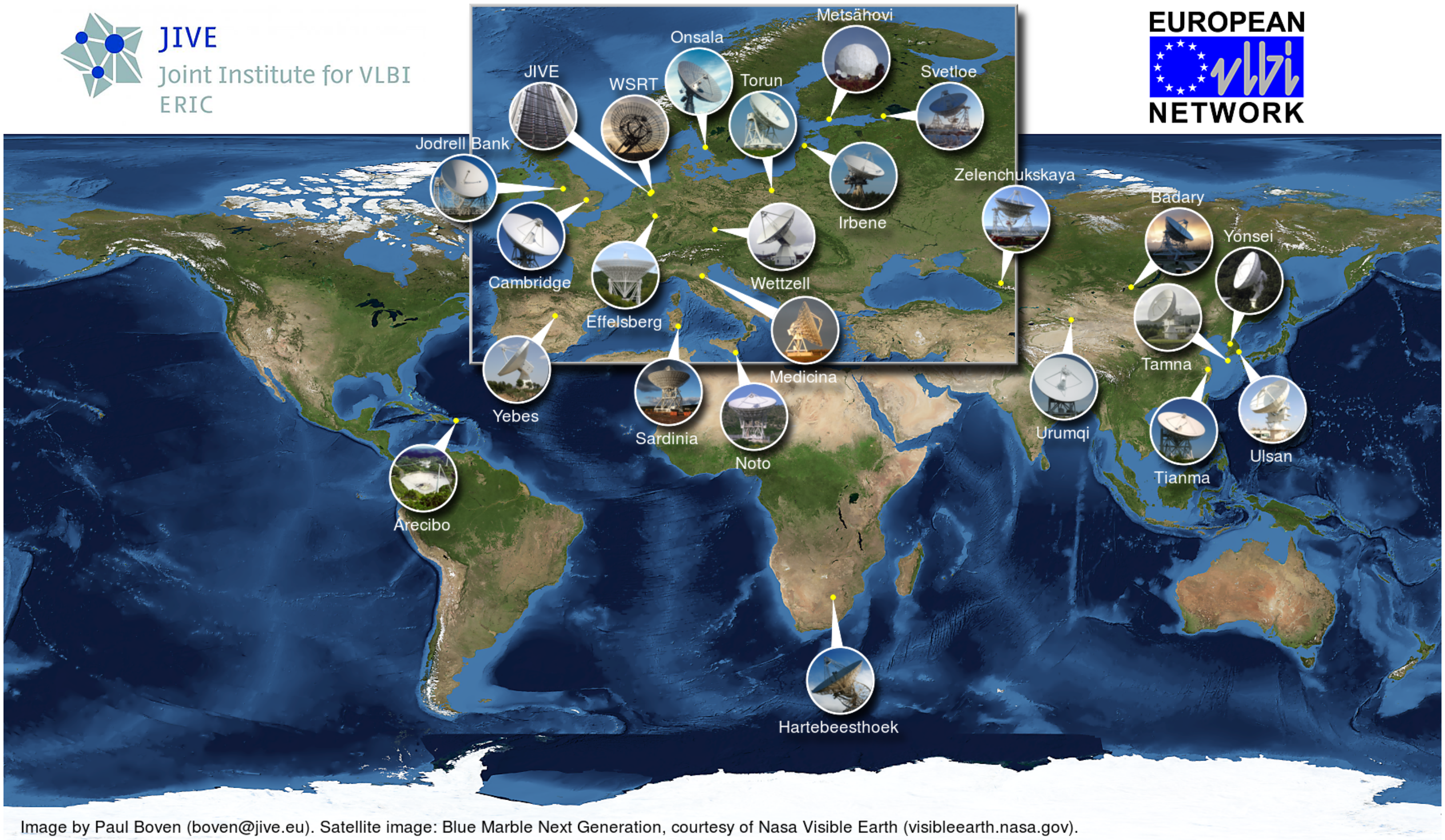

Figure 2 A global map of European VLBI Network telescopes as of December 2016. (Courtesy of P. Boven.)

image for atmospheric interference. If the nearest calibrator is too far from the target, atmospheric conditions might vary at this scale, resulting in poor image quality. If the calibrator is within 2^o of the target, calibration can be performed, but the telescopes have to be periodically steered back-and-forth between the target and calibrator, a practice known as *nodding*. Ideally, a phase reference source should be within 2" of the target, in which case both sources are contained inside the array's synthesized beam and can be observed simultaneously, yielding results of the highest quality.

These considerations greatly impact mission and observation planning, so the focus of the following sections is on locating suitable calibrator sources and therefore PRIDE opportunities for two currently ongoing Martian missions.

A DUAL-SPACECRAFT PRIDE EXPERIMENT

The increasing number of artificial satellites in Mars orbit is a testament to the wealth of scientific insight gained from continuous studies of our most Earth-like planetary neighbour. Out of six currently active orbiters in the Martian system, two are operated by the European Space Agency (Fig.3): Mars Express (Schmidt 2003) and the ExoMars Trace Gas Orbiter (Gibney 2016)

Mars Express (MEX) was Europe's first mission to Mars, an international effort including a stereoscopic camera from Germany, a mineralogical mapping device from France and an atmospheric sounder from Italy. Efforts were joined with the Jet Propulsion Laboratory in California to engineer a radar probe for subsurface water, and with the UK for the construction of the accompanying Beagle-2 lander. Launched in 2003, its impressive science return has justified six mission extensions, lengthening the lifespan of the durable orbiter well into its second decade. MEX has since become an invaluable communications relay between landers on the Martian surface and Earth, transmitting a downlink signal at X-band (8.4 GHz). MEX has been the favourite target of the Space Science and Innovative Applications group at JIVE for many years. Analysis of its signal allowed them to characterize the solar wind, including the study of a Coronal Mass Ejection (Molera Calvés 2017). Observed for over a decade, it has served as a prototype study for the Planetary Radio

Interferometry and Doppler Experiment (PRIDE).

In October 2016, the **ExoMars Trace Gas Orbiter** (TGO), a collaboration between ESA and Russian Roscosmos, was successfully injected into Mars orbit. The TGO is a hybrid science and telecom orbiter tasked with analyzing the Red Planet's atmosphere for traces of methane and other atmospheric signatures of biological activity, as well as providing a communications link for upcoming surface missions such as the 2020 ExoMars rover. The TGO is expected to complete its aerobraking procedure in March 2018 and settle into a 400 km circular orbit, where it will perform its science operations.

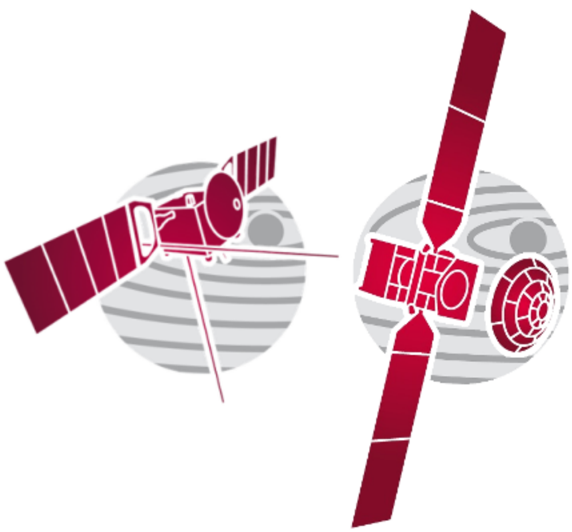

Figure 3 Mission insignia for Mars Express (left) and ExoMars 2016 (right), consisting of the Trace Gas Orbiter and Schiaparelli lander. (Copyright: ESA)

High-precision reconstruction of MEX's orbit during the Phobos fly-by in 2015 enabled the gravitational field of Phobos to be studied, shedding light on the moon's internal geological composition and in turn its mysterious origin (Rosenblatt, in prep). Now, the presence of two simultaneously transmitting spacecraft in Mars orbit offers an opportunity for a dual PRIDE experiment, resulting in twice the science return at the cost of one observation (a more humane equivalent of 'two birds with one stone'). The resulting data could theoretically be used to better constrain the ephemeris (trajectory) of Mars, as well as providing a valuable case study for future PRIDE experiments in the Jovian system. In the following subsection, we will explore potential observing opportunities for this experiment to be conducted.

The search for phase calibrators

As mentioned earlier, the quality of a VLBI observation depends on the availability of a calibrator (phase reference) source in the immediate vicinity of the target source. Considering that our target is a planet, or rather the spacecraft in its orbit, the target noticeably moves across the sky relative to distant extragalactic radio sources over the course of several hours. Therefore, the first step is to generate a **finding chart**: a list (or plot) of the coordinates of Mars in the sky for a given time period as observed from Earth.

The motion of planets is a highly complex numerical integration of an n-body problem, involving perturbational effects due to the interaction of all Solar System bodies, tidal forces, libration, relativistic corrections and many more considerations. To generate the ephemeris of Mars, we will use the Jet Propulsion Laboratory Development Ephemeris DE432s (Folkner et al. 2014), the latest model of the Solar System produced at the Jet Propulsion Laboratory in Pasadena, California, primarily for purposes of spacecraft navigation and astronomy. The model consists of computer representations of positions, velocities and accelerations of major Solar System bodies.

The JPL ephemerides are accessed through `astropy`, a community Python package for astronomy. The observing location is set to Greenwich, as it will not significantly impact the ephemeris at the arcminute scale. The ephemeris of Mars is computed in GCRS[3] for the time range of 25th October 2017 to 1st October 2019, sufficient time for the it to wrap fully around the celestial sphere.

The next step is to form a strip of sky two degrees wide, centered on the ephemeris, and to look for radio sources within this strip. These sources could all be used as potential calibrators for the PRIDE experiment if the telescopes are set to nodding mode.

We perform a coordinate search in the Radio Fundamental Catalogue (RFC) (Petrov 2017), currently the most complete catalogue of compact radio sources produced by analysis of all available very long baseline interferometry (VLBI) observations under absolute astrometry and geodesy programs since year 1980. It contains precise positions with milliarcsecond accuracies for 14,786 objects.

The resulting 278 potential calibrators are shown in red in the resulting finding chart in Figure 4. We find that they are more or less uniformly distributed along the ephemeris. Now we wish to further con-

[3] The Geocentric Celestial Reference System.

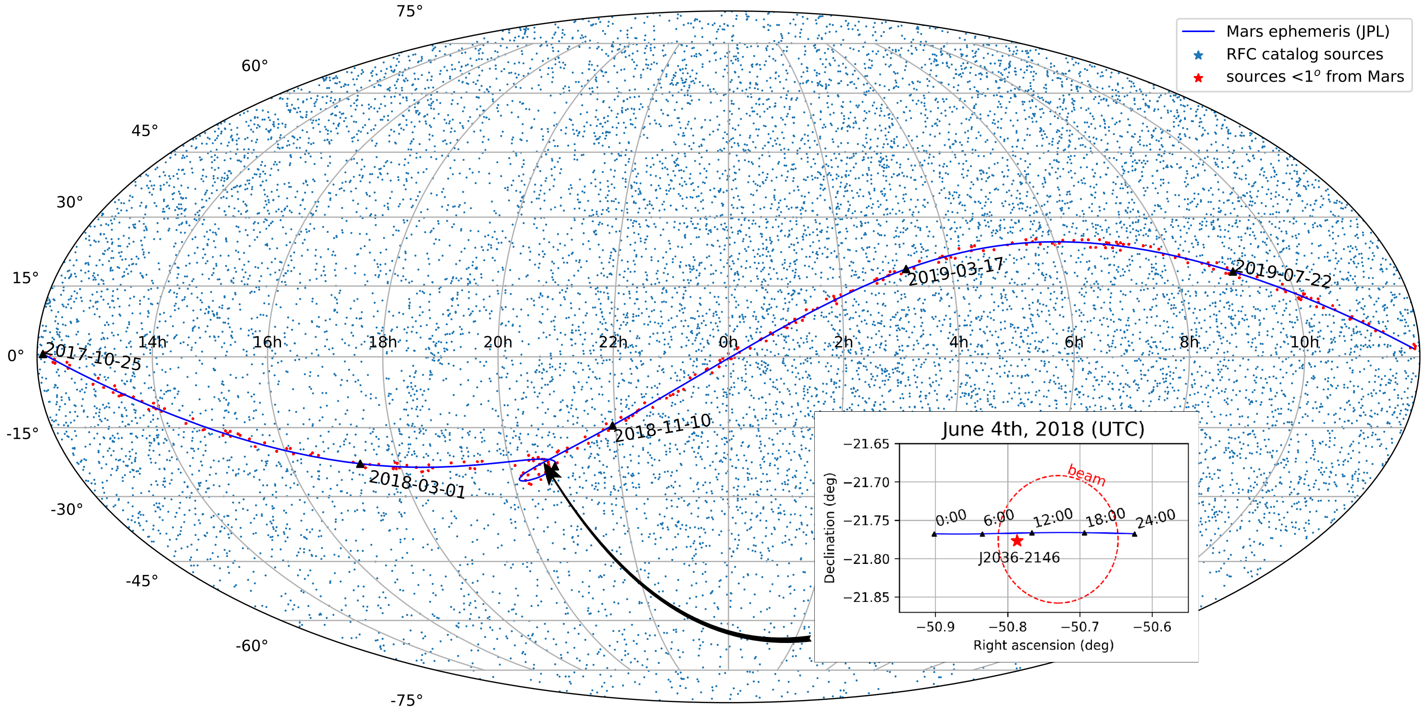

Figure 4 A finding chart for Mars for the time period of 25th October 2017 to 1st October 2019 displayed in the Mollweide projection. The ephemeris is plotted in blue and timestamped (YYYY-MM-DD), Radio Fundamental Catalogue sources are marked with blue stars, potential calibrators are marked with red. The inset shows an in-beam phase-referenced observing opportunity on June 4th, 2018. The beam width is set to 5 arcminutes.

strain the angular separation between Mars and the calibrators to 2 arcminutes, seeking opportunities for in-beam observations.

The instances of near-passes at less than 2 arcminute separation are listed in Table 1. The RFC coordinates were cross-checked with the NASA Extragalactic Database (NED) through the `astroquery` package to provide additional information about the sources. We are presented with 5 observing opportunities for an in-beam dual-spacecraft PRIDE experiment.

However, only the first of these events coincides with the Standard EVN observing sessions scheduled for this year (Session 2: May 24th - June 14th, see the EVN Call for Proposals online). Hence, we will focus on planning an observing campaign for June 4th. If time on the telescope cannot be granted on the target date, then we could also present the other out-of-session alternatives.

Table 1 Potential in-beam phase reference sources

RFC name	RA (h:m:s)	dec (d:m:s)	NED name	near pass date	Type
J2036-2146	20:36:51.172722	-21:46:36.74937	LQAC 309-021 001	2018-06-04	QSO
J2033-2253	20:33:16.629404	-22:53:17.00751	PKS 2030-23	2018-09-29	G
J2247-0850	22:47:52.193173	-08:50:22.07846	WISE J224752.19-085022.0	2018-12-02	*
J0033+0335	00:33:12.887751	+03:35:50.16565	GALEXASC J003312.82+033549.7	2019-01-14	UvS
J0103+0659	01:03:31.757397	+06:59:21.22107	PMN J0103+0659	2019-01-27	RadioS

Scheduling an observation

The observing opportunity on June 4th 2018 will use source J2036-2146 (Fig.5) as a phase-reference calibrator. A query of NED and Veron-Cetty catalogue reveals this object to be a flat-spectrum[4] radio source classified as a quasar at redshift z=2.299. Integrated flux density at X-band is 229 mJy.[5] The source is compact and unresolved with position accuracy better than 25 nrad, which means it is suitable for use as a VLBI calibrator.

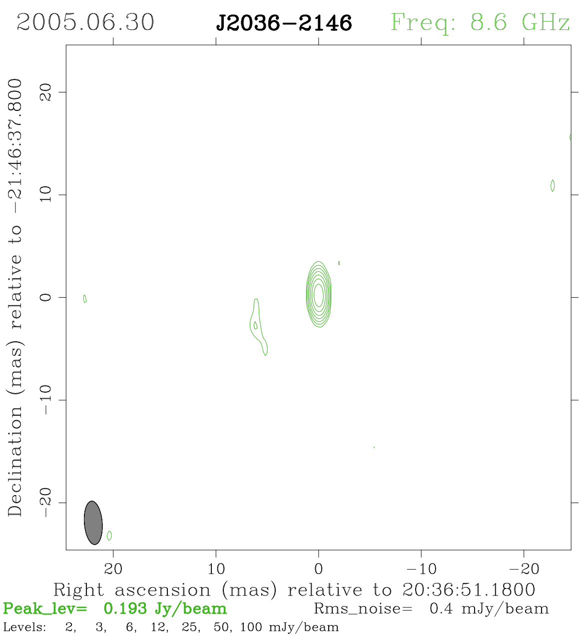

Figure 5 A contour map of brightness distribution at X-band for source J2036-2146. (Credit: Yuri Y. Kovalev, astrogeo.org database)

The observation will be planned and scheduled using SCHED, the universal program for creation and distribution of schedules to VLBI telescopes and correlators.

Among other things, SCHED can offer useful elevation-time and uptime plots for each of the observing stations. This is crucial in planning the observing time and deciding on the participating telescopes. These plots are shown in Figure 6 for our calibrator source and 16 stations (east to west): Effelsberg (DE), Medicina (IT), Onsala (SE), Wettzell (DE), Metsähovi (FI), Hartebeesthoek (SA), Zelenchukskaya (RU), Urumqi (CN), Shanghai (CN), Badary (RU), Tianma (CN), Katherine (AU), Ulsan (KR), Kashima (JP), Hobart (AU), Parkes (AU). Evidently, the low target declination (-21.46^o) is inconvenient for the European stations, as the maximum elevation the source reaches is around 20^o or less. On the other hand, much longer simultaneous uptimes and elevations are achieved with the lower-latitude Chinese, Korean, Japanese and Australian telescopes.

This suggests that we should constrain our observing time from 16:00 UT to 22:00 UT and use the stations Hobart, Parkes, Kashima, Ulsan, Katherine, Tianma and Shanghai.

The primary beam size will be determined by the largest antenna, according to Rayleigh's formula θ [rad] $= 1.22\lambda/D$. Since the two spacecraft emit at X-band (8.4 GHz), the waveband of interest is λ=3.6 cm. We can estimate the optimal beam size by examining the angular separation of Mars and the calibrator during our observing time. The separations are presented on an hourly basis in Table 2. Clearly, for both sources to stay in-beam during the observation, we would like the beam radius to be no smaller than 5 arcminutes, as is shown in the inset in Figure 4. This means we cannot observe with antennas larger than 30 m, disabling Tianma and Parkes, both >60 m in radius.

Table 2 Angular separation between Mars and calibrator

Time (ISO, UTC)	Separation (d:m:s)
16:00:00.000	0:04:12.1915
17:00:00.000	0:04:52.4167
18:00:00.000	0:05:32.5103
19:00:00.000	0:06:12.2883
20:00:00.000	0:06:51.6035
21:00:00.000	0:07:30.3479
22:00:00.000	0:08:08.4561

Finally, we need to specify the recording format for the observation, taking into account the transmission specifics of the spacecraft. The observation should be recorded in 128 Mbps bitrate in a single polarization. The polarization should be divided in 4 subbands, each 8 MHz wide, all centered on 8420.432 MHz, the telemetry/tracking frequency for MEX and TGO. This information, combined with the scheduling parameters produced by SCHED, completes the setup for a future PRIDE experiment.

[4] A spectrum is *flat* if flux density is constant as a function of frequency.

[5] Jansky is a typical radioastronomical unit of spectral flux density, $1\text{Jy} = 10^{-26}\ \text{Wm}^{-2}\text{Hz}^{-1}$.

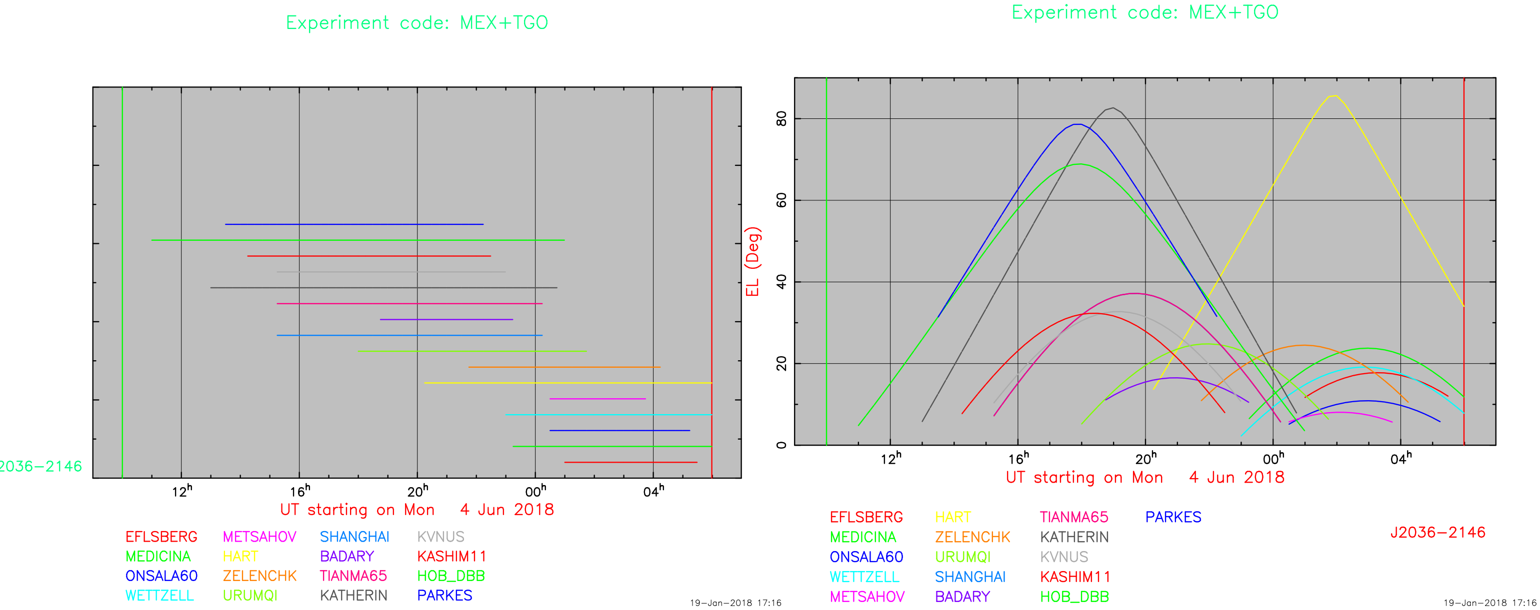

Figure 6 SCHED output for uptime per telescope (left) and elevation vs. universal time (right) for target J2036-2146 on June 4th 2018. The 16 telescopes are listed below the image and in the text.

CONCLUSIONS

In the 50 years since its conception, Very Long Baseline Interferometry has provided some of the sharpest images of the Universe. VLBI arrays now span entire continents and even extend beyond our planet. The milliarcsecond resolution of these arrays has successfully been applied to planetary mission support as part of the Planetary Radio Interferometry and Doppler Experiment. PRIDE is able to locate spacecraft in the Solar System by shadow-tracking their radio transmissions, yielding ultra precise estimates of their state vectors. In anticipation of the key role PRIDE is going to play in future missions to the outer planets, a rare opportunity was found to further improve the technique and enhance its return. A simultaneous observation of two orbiters around Mars together with an in-beam phase-reference source has been pinpointed to June 4th, 2018, forming the basis of an EVN observing campaign. The scientific return from this experiment is expected to offer valuable insight into dynamics of the Martian system, including an improved constraint on the ephemeris of Mars.

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