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The science case for simultaneous mm-wavelength receivers in radio astronomy

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ABSTRACT

This review arose from the European Radio Astronomy Technical Forum (ERATec) meeting held in Firenze, October 2015, and aims to highlight the breadth and depth of the high-impact science that will be aided and assisted by the use of simultaneous mm-wavelength receivers.

Recent results and opportunities are presented and discussed from the fields of: continuum VLBI (observations of weak sources, astrometry, observations of AGN cores in spectral index and Faraday rotation), spectral line VLBI (observations of evolved stars and massive star-forming regions) and time domain observations of the flux variations arising in the compact jets of X-ray binaries.

Our survey brings together a large range of important science applications, which will greatly benefit from simultaneous observing at mm-wavelengths. Such facilities are essential to allow these applications to become more efficient, more sensitive and more scientifically robust. In some cases without simultaneous receivers the science goals are simply unachievable. Similar benefits would exist in many other high frequency astronomical fields of research.

1. Introduction

Very Long Baseline Interferometry (VLBI) studies at cm wavelengths is a well-established field, with advanced technological developments and analysis techniques that result in superb quality images, including those of very weak μJy sources (e.g., Garrett, 2005) and with micro-arcsecond (μas) astrometry (e.g., Reid and Honma, 2014), using phase referencing (*hereafter* PR) techniques.

VLBI at mm and sub-mm wavelengths (*hereafter* mm-VLBI) can result in the highest angular resolutions achieved in astronomy and has a unique access to emission regions that are inaccessible with any other approach or at longer wavelengths, because the compact areas of interest are often self-absorbed or scatter-broadened. Therefore it holds the potential to increase our understanding of the physical processes in, for example, Active Galactic Nuclei (AGN) and in the vicinity of super-massive black holes, and for studies of molecular transitions at high frequencies.

Nevertheless the scientific applications of mm-VLBI have to date been much less widespread, the reason being that the observations become progressively more challenging as the wavelengths gets shorter because of the: limited telescope surface accuracy and efficiency, higher receiver system temperatures and lower sensitivity and shorter atmospheric coherence times. Also most compact extra-galactic sources used as cm-wave phase references are intrinsically weaker, if not resolved-out, at shorter wavelengths. These in turn prevent the use of phase referencing calibration techniques, which are routinely used in cm-VLBI, and all benefits resulting from them, beyond $\sim$ 43 GHz (with a single exception (to date) of PR at 86 GHz by Porcas and Rioja (2002)).

Continuous development and technical improvements have led to a sustained increase of the high frequency threshold for VLBI

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observations in the last two decades (e.g., Krichbaum et al., 2014). Regular observations up to 86 GHz are being carried out with well established networks such as the Very Long Baseline Array (VLBA) and Global mm-VLBI Array (GMVA), most recently with the Korean VLBI Network (KVN) up to 130 GHz, and ad-hoc observations at the highest frequencies up to 240 GHz with the Event Horizon Telescope (EHT) (Doeleman et al., 2008). The field of mm-VLBI will benefit from the arrival of phased-up Atacama Large Millimeter and submillimeter Array (ALMA) (Matthews and Crew, 2015; Tilanus et al., 2014) for joint VLBI observations.

The benefit of multi-frequency based calibration techniques in observations at high frequencies, which are dominated by non-dispersive fast tropospheric fluctuation errors, has long been known. It relies on using the correctly scaled calibration derived at lower frequencies to correct the higher frequencies; see, for example, Carilli and Holdaway (1999); Asaki et al. (1996) for connected interferometers. This has been extended to VLBI observations using the frequency agility capability (i.e. fast frequency switching) of the VLBA, initially offering an increased coherence (Middelberg et al., 2005) and, after further development, bona-fide astrometric measurements (Dodson and Rioja, 2009; Rioja and Dodson, 2011) at the highest frequency of 86 GHz. The first step is known as Frequency Phase Transfer (FPT), where the solutions for the low frequency $\nu_{\rm low}$ are applied to the high frequency $\nu_{\rm high}$, scaled by the ratio of the frequencies. This does not provide astrometry because of dispersive terms, such as the ionosphere, and also the inherent phase ambiguities in the phase solutions at $\nu_{\rm low}$. The latter is not a problem if the ratio is an integer, as then the ambiguities continue to cancel, or if the number of ambiguities are zero, which requires the positions to be well known. The FPT calibration step eliminates all the common non-dispersive residual errors on the target source. The second step provides Source Frequency Phase Referencing (SFPR) by including an additional 'conventional' phase referencing step on a second source, which eliminates all other common residual errors, which are mainly dispersive and/or instrumental. This switching can be over long cycle times and large angular separations, as these terms are slow changing and have weak angular dependence.

The use of this calibration technique on the VLBA has not been widespread, the reason being that the data reduction was challenging because of the fast temporal variations arising from the troposphere. Nevertheless there are a few examples of such analysis (Rioja and Dodson, 2011; Rioja et al., 2014; Marti-Vidal et al., 2016). The KVN has introduced a new engineering development in receiver technology (Han et al., 2013) to address this issue, with the capability for simultaneous multi-frequency observations at four bands. Using KVN observations and multi-frequency based calibration techniques it is possible to phase reference the observations at frequencies up to 130 GHz. In this document we will explore some of the scientific topics and current issues that will benefit from this technical capability.

Simultaneous multi-frequency observing enhances mm-VLBI in two main areas: massively increasing the coherence time, for observing weak sources at high frequencies, and enabling accurate astrometric registration between frequency bands. The raw increase in coherence time, even at 130 GHz, has been shown to be easily enlarged from tens of seconds to a few tens of minutes, using observations of the target source only (Rioja et al., 2015). This increase in coherence time would be the equivalent to a three-fold increase in the dish diameter, or an increase of two orders of magnitude in the recorded bandwidth. Furthermore the latter would only apply for continuum science, as this does not assist the important spectral line science cases. The coherence time can be further increased by including the observations of a calibrator source.

Accurate astrometry is required to allow bona-fide spectral index or Faraday rotation measure investigations in continuum sources and the measurements of the frequency-dependent position of the continuum cores in extragalactic radio sources (Wrobel, 1993; Hovatta et al., 2012). Spectral line models enable high-precision measurements of the structure and kinetics of the various components of the studied sources, using different tracers (e.g. Dodson et al., 2017a; Soria-Ruiz et al., 2004), or by using absorption of continuum flux by intervening gas (van Langevelde et al., 20s05; Momjian et al., 2003). VLBI is the most developed area driving the demand for simultaneous mm-wavelength receivers, but it is not the only field. Time domain radio astronomy is a growth area, and for rapidly changing sources with strong mm-wavelength emission simultaneous mm-wavelength receivers add an important new capability to aid the interpretation of observations. The study of pulsars is a well-known example and is a target of the BlackHole Cam ERA project, but the examples we review in this paper are results from the spectral evolution of the strong and rapidly changing mm emission from the jets in compact X-ray binaries.

Therefore there is a wealth of possibilities opened up by the application of simultaneous multi-frequency mm-wavelength observing, using demonstrated methods and technology. In this paper we present some of the headline cases for continuum and spectral line VLBI and time-domain observations.

Table 1
Baseline sensitivities for the lower observing frequency in the range and for the higher observing frequency, after Frequency Phase Transfer to increase the coherence time, for current mm-wave facilities capable of this style of observing. [a]1/3 cycle time of 2 min at 2Gbps [b]1/3 cycle time of 30 min at 2Gbps, [c]2 min at 0.5 Gbps, [d] 30 min at 0.5 Gbps, [e] 1min at 0.5 Gbps, *f* 30 min at 0.5 Gbps.

Facility	Freq. range	Baseline sensitivity mJy ($\nu_{\rm low}$)	FPT Baseline sensitivity mJy ($\nu_{\rm high}$)
VLBA	22–86 (switched)	4[a]	8[b]
KaVA	22–43	10[c]	4[d]
KVN	43–130	22[e]	12[f]

1.1. Current achievable sensitivities for mm-wave observatories

We review the current status and sensitivities of facilities capable of supporting simultaneous mm-wave observing. VLBA is capable of switching between receivers in 10–20 s, depending on the pairing. KVN was built for simultaneous observing, and this capability is now been extended to all of KaVA (the KVN and VERA Array). Table 1 lists the expected baseline sensitivities[1] for these arrays with current standard recording bandwidths and observing modes (i.e. fast frequency switching or simultaneous), using the lowest frequency in the range (with typical coherence times) and the highest frequency in the range (with a typical post-FPT coherence time of 30 min). Overheads for FFS are included. Post-SFPR coherence time is essentially infinite, theoretically providing infinite sensitivity. A typical SFPR image for a long observation (5 h of on-source time) would be about three times more sensitive than the FPT image (and astrometrically registered).

We note that these results are for current (2017) facilities and bandwidths, and facilities are being upgraded and/or built around the world: ALMA offers a generational leap in sensitivity and maximum frequency for interferometric arrays, additionally a number of large mm-wave single dishes have been built (Yebes 40m, LMT 50 m, the ALMA 12 m prototypes now located in Arizona and Greenland, KVN, Metsahovi 14m, and several others proposed). Single dish antennas can be easily upgraded to host simultaneous multi-frequency receivers, as has been done at VERA and Yebes. Discussions are on-going as to whether this should be done at ALMA, largely to aid in the long baseline observing at their highest frequencies. In addition Australia Telescope Compact Array (ATCA), ALMA and the Jansky Very Large Array (JVLA) are all capable of sub-array mode observing, which does allow for - at the very least - Frequency Phase Transfer and should allow SFPR in compact configurations.

[1] from the EVNCalc tool http://www.evlbi.org/cgi-bin/EVNcalc.pl.