PROCEEDINGS OF SCIENCE

Real time cosmology - A direct measure of the expansion rate of the Universe with the SKA

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In recent years cosmology has undergone a revolution, with precise measurements of the microwave background radiation, large galaxy redshift surveys, and the discovery of the recent accelerated expansion of the Universe using observations of distant supernovae. All these groundbreaking observations have boosted our understanding of the Cosmos and its evolution. Because of this detailed understanding, more detailed tests of cosmological models require unprecedented precision that is only available with the next generation of astronomical observatories. Radio observations in particular will be able to access more independent modes than optical, infrared or X-ray facility and will show very different systematics compared to these other wavebands.

The SKA enables us to do an ultimate test in cosmology by measuring the expansion rate of the Universe in real time. This can be done by a rather simple experiment of observing the neutral hydrogen (HI) signal of galaxies at two different epochs. The signal will encounter a change in frequency imprinted as the Universe expands over time and thus monitoring the drift in frequencies will provide a real time measure of the cosmic acceleration. Over a period of 12 years one would expected a frequency shift of the order of 0.1 Hz assuming a standard ΛCDM cosmology. However, monitoring such changes would require some modifications to the current baseline design of the SKA. In particular, the design needs to be adapted to achieve higher spectral resolution, at least within sub-bands (strong requirement), and to allow for a well monitored distribution of the local oscillator signal, preferably at milli-Hz accuracy over a period of 12 years (weaker requirement, which could be circumvented by pulsar observations). Based on the sensitivity estimates of the SKA and the number counts of the expected HI galaxies, it is shown that the number counts are sufficiently high to compensate for the observational uncertainties of the measurements and hence allow a statistical detection of the frequency shift. In addition, depending on the observational setup, it is shown that the evolution of the frequency shift in redshift space can be estimated to a precision of a percent.

Although technically challenging, the direct measurement of the frequency shift and hence the cosmic acceleration can provide a model independent confirmation of dark energy. At highest precision it can distinguish between some competing cosmological models and combined with probes at other wavelength can break degeneracies and improving the figure of merit of cosmological parameters.

Advancing Astrophysics with the Square Kilometre Array
June 8-13, 2014
Giardini Naxos, Italy

http://pos.sissa.it/

PoS(AASKA14)027

1. Introduction

The Big Bang concept of our Universe is well established as “the standard model of cosmology”, but currently the observational data cannot tighten constraints on the physics at work at the very earliest phase in its evolution. In this picture, shortly after the big bang, 13.8 billion years ago, the Universe was dominated by an energy field with negative pressure that drove a period of accelerated expansion, “the inflation” phase. Since then the Universe has expanded, cooled down, and changed from a radiation- to a matter-dominated composition. If its content is dominated by a composition of baryonic and cold dark matter one would expect a decelerated expansion of the Universe. However by using type Ia supernovae (SNIa), as standard candles, a surprising discovery has been made, that the expansion of the Universe is undergoing a second epoch of acceleration (Riess et al. 1998, Perlmutter et al. 1999, this research was awarded a the Nobel prize in physics 2011). The reason for this recent accelerated expansion is still a mystery and points to an additional phase of negative pressure contribution of the mass-energy field and a possible modification of Einstein’s general relativity. Thus measuring the recent acceleration will provide an additional route to probe the equation of state and the interplay of dark energy.

Techniques to measure expansion rates in the Universe were already explored in 1962 by Sandage (Sandage 1962), but the technological limitations at these time kept these measurements out of reach. It took more than 30 years for this idea to be revisited and Loeb proposed in 1998 to use Lyman-alpha forest absorption lines toward quasars for this measurement. The author concluded that the signal might be marginally detectable with a 10-m class telescope (Loeb 1998). Now with the E-ELT, a 40-m class telescope, to be built in the near future it seems possible to perform the “Loeb’ test” with a specially designed spectrograph (for more information on the CODEX[1]-like experiments see e.g. Pasquini et al. 2005; Liske et al. 2008a, Liske et al. 2008b, Maiolino et al. 2013). Unfortunately this test is greatly affected by the cut-off restriction of ground based observations introduced by the atmosphere. Due to this cut-off, Lyman-alpha photons can only trace redshifts ($z \geq 1.65$) at which most of the cosmological models describe the expansion rate of the Universe by deceleration only. SKA observations in contrast, of the neutral hydrogen (HI) signals of Milky Way-type galaxies up to redshifts of unity, are not greatly affected by the atmosphere or ionosphere. This redshift regime is the one at which most of the “nearby” acceleration takes place and therefore is the most promising to investigate the influence of dark energy in the Universe.

The real time measurements of the cosmic acceleration its a very appealing experiment that promises a model independent confirmation of dark energy and a test to distinguish between cosmological models. Despite the technical challenges this experiment may face, is there a feasible SKA experiment in the radio regime that could measure the frequency shift caused by the evolving Universe?

2. The basic experiment

The basic experiment is to detect the changes over time of properties of individual galaxies caused by the expansion of the Universe. Generally various observables could be used to constrain the parameters needed to describe the expansion history of the Universe which are the source brightness,

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[*] Speaker.

[1] “Cosmic Dynamics Experiment”

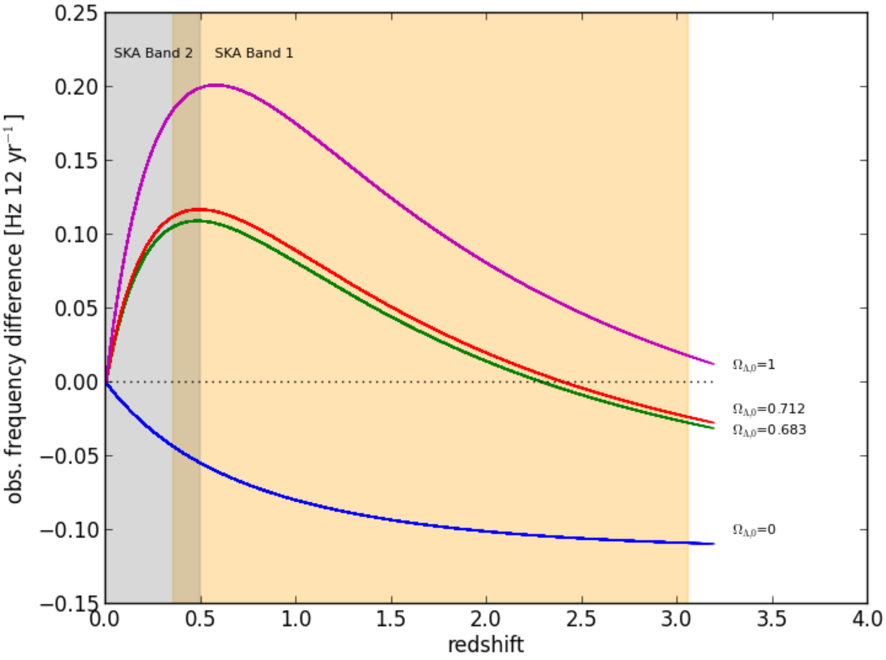

Figure 1: The expected redshift drift introduced by the cosmic acceleration against the redshift regime covered by the SKA. The redshift drift in 12 years is shown as a change in frequency of the neutral hydrogen signal for various ΛCDM cosmologies ($\Omega_m = 0.27$; $\Omega_\Lambda = 0.0$, WMAP, Planck, 1). The characteristic frequency shift shows a maximun shift of about 0.1 Hz, this translates into $dz/dt \sim 10^{-10}$ or ∼3 cm in redshift- and velocity-space, respectively. The coloured background indicates the frequency regimes of band 1 and 2 of the SKA basic design that are used to measure neutral hydrogen signals from galaxies (350 – 1050 MHz, 950 MHz – HI rest frame frequency).

the apparent angular size, the cosmic parallax, or the redshift (see e.g. Gudmundsson & Björnsson 2002, Quercellini et al. 2012). However to measure the changes of the first three observables seem to be out of reach to the current technical capabilities of the SKA. But it seems feasible for the SKA to trace the change of redshifts of individual galaxies and, compared to the CODEX-like experiment, a different approach is envisaged to measure the cosmic acceleration. The basic experiment would make use of the fast survey capabilities and the sensitivity to observe a billion of HI galaxies up to redshift 1. Based on two HI surveys the task is to combine the individual HI-line signals of a galaxy and statistically merge up to a billion of these measurements. The high number counts of galaxies will compensate the uncertainties of the measurements and therefore permit a statistical detection of the redshift drift (the initial setup of the experiment has been described in Klöckner 2012).

The redshift measurements are in general independent of a cosmological model and rely only on the knowledge of the rest frame frequency and the assumption that the fundamental constants do not change over the evolution of the Universe (Kanekar 2012). In a theoretical framework the change of redshifts can be described by $\dot{z} = \mathrm{H(z)} - (1+z)\mathrm{H}_0$ and the fraction $\mathrm{H(z)}/\mathrm{H}_0$ is used to relate the acceleration to different kinds of cosmological models. Therefore measuring the redshift drift at various redshifts provides a unique test of different cosmologies (Balbi & Quercellini 2007). In the following a ΛCDM cosmology is assumed and the Hubble parameter is described as

$$\mathrm{H(z)} = H_0[\Omega_\mathrm{m} \times (1+z)^3 + \Omega_\lambda + \Omega_\mathrm{k}(1+z)^2]^{\frac{1}{2}}, \tag{2.1}$$

with $\Omega_\mathrm{k} = 1 - (\Omega_\mathrm{m} + \Omega_\lambda)$. Note that the first equation has been written in such a way that the acceleration is positive ($\dot{\mathrm{v}} > 0$) and the deceleration is negative ($\dot{\mathrm{v}} < 0$) defined in the velocity frame. Figure 1 displays the expected frequency shift at different redshifts for various values of the cosmological parameter, Ω_λ, and a fixed Ω_m of 0.27. Depending on Ω_λ an acceleration of the Universe is expected up to redshifts of 3 (positive frequency shift), after this the expansion of the Cosmos will slow down (decelerate, negative frequency shift). Furthermore, depending on Ω_λ the frequency shift shows a distinct relationship with redshift and a pronounced signature with a maximum at 0.4 and 0.6 in redshift. In the case of the cosmological parameter measured by the WMAP and Planck mission (Hinshaw et al. 2013, Planck Collaboration 2013) a maximum frequency shift of 0.1 Hz can be expected after an observing period of 12 years.

The direct measurement of the frequency shift and the capability to distinguish between competing cosmological models requires a precisions of up to a few percent (e.g. 1% = 0.001 Hz). In order to reach this kind of accuracy the main task of this experiment is to utilise the HI line signals of a galaxy at 2 epochs and statistically combine up to a billion of these measurements. In this light the feasibility of this experiment depends on the projected sensitivity estimates and the number counts of HI galaxies up to cosmological redshifts. The expected number counts and the properties of individual HI galaxies are based on the SAX-SKA sky simulation (Obreschkow et al. 2009) and the image sensitivity can be determined via the following equations (see e.g. Klöckner et al. 2009):

$$\Delta\mathrm{I} = \frac{\mathrm{SEFD}}{\eta_s\,\sqrt{\mathrm{t}\Delta\nu}}, \tag{2.2}$$

with $\eta_s = 0.9$ is the system efficiency, t integration time [s], and $\Delta\nu$ is the channel width or bandwidth [Hz]. The system equivalent flux density (SEFD) is determined via

$$\mathrm{SEFD} = \frac{2\mathrm{kT_{sys}}}{\mathrm{A_{eff}}}, \tag{2.3}$$

where $\mathrm{T_{sys}}$ is the system temperature [K], k is the Boltzmann constant, $\mathrm{A_{eff}}$ is the effective collecting area [m^2].

In order to investigate if the SKA is capable of detecting the global signal of the redshift drift shown in Figure 1 a generic observational setup is assumed. The experiment would based on two-“all-sky” HI surveys with the following system parameters: SKA ($\mathrm{A_{eff}}$ / $\mathrm{T_{sys}}$ = 13.000 m^2 K^{-1}), 1 hour integration per pointing, 20 sq. degrees field of view, survey coverage of 30.000 sq. degrees. This setup will result in a sensitivity of about 45 μJy for the system channel width of 3.9 kHz and 28 mJy for 0.01 Hz wide channels (10% accuracy). Based on the sensitivity limit of 45 μJy the expected number count of HI galaxies in the redshift range z = 0.2-1 is of the order of 10^7 sources (#N). To derive the frequency shift from the observed HI line spectra of two epochs two approaches can be applied. Either combining the cross-correlation spectrum of each source or fitting signal components to line spectra and determine their statistical means.

In the first case one would use the high-resolution spectra of the two epochs and stack the power spectrum of the cross-correlation spectra of all galaxies. Assuming that the noise properties of these spectra are independent, the noise of the resulting averaged power-spectrum will drop as $\sim 1/\sqrt{\#\mathrm{N}}$ to 2.8 μJy and therefore allowing the detection of the global signal of the redshift drift at a significance of $\sim 15\sigma$.

In the second case one would use the low-resolution spectra and determine the line properties by fitting a analytic function to the line profile (e.g. using a busy function Westmeier et al. 2013). In this way one assumes that all the observational parameters (the space velocity vector of the observatory) can be modeled with such precision that the residual data do not show any systematic effects above millimeter accuracy. The difference of the modelled centre frequencies determines the cosmic signal and its uncertainty will drop with $\sim 1/\sqrt{\#\mathrm{N}}$. Reversing the arguments, based on the assumption that the uncertainties need to match some fraction of cms^{-1}, this experiment is only possible if the redshifts or the velocities of 10^7 galaxies can be estimated at the observatory to a precision of 10 ms^{-1}.

Based on the generic observational setup both methods indicates that in general the SKA would be capable to measure the global signal of the redshift drift.

3. A feasible experiment with the SKA

Tracing the signature of the cosmic acceleration at various redshifts would be the ultimate experiment to test cosmological models. In the case of a ΛCDM cosmology the redshift drift shown in Figure 1 indicates a characteristic feature up to redshift of unity. The anticipated system performance of the SKA is an ideal match to one of the key requirements of this experiment. In particular the sensitivity figures of the SKA will be optimised to trace the HI line (in emission) of Milky Way-like galaxies up to a redshift of unity and therefore will produce the most complete HI/redshift surveys in this redshift range.

The main aim of this experiment is to measure a shift in frequency of about 0.1 Hz over a period of about 12 years (2.9 cms^{-1} in velocity space and 10^{-10} in redshift space). However these measurements may suffer from various systematic effects influencing the accuracy of the experiment. The potential contributions to the uncertainties of the redshift drift can be grouped as follows: (a) The probe of the redshift drift at cosmological distances show intrinsic variations. (b) The model of the Earth position in space and the observatory is insufficient for the accuracy needed. (c) The technical hardware of the observatory.

Case (a): Probing redshifts via the neutral hydrogen signal seems to be one of the most promising probes in the radio regime, even if our current knowledge of HI selected galaxies is limited up to redshifts of 0.2. Generally these galaxies do not show any evidence for clustering or a preference to populate over-dense regions in the Universe and hence their redshift estimates are less affected than optically selected galaxies (Papastergis et al. 2013; Klöckner & Romano-Diaz in prep.). The contribution of the peculiar motion to the apparent redshift has been estimated using the SAX-SKA- and the millenium-simulations (Obreschkow et al. 2009, De Lucia & Blaizot 2007). For the individual galaxies, with redshifts larger than z=0.2, the peculiar motion in redshift space has been estimated to $\mathrm{d}(\mathrm{z}+\mathrm{z_{pec}})/\mathrm{dt} \sim 10^{-14}$. This effect is a factor 10 smaller than the cosmological signal at the percent level and can be neglected in the future.

Case (b): The most challenging step in observing an extragalactic redshift at the needed precision is to relate this measurement to an accurate reference system in time and celestial direction (e.g. Barycentre see Lindegren & Dravins 2003). Furthermore, the astrometry, the time standard, and the pointing accuracy can influence the modelling of the line-of-sight doppler shift contribution of the observatory. To match the precision requirements of the redshift-drift estimates the pointing accuracy need to be of the order of 1 arcsec. The accuracy in astrometry and the distribution of the time standard is related to the accuracy of the correlator model, including an Earth model and the JPL ephemeris. However changes in the position of the observatory e.g. due to tides (Solid-Earth: 30 cm, B. Campbell private comm.), ocean- or atmospheric-loading (2 cm, B. Campbell private comm.) etc. need to be taken into account in the post-processing of the full-sky survey.

Case (c): The major technical challenge to overcome is the constraint on the long time stability of the SKA system. The key is to reduce or handle systematic effects of the observatory in timing precision and frequency stability. Such requirements are difficult to evaluate and need to be assessed in more detail in future discussions. Nevertheless, it is assumed that pulsar observations will be used to monitor the long time stability of the system. These observations are sensitive enough to detect systematic effects within the observatory like time drifts or global changes of the observatory's 3-d velocity vector in the JPL ephemeris. Modelling of the arrival time of the pulse of a network of pulsars should enable us to correct for such systematics effects (Champion et al. 2010, Hobbs et al. 2012).

An additional technical limitation is the number of correlator channels in order to fully trace the neutral hydrogen signal of the galaxy. Generally the signal properties of the HI emission depends on the rotational velocity and the inclination of the galaxy. Assuming that the majority of the surveyed galaxies are Milky Way-type galaxies with a rotational velocity of 300 kms^{-1} a spectral window of 500 kms^{-1} would be sufficient to trace the entire signal. Tracing such a spectral window with the precision needed to estimate the redshift drift $\sim 10^{8-9}$ correlator channels are needed. Such a high number of channels could be realised by a dedicated pipeline, streaming the data from the predefined spectral window into a software correlator. The setup of the spectral windows and how the observations would be organised to set the frequency standard needs to be investigated in the future.

3.1 The experiments

In order to investigate the feasibility of tracing the signature of cosmic acceleration at various redshifts two approaches with low- and high-spectral resolution datasets are discussed.

In case of low-spectral resolution datasets and an observing precision of 10 ms^{-1}, the main constraint is to measure redshifts of $\sim 10^7$ galaxies per redshift interval. In general these high number counts can be achieved using an integration time of about 6 hours per pointing, assuming the same observational setup as used in the following discussion for the high-spectral-resolution case. The survey time for this experiment would be of the order of one year with a 10% precision on the redshift drift measurement. In order to archive higher precision the observing precision and hence the channel resolution in frequency space needs to be adapted.

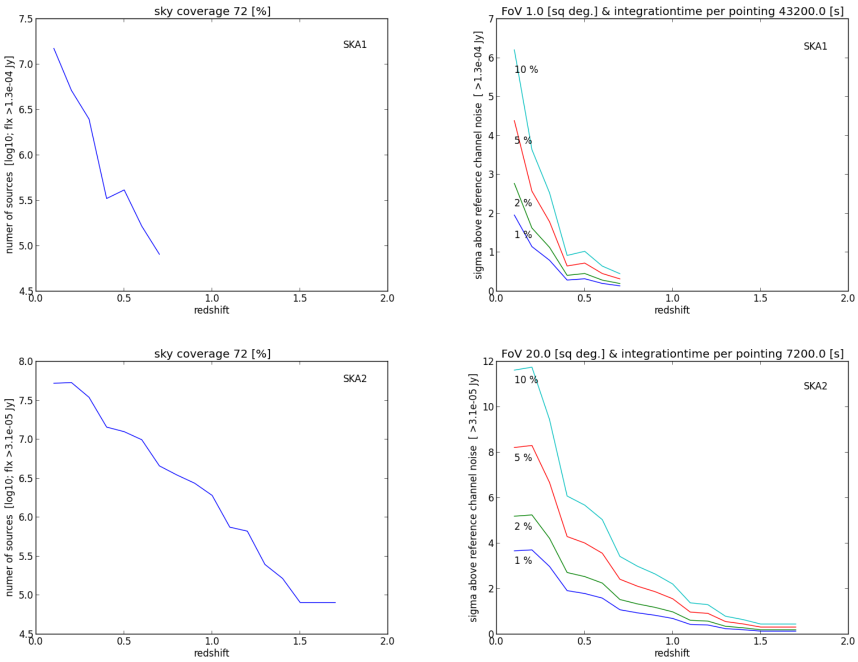

Figure 2: The basic ingredient of this experiment is the high number counts of galaxies and the sensitivity. The figures show the number counts and the significance per channel precision of detection versus redshift. The top panel show the results for a hypothetical SKA$_1$ with increased channel resolutions and the bottom displays the results for the full SKA.

In the following the feasibility of this experiment is explored by high-spectral resolution datasets ($\Delta\nu = 0.001, 0.002, 0.005, 0.01$ Hz). This discussion will address both phases of the SKA, the SKA and a SKA$_1$ with hypothetically channel width of this order.

SKA Phase 1 (SKA$_1$)

For the SKA$_1$ a generic observational setup is assumed with the following system parameters: SKA$_1$ (A$_{\rm eff}$ / T$_{\rm sys}$ = 1300 m^2 K^{-1}), various channel resolutions, 12 hours integration per pointing, 1 sq. degrees field of view, survey coverage of 30000 sq. degrees. The results are shown in the top panels of Figure 2. The results indicate that the number counts would be sufficient to detect a redshift drift at redshifts less than 0.3 with 5% to 10% precision. These results are somewhat misleading because to survey the entire sky with this setup would require 42 years which is not feasible, but it shows the importance of survey speed to this experiment.

In summary, the redshift drift experiment with the SKA$_1$ or 30% of the SKA is not possible. Despite the fact that the cosmological redshift drift can not be observed, a pathfinder experiment could be initiated to aim for 10 ms^{-1} accuracy to test the "low spectral resolution" case of the SKA$_2$ experiment. The anticipated accuracy of 10 ms^{-1} is already a factor 10 better with respect to the radial velocity measurements of nearby standart stars and may provide already some clues to the systematics and the ephemeris (Chubak et al. 2012).

SKA Phase 2 (SKA)

For the SKA a generic observational setup is assumed with the following system parameters: SKA ($A_{\rm eff}$ / $T_{\rm sys}$ = 13000 m^2 K^{-1}), various channel resolutions, 2 hour integration per pointing, 20 sq. degrees field of view, survey coverage of 30000 sq. degrees. The observations would take 125 days and the results are shown in the bottom panel of Figure 2 . The results show that the number counts would be sufficient enough to trace the functional dependency of the frequency shift caused by the cosmological expansion up to redshift of unity. The level of precision reached is a few percent and may even reach the percent level if the integration time per pointing is 12 hours.

Due to the relatively short survey duration this experiment could even be done several times within the life time of the SKA of 50 years.

4. Discussion & Summary

Measuring the expansion history of the Universe includes distances and the linear growth of density perturbations, and a combination of both observed at different epochs. The observations at different epochs allows for a direct measure of the expansion history, whereas SNIa surveys, weak lensing (Heavens 2003) and Baryon Acoustic Oscillations in the galaxy power spectrum (BAO; Wang 2006) are generally considered to be indirect probes of the acceleration. Their results rely on a priori knowledge of the cosmological model and even simple parameterisations of dark energy properties can result in misleading conclusions (e.g. Bassett et al. 2004, Shapiro & Turner 2006). In this light redshift-drift measurements are direct probes and rely only on the knowledge of the rest frame frequency of the measured signal. Its uncertainty in testing cosmological models is the knowledge of H_0. Compared to other probes with many more systematic uncertainties in parameterisation and calibration (e.g. cosmic chronometers; Moresco et al. 2012), the HI measurements offer less biased measurement and can be assumed to be a model-independent consistency test of cosmological theories. In addition, redshift drift measurements are sensitive to different combinations of cosmological parameters and thus combined with other probes can break degeneracies and will place stronger constrains on cosmologies (e.g. CMB, BAO, weak lensing). This complementarity nature of the redshift drift has been shown e.g. for the E-ELT case improving the CMB constraint by a factor of 2-3 and even has the potential to constrain new physics (Martinelli et al. 2012, Vielzeuf & Martins 2012).

The SKA will be able to measure the redshift drift to levels of a few percent precision up to redshifts of unity. The quoted measurement accuracy can be used to derive first constrains on cosmological model and detailed forecasting on the accuracy of cosmological parameters will be addressed in future investigations. However these precision enables us to compare the SKA experiment already to a study of optical redshift-drift measurements. This study indicates for a dynamical dark energy wCDM cosmology the greatest leverage on figure of merit (FOM) of the dark energy properties. In particular, an excess of 100 of FOM for dark energy at 1% precision and 1000, if combined with the CMB. For a lower precision of 5% the FOM is 290 if combined with the CMB and the Hubble constant (Kim et al. 2015).

Real time cosmology is possible with the SKA. The SKA is the only experiment that enables us to trace the nature of the “close by” acceleration and may provide essential information on possible mechanisms in place during the inflation phase and the evolution of the Universe. However the proposed experiment does need the full sensitivity of the SKA array, the survey speed to detect a billion galaxies, and its technical requirements might imply some minor changes of the SKA baseline design. In addition, this experiment would benefit from a larger field of view of about 40 sq. deg. per pointing to allow for more sensitive observations per pointing. Nevertheless, the already relatively short survey time of the SKA allows for a even more ambitions experiment, measuring the cosmic jerk term. Such measurement might be feasible if the redshift drift experiment is performed several times within the life time of the SKA of 50 years.

Assuming the observational systematics can be modeled to $1^{-3}\mathrm{ms}^{-1}$ accuracy, the required spectral resolution of 10% (0.01 Hz) can be sufficiently reduced by a factor of hundred or more. In case the correlator can not provide the spectral resolution needed for this experiment, raw-data of individual galaxies of Band 1 or Band 2, or a part of it, could to be streamed to a dedicated software-correlator pipeline. In both cases the SKA will be able to detect the global signal of the redshift drift and with a dedicated observational setup the SKA will measure the redshift dependency of the redshift drift.

Even though this is a full SKA experiment; there are precursor observations possible with the SKA in Phase 1 to investigate the systematic effects within the ephemeris. These experiments would aim to investigate the properties of the 3-dimensional velocity vector of the Earth at resolutions of meter/s using the HI signal of nearby galaxies and HI in absorption toward quasars. Measurements of the 3-dimensional velocity vector will not only have cosmological applications they may also have the potential to model the Earth's gravitational field and could open up new synergies between the SKA and lunar ranging experiments.

Finally, the measurements of the redshift drift in redshift space by the SKA and the E-ELT (both sampling different redshift ranges) and the combination of their measurements are the only experiments that will fully trace the real-time evolution of the dark energy in the Universe.

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