# Preliminary Results of the VLBI2010 subgroup ”RF/IF, frequency and time”

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**Abstract**

This subgroup discusses how a future VLBI systems should be designed with respect to the problems of existing RFI, the existence of new antenna concepts, the developments of high speed samplers, the demands for high frequency stability of the reference oscillator. The current status of the discussion will be presented.

## 1. Goals and Limits

Based on the Charter for the IVS Working Group 3 ”VLBI2010” [1] this subgroup was examining the future requirements for VLBI geodetic systems focusing on the observed spectra (RF), the signal conversion (IF), the observing instruments (antennas) and its scaling versus time (T&F).

The Charter requests *”highest-precision geodetic and astrometric results”* as a goal. Also the IAG-Project of the Integrated Global Geodetic Observing System (IGGOS) in which VLBI will be an important contributor demands the transition from global geodetic measurements to approach in the coming years the millimeter precision.

**A precision of 1 millimeter in the space domain corresponds to only 3 picoseconds in the time domain. These values should be achieved as design goals for the VLBI2010 vision.**

The technical realization of a VLBI observing system introduces another characterizing quantity: the signal-to-noise-relation (SNR), which finally decides whether or not an observation comes out successful of the correlation process.

Limiting factors in geodetic and astrometric VLBI are:

- **Atmosphere.** Observing conditions are on each coobserving site different. The turbulent and chaotic nature of the atmosphere make it very difficult to model the observing conditions properly in the processing of the VLBI data.
- **Radio Frequency Interference** lower the SNR at the observed spectrum in the affected channels and degrades the precision. The access to undisturbed S-band data is due to the shared use by telecommunications decreasing.
- **Instrumentation.** The goal of 1mm and 3ps can only be achieved, if the instrumentation (front end, antenna, back end) permit sufficient stability in space and time. Any improved component

contributes potentially to an improved VLBI system. Limiting factors in the instrumenation are the

- Antenna. The mechanical structure and the antenna controlling system have to resist acting forces like gravitation, temperature effects and wind loads. A larger antenna has larger deformations simply due to its weight and exposure to wind and sunlight during the day limiting its spacial stability.
- HF-components. The quality of the dish-surface, the feed as a first filter limit the sensitivity to certain RF-spectra. The active HF components like amplifiers, mixers and cables determine the system temperature and have due to their characteristics technical limits.
- Samplers. The Nyquist sample rate depends on the technical limitations. The sample rate determines the timely resolution.
- Data buffering. The limit is the maximum recording bandwidth or the maximum throughput rate on communication networks.
- Frequency standards. The frequency stability of the used frequency standard (H-maser) limits the resolution in the time and finally in the space domain of the geodetic VLBI.

## 2. Atmosphere

The propagation of electromagnetic radiation from the radio source to the antenna is affected by the

- plasmas of interstellar and interplanetary media,
- the ionosphere,
- neutral atmosphere with water vapor in its troposphere.

The largest impact on geodetic measurements have the variability of water vapor in the troposphere and of the electron content in the ionosphere; both varying up to several nanoseconds (S-/X-band).

The idea of eliminating the atmospheric delay requires path length correction based on additional information from other sensors, like humidity sensor and water vapour radiometer. While the humidity sensors are ground based and not very representative for the signal path, the water vapour radiometers even used coaligned to the radiotelescope targeting axis did not fulfill their expectations yet, because of the relatively wide beam compared to the narrow beam of the radiotelescope. Promising investigations at 183GHz show, that it is possible to determine at a high and dry site like Mauna Kea using the primary optics the atmospheric path lengths with an error of 0.2ps [2].

**VLBI2010 conclusion: Water vapor radiometry should be further developed and become an integral part of the VLBI2010 system.**

The ionospheric delay scales as the inverse of the observed frequency squared. E.g. At observed frequency of 2GHz the ionospheric excess equals the tropospheric excess; thus at 20GHz the ionospheric excess is only about 1% of the tropospheric one. Hence the effect of ionospheric delays is below a few picoseconds at frequencies above 100 GHz ([3], p. 555).

**VLBI2010 conclusion: RF below 100GHz must be at least dual-band for ionospheric correction.**

## 3. Radio Frequency Interference

Today RFI is already a problem in the on-going VLBI-operations, especially in S-band. The fast developments of wireless communications are a serious threaten to high-quality data obtained by VLBI from quasars. RFI can be treated in two ways:

- avoidance of polluted spectral bands, using unpolluted spectral bands only, or
- treatment of RFI with mitigation technology.

RFI is generated by ground- or space-based transmitters which have either a predictable or unpredictable noise figure. RFI mitigation applies to the predictable noise and has the capability to lower its impact, but not canceling.

The alternative of using unpolluted bands might have its weakness in a temporarily solution until RFI swaps into the new bands as well.

Given the current situation the S-band needs a replacement with a higher frequency band, because at lower frequencies the situation is worse. S-band was basically needed to do the ionospheric calibration of the X-band observations, on which nowadays the ICRF with its 20 years of recorded data is based. A replacement of S-band by a spectral band higher than X-band raises the question, if X-band will continue to be the band to be calibrated or if it will calibrate the higher frequency/shorter wavelength band, which promise higher spatial precision. In either case going beyond X-band with the second spectral band offers an advantage.

**VLBI2010 conclusion: S-band needs to be replaced by another spectral band, ideally higher than X-band.**
Candidate spectral bands are listed in Table 1.

| Name | $\nu$ -range | $\lambda$ -range |
|---|---|---|
| S | 2 - 3 GHz | 15 - 10 cm |
| X | 8 - 10 GHz | 4 - 3 cm |
| Ku | 15 - 17 GHz | 2 - 1.75 cm |
| Ka | 22 - 24 GHz | 1.4 - 1.25 cm |
| | 30 - 32 GHz | 1.0 - 0.9cm |

Table 1. Existing S/X-band parameters and those of the candidate spectral bands to replace S-band.

The higher the frequencies the higher also the attenuation due to water vapour. We encounter two $H_2O$ spectral lines at 23.8 GHz and 31.5 GHz, which are close to the proposed bands. This disadvantage may be transformed into an advantage, if the radiometery of water vapour becomes an integral part of the VLBI observing system in order to measure the atmospheric delay directly within the VLBI-observations.

**VLBI2010 conclusion: $H_2O$ spectral lines suggest to observe near-by spectral band as replacement for S-band, in order to enable on-axis narrow beam WVR simultaneously to the quasar observation.**

## 4. Instrumentation

The instrumentation of a VLBI system is defining the geodetic reference point in space and time. The complexity of a VLBI system requests an analysis of various features in the system.

The instrumentation is characterized by the achievable signal-noise-relation.

$$SNR = f \cdot V \cdot \sqrt{\frac{T_{a_1} \cdot T_{a_2}}{T_{s_1} \cdot T_{s_2}} \cdot 2\Delta\nu \cdot \tau} \tag{1}$$

where $f = 0.5$ is the VLBI processing factor for one bit sampling, $V = 1$ is the normalized visibility for an unresolved source, $T_{a_i}$ is the antenna temperature, $T_{s_i}$ is the system temperature, $2\Delta\nu$ is the Nyquist sample rate, $\tau$ is the integration time interval.

The higher the SNR the lower the errors of the correlation output signal, thus the higher the precision. From (1) it can be seen, that a high SNR can be achieved by

- efficient antennas ($T_a$), with
- small system temperatures at each site ($T_s$),
- high sample rates ($2\Delta\nu$) and
- high number of bitquantization ($f$),
- long integration time intervals ($\tau$).

With respect to a better atmospheric sampling and geometrical more stable solutions in geodetic VLBI the number of scans per time unit should be as high as possible. This can be achieved by

- short scans and short integration times,
- multidirectional or simultaneous observation of different directions.

*Long integration times* for high SNR and *short scans* for better geometry are contradictory requests which require an optimization scheme. Practice has shown, that a $SNR = 20$ offers sufficient signal for a robust geometrical solution. Therefore any improvement on higher antenna temperatures, lower system temperatures, higher sampling rates will allow to observe more shorter scans per time unit resulting in better geometrically solutions and in the time domain e.g. a better short-term sampling of Earth rotation and atmospheric modelling. This approach can be even topped by multibeam observations.

**VLBI2010 conclusion: New technology promising higher SNR have to be considered in future instrumentation.**

### 4.1. Antenna

Desirable improvements in geodetic VLBI can be achieved by multibeaming in a GPS-like fashion. More data per time unit of different sources will enable a subhourly resolution of Earth-orientation variation - one of the IVS goals. The status quo of the geodetic VLBI is based on the concept of monolithic radiotelescopes observing sequentially source by source. Observing two or more sources simultaneously can be done in a differential or non-differential mode. Differential observations allow the phase connection between a strong and a nearby weak radiosource. This method permits the reduction of atmospheric delays, as long as they can be considered to be identical due to its small angular separation. However the distribution of the roughly 600 ICRF sources at the entire sky shows generally larger angular separation than a few beamwidth of a small antenna. With larger antennas at higher frequencies there would be almost nothing to be observed.

The non-differential mode allows to observe more than one source per time unit with larger angular separation simultaneously. Other than the omnidirectional GPS-antennas the geodetic VLBI needs the high directivity of larger dishes (to avoid RFI). This type of observation will be made under almost the same atmospheric conditions and if connected to same frequency standard depending on the same clock modelling. If differenced the dependency on the reference oscillator cancels out.

**VLBI2010 conclusion: Multibeam observations in non-differential mode are desired.**

Multibeam observations can be made by one antenna with many receivers or many antennas with one receiver. Radioastronomists are following both concepts to reduce the atmospheric disturbance (differential mode) and to gain more sensitivity (phased arrays). For the sky research radioastronomists are interested in using broadband antenna technology, large-scale integrated circuits for a large increase in the collection area. The ongoing radioastronomical projects like *Square Kilometer Array (SKA)* and *Atacama Large Millimeter Array (ALMA)* are examples for future antenna installations.

The phased array concept looks attractive compared to the monolithic concept:

- sensitivity depends on the number of elements per site and can be easily increased in upgrades,
- splitting the array allows differential measurements by multibeam observations, which allows the cancelation of some equipment errors and reduction of the atmospheric delay, if antenna observation direction are close enough to sample the same part of the atmosphere.
- elements can be smaller and products of massproduction.

Disadvantages of the array concept are:

- the replacement of one geodetic reference point at the intersecting axes of a monolithic radiotelescope by $n$ referencepoints at each dipol of the elements,
- the requirements for the calibration of path lengths multiple by the number of $n$-elements.

An interesting antenna concept is the Luneberg lense. One microwave refractive sphere allows $n$-receivers moving around defining $n$-beams on the sky. A sphere is an ideal geodetic reference marker. However it must be investigated to which size and which frequency range a Luneberg lense can be realized. Many small of them would give the delay calibration problem like the other SKA proposed concepts. One big Luneberg lense (equivalent to a 12m-dish) for the RF-range from 8-40GHz seems to be an interesting alternative for geodesy. Accomplishing the refractive index gradient for a wide range of frenquencies is not trivial.

**VLBI2010 conclusion: Multibeam observations should be realized by multiple antennas capable of 8-40GHz with sufficient directivity.**

In order to make the water vapour radiometry an integral part of the new antenna system, one could think of installing the radiometer at the backstructure of a subreflector in a cassegrain construction (limiting the directivity of the radiometer to the size of the subreflector) or observe the spectral lines of $H_2O$ within the entire system reflector system with appropiate feed and reflector design.

In geodesy there is also the need to collocate instruments in order to detect systemimmanent errors, to tie different global reference systems and to complement sensor characteristics. The installation of a Global Navigation Satellite System (GNSS) permanent receiver at the VLBI-antenna allows control of the stability of the instrument with respect to a local geodetic network.

**VLBI2010 conclusion: Antenna construction must allow installation of complementing sensors like WVR and GNSS-receiver.**

### 4.2. HF-components

The characteristics of the feed are defined by the selected RF (tab. 1). Log periodic pyramidal feeds and wide band amplifiers allow continuous RF bandwidth over ranges up to 10GHz. Those feeds focal point varies with frequency, but as VLBI is a differential technique the difference between two antennas at one specific frequency will be constant and should disappear in the clock offset. Another difference to existing S-/X-band feeds is their linear polarization, which requires to observe both circular components or rotate the feed during observing.

**VLBI2010 conclusion: New feeds and wide band amplifier enable to observe the entire spectral bandwidth, which have been previously been spanned by bandwidth synthesis.**

The need of a phasecal system is questionable if the entire spanned bandwidth is sampled. The bandwidth synthesis is requiring a phasecal system in order to compensate for different instrumental delays and to align the phase in the correlation process. As a diagnostic tool at least the phasecal system is indispensible.

**VLBI2010 conclusion: Phase calibration systems are needed in coming systems, not to exclude the possibility of bandwidth synthesis.**

Delay calibration systems measure the delay due to temperature variations during the 24h cycle between front and back end. Even if data may be processed at the front end, there remains a need to measure cable delays between the frequency standard and the involved local oscillators.

**VLBI2010 conclusion: Delay calibration systems continue to be necessary.**

If new generations of uncooled low-noise-amplifiers have lower system temperatures as the cooled one, the maintenance of cryogenic cooling systems becomes superfluous. However precise hot and cold loads for radiometric purposes may be realized by the temperature controlled environment.

**VLBI2010 conclusion: Any design should concentrate on minimizing the noise temperature of front end, especially the LNA.**

### 4.3. Samplers

Classical VLBI has used mostly one-bit sampling. In most cases of recording VLBI, the limit is given by the rate which can be stored (or transmitted) at a maximum sustainable bit rate. One-bit (two level), two-bit (4 level), and three-level data sampling (with 5 samples stored in 8 bits) can be used for VLBA observing. All three sampling schemes produce almost the same sensitivity for bit-rate limited observing - which continuum (and geodetic) VLBI will be for the foreseeable future ( [3], p. 272).

However some consideration to RFI treatment should be given. To avoid saturation due to RFI, the samplers also need to be as linear as possible, i.e. the larger the number of bits per sample the better. Unfortunately, this is in conflict with the usual VLBI rule of thumb to never use more than 2-bit samples (which is of course applied to maximize information density during transmission to the correlator). However, there is a solution to this inconsistency. It is possible to sample the data with a large number of bits. Then, using a dynamic digital filter, cut out the RFI; and finally, requantize to 1 or 2 bits per sample for transmission to the correlator. What sort of sample rates can be expected for multi-bit samplers? In the EVLA design, each band will have 2 3-bit 4 Gs/s digitizers (one for each polarization), and 1 8-bit 2 Gs/s digitizer (primarily for L and S band where interference is expected to be worse). This is probably a good indication of the current state of the art for multi-bit samplers. With these samplers the full 8-24 GHz band would be split into either 8 or 16 sub-bands, depending on the number of bits per sample desired.

If we consider as an example a continous RF band from 8-24GHz, the whole 16 GHz bandwidth were 2-bit Nyquist sampled, then the output data rate per site would be 64 Gb/s. Right now, the maximum practical record rate is 1 Gb/s. This number will no doubt go up in the future, but 64 Gb/s is probably not yet justified and nowhere on the forseeable horizon. We are faced with trying to synthesize a 16 GHz bandwidth using a record rate of a few Gb/s. This cannot be done without using some form of bandwidth synthesis.

**VLBI2010 conclusion: Bandwidth synthesis has a future, also in the light of broadband sampling.**

There are three ways of doing bandwidth synthesis:

1. **Sparse in Frequency.** This is what is done in the Mk3/4/5. It requires a large number of comparatively narrow bandwidth channels each with its own baseband converter and sampler. As a result it tends to be hardware intensive, although the design per channel is generally easier due to the lower sample rates etc. It suffers from the problem though that if RFI happens to land on a critical channel within the frequency sequence, then the ability to synthesize the full bandwidth at a modest SNR may be jeopardized, often making the observation useless. The situation may be improved by selecting a more robust sequence. It also requires a commitment to a predetermined number of channels and unless proper planning is applied it may be difficult to upgrade when higher record rates become practical.

2. **Sparse in Time.** In this approach, the fully sampled 16 GHz bandwidth is acquired in bursts using a duty cycle that allows the rapidly sampled data to be sent to the recorders at a much lower rate commensurate with the capability of the record device. This approach is very robust against RFI since it uses as much of the full bandwidth as is available at any particular time. Like the *sparse-in-frequency* approach, it is also hardware intensive. But in this case the design per channel is difficult since the channels are much wider bandwidth. Upgrades inspired by increased record bandwidth should however be fairly straight-forward to implement since the full RF bandwidth is already being sampled.

3. **Frequency Switching.** In this approach, there is only a single channel, but it can be used to select any portion of the entire 8-24 GHz input RF bandwidth. By cycling through all possible frequencies in sequence, the entire RF band could be acquired. This approach is economical in hardware and is just as robust against RFI as the *sparse-in-time* method. Using a channel that incorporates the 4 Gs/s EVLA samplers to produce 2-bit RFI-cleaned VLBI data, the frequency switched channel could produce data at a rate of 8 Gb/s. To interface to a lower rate recorder, the *sparse-in-time* approach could be applied to achieve a sort of hybrid system. This would allow a fairly straight-forward upgrade path for record rate increases up to 8 Gb/s. After that an additional channel would be needed to be included.

**VLBI2010 conclusion: Frequency switching capabilities are not contradictary to the sparse-in-frequency approach. Several channels with frequency switching allow flexibility.**

**VLBI2010 conclusion: One- or two-bit sampling IF should enter the correlator. RFI mitigation might require a higher bit quantization at the frontend.**

### 4.4. Data Buffering

The VLBI data will be either recorded or transmitted. In either case some data buffering media will be involved. This is subject of the corresponding subgroup.

### 4.5. Frequency Standards

The requirements for the clock and frequency generator can be estimated from the basic equation in VLBI, with the extension due to the clock parameters time offset and frequency.

$$c\tau = \frac{1}{c}\vec{s}\vec{b} + c\Delta T + c(T - T_0)\frac{\Delta f}{f} + \ldots \tag{2}$$

as

$$cd\tau = cd\Delta T + c(T - T_0)\frac{d\Delta f}{f} \tag{3}$$

where $c$ is the velocity of light, $\tau$ is the time delay, $\Delta T$ is the clock offset, $d\Delta T$ the error of the clock offset, $T - T_0$ the elapsed time interval, $\Delta f/f$ the relative frequency offset and $d\Delta f/f$ the error of the frequency offset.

If $cd\tau < 1mm$, follows

$$d\Delta T = \frac{1}{c} \quad \approx \quad 3ps \tag{4}$$

$$\frac{d\Delta f}{f} = \frac{1}{c(T - T_0)} \quad \approx \quad \frac{3.3 \cdot 10^{-12}}{T - T_0} \tag{5}$$

Equation 4 proves, that 1 mm spatial precision depends on the clock offset to be known better than 3 ps. Between remote stations no timetransfer allows this accuracy so far. As VLBI is a differential method the clock offset will be estimated as one parameter out of several observations. However, if the clock offset is known apriori to this level, the geodetic VLBI solution would be much more constraint to the time scale.

A need to approach better apriori clock offset determinations can be derived. Current time GPS-time transfers reach the following accuracies:

- Total Accurate Clock: ~20 ns
- GPS Time receivers, common view technique: ~5-15 ns
- Modified geodetic GPS receiver Ashtec Z12 (Metronome) : ~1 ns

**VLBI2010 conclusion: Better apriori station synchronization should be realized.**

The frequency offset introduces a scale error in the VLBI measurements. It should be known better than $10^{-12}$, which can be achieved by time transfer techniques. As the clock parameters show high correlation with atmospheric parameters and the height component of the station coordinates, any monitoring of frequency offsets and information about to the analysts should stabilize the geodetic VLBI results.

**VLBI2010 conclusion: Frequency offset of the reference oscillator has to be monitored.**

Frequency instabilities are usually expressed with the Allan variance. For the realization of millimeter precision of geodetic VLBI results, the Allan variance of the reference oscillator must be about $10^{-15} - 10^{-16}$ which requires well setup and monitored H-masers. Newer developments like Mercury ion tramps promise to be show even lower Allan variances, but are still in laboratory status and so far not practical for field use.

**VLBI2010 conclusion: The primary reference oscillator should have an Allan variance better than $10^{-15}$.**

## References

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