Hayo Hase et al.: Preliminary Results of the VLBI2010 Subgroup "RF/IF, Frequency and Time", IVS 2004 General Meeting Proceedings, p.65–69
http://ivscc.gsfc.nasa.gov/publications/gm2004/hase1

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, and the demands for high frequency stability of the reference oscillator. The current status of the discussion is presented in a shortened form.

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 focussing 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 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-ratio (SNR), which finally determines whether or not an observation comes out successfully from the correlation process.

Limiting factors in geodetic and astrometric VLBI are: a. *atmosphere*, b. *radio frequency interference*, c. *instrumentation.*

2. Atmosphere

The propagation of electromagnetic radiation from the radio source to the antenna is affected by a. interstellar and interplanetary plasmas, b. the ionosphere, c. the neutral atmosphere, including tropospheric water vapor.

The largest impact on geodetic measurements is caused by the variability of water vapor in the troposphere and of the electron content in the ionosphere; both vary 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 sensors and water vapour radiometers. While the humidity sensors are ground based and not very representative of the signal path, the water vapour radiometers even used coaligned to the radio telescope targeting axis did not fulfill their expectations yet, because of the relatively wide beam compared to the narrow beam of the radio telescope. 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. RFI can be treated in two ways: avoidance of polluted spectral bands, using unpolluted spectral bands only, or treatment of RFI with mitigation technology.

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.

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.

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

Name	ν-range	λ-range
S	2 - 3 GHz	15 - 10 cm
X	8 - 10 GHz	4 - 3 cm
Ku	15 - 17 GHz	2 - 1.75 cm
K	22 - 24 GHz	1.4 - 1.25 cm
Ka	30 - 32 GHz	1.0 - 0.9cm

4. Instrumentation

The instrumention of a VLBI system is defining the geodetic reference point in space and time. The instrumentation is characterized by the achievable signal-noise-ratio.

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

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

VLBI2010 conclusion: New technology promising higher SNR has 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 geodetic VLBI is based on the concept of monolithic radio telescopes observing sequentially source by source. Observing two or more sources simultaneously can be done in a differential or non-differential mode.

The non-differential mode allows observing more than one source per time unit with larger angular separation simultaneously. 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 each. 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: a. sensitivity depends on the number of elements per site and can be easily increased in upgrades; b. 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; c. elements can be smaller and products of mass production. Disadvantages of the array concept are: a. the replacement of one geodetic reference point at the intersecting axes of a monolithic radio telescope by n reference points at each dipol of the elements; b. the requirements for the calibration of path lengths multiple by the number of n-elements.

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

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

4.2. HF-Components

The characteristics of the feed are defined by the selected RF (table 1). Log periodic pyramidal feeds and wide band amplifiers allow continous RF bandwidth over ranges up to 10GHz. Those feed's 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 observing both circular components or rotating the feed during observing.

VLBI2010 conclusion: New feeds and wide band amplifiers enable observing the entire spectral bandwidth, which have previously been spanned by bandwidth synthesis.

The need of a phasecal system is questionable if the entire spanned bandwidth is sampled. Bandwidth synthesis requires 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 phase calibrators.

VLBI2010 conclusion: Delay calibration systems continue to be necessary.

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

VLBI2010 conclusion: Any design should concentrate on minimizing the noise temperature of the 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 at which data 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).

If we consider as an example a continous RF band from 8-24 GHz, 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. 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: a. *Sparse in Frequency.* This is what is done in the Mark III/IV/5. It requires a large number of comparatively narrow bandwidth channels each with its own baseband converter and sampler; b. *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; c. *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 (S2). This approach is economical in hardware and is just as robust against RFI as the *sparse-in-time* method.

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 front end.

4.4. Frequency Standards

1 mm spatial precision depends on the clock offset to be known better than 3 ps. Between remote stations no time transfer allows this accuracy so far.

VLBI2010 conclusion: Better apriori station synchronization should be realized.

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

References

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