

CAPABILITIES AND PERFORMANCE OF THE UPGRADED MARK III CORRELATOR SYSTEM

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ABSTRACT. The Mark IIIA correlator system is currently operating at the U. S. Naval Observatory in Washington, D.C. in support of VLBI geodetic measurements being made by NASA, NGS, NRL, and USNO. This correlator system, developed at Haystack Observatory, is a second-generation version of the original Mark III correlator, and adds significant new capabilities such as double-speed operation, longer integration periods, and improved internal modelling.

The Mark IIIA correlator can simultaneously process up to 10 baselines of data from 5 stations. Experiments including more than 5 stations may be processed with multiple passes through the correlator. The architecture of the correlator allows a future expansion to a maximum of 16 stations. Due to a simple modular design and the low cost of required computer-support equipment, expansion is straightforward and relatively economical.

Although current geodetic VLBI observations are made using data from distant natural continuum radio sources, the Mark IIIA correlator was designed to also support processing of data collected from pulsars, artificial earth satellites, and from earth-orbiting antennas receiving signals from natural sources. These capabilities may be important in the future as efforts continue, for example, to tie satellite-related reference frames to current VLBI reference frames.

The design approach of the Mark IIIA correlator will be discussed, including its performance with respect to systematic and random errors which may affect geodetic VLBI data.

1. INTRODUCTION

The Mark III VLBI data acquisition system was originally designed for the NASA Crustal Dynamics program. It has been operating since approximately 1978 (see Ref 1), and is now in place in approximately 25 radio observatories around the world. This system was designed specifically for collecting high-precision geodetic VLBI data, and represents a major advance in VLBI technology. The salient features of the Mark III are: 1) increased recording bandwidth (to 112 Megasamples/sec on 1"-wide tape operating at

135 inches/second), 2) improved epoch accountability of each data sample (to order of one nanosecond, and 3) greatly improved instrumental calibration and stability (to a few picoseconds).

The development of the Mark III processor (Ref 2) proceeded concurrently at Haystack Observatory with the development of the Mark III data acquisition system, resulting in an operational one-baseline correlator in 1979, and a 4-station 6-baseline (28 MHz) correlator in 1982. The correlator has been operating 24-hours/day, 365 days/year ever since its initial installation, processing over 200,000 data tapes and 2,000,000 single observations since that time.

In 1984, four US government agencies¹ contracted with Haystack Observatory to develop and build a next-generation Mark III correlator to be installed at the U.S. Naval Observatory in Washington, D.C. This correlator, dubbed the Mark IIIA correlator, was to have significantly improved capabilities in several areas, primarily in modelling and data-throughput improvements. This new correlator system was initially installed at USNO in January 1986, and has since been expanded to 5-station 10-baseline (28 MHz) capability. During its operational period to date at USNO, the correlator has processed approximately 40 24-hour IRIS experiments, plus about 250 MERIT-intensive UT1 daily observations. Correlator up-time has averaged about 90%.

2. THE FUNCTION OF THE CORRELATOR

Figure 1 shows a simple schematic of a 2-station VLBI experiment. Two antennas, labelled "reference" and "remote", at widely-separated locations, simultaneously collect data from a radio star. Each station has its own independent clock and frequency standard, typically based on a hydrogen maser, to which all local-oscillator frequencies are referenced, and with which all collected data is time-tagged. The radio-frequency data are typically collected over many (usually 14) independent channels or "windows" of 2 MHz bandwidth each; the windows themselves are typically positioned to cover several hundred megahertz of "spanned" bandwidth, which allows use of the bandwidth-synthesis technique (Ref 1) to recover high-precision group-delay estimates. Geodetic observations typically observe sky frequencies around 8400 MHz and 2300 MHz; this dual-band coverage allows the effects of the ionosphere to be calibrated and removed from the data. The data from each "window" is sampled, digitized, time-tagged, and recorded on magnetic tape, typically at an aggregate rate of 56 Megasamples/sec. These data tapes are then transported to the correlator for cross-correlation processing.

Due to the earth/radio-star geometry, the radio star signal arrives at the "remote" antenna delayed by a time τ_g with respect to arrival of the same signal at the "reference" antenna. Of course, due to the rotation

¹NASA, NGS, USNO, NRL

of the earth, τ_g is a function of time, and also includes components due to ionosphere, atmosphere, instrumentation, etc. Furthermore, the signals at each antenna are Doppler-shifted with respect to each other due to different velocities along the line-of-sight from the stations to the radio star.

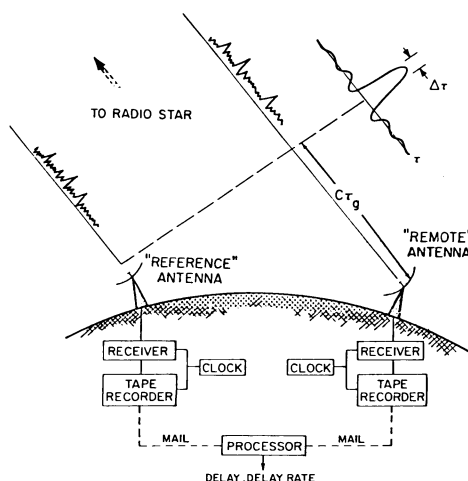


Figure 1. Schematic Diagram of VLBI Observation

The job of the correlator is to cross-correlate the data streams from the data-taking stations to determine the value of τ_g at some particular epoch, t_0 , as read on the clock at the "reference" station. In order to do this, the correlator must have a sufficiently accurate model of data-taking geometry and conditions so that it can cross-correlate the actual data over a wide-enough range of trial delays so that the actual correlated signal falls within this range. As a matter of practicality, the model must be sufficiently accurate to effectively remove all effects of order $\dot{\tau}_g(t)$ and higher, so that only estimates of $\tau_g(t_0)$ and $\dot{\tau}_g(t_0)$ need to be made from the actual data itself². This is mandated by the fact that typical correlation coefficients, particularly those involving small antennas, are only a few parts in 10^{*4} , with a signal-to-noise ratio of order 10-to-1.

The process of cross-correlation must be very tightly controlled so that the time-tag on each data sample is acknowledged and honored, and that the processes performed within the correlator hardware are fully

² $\tau_g(t_0)$ is determined by combining the data from all of the frequency "windows" to form an estimate of group delay. $\dot{\tau}_g(t_0)$, on the other hand, is fundamentally a phase-delay-rate measurement (Ref 1).

accountable to the higher-level modelling in the control computer. Because $r_g(t)$ is usually rapidly-changing, as well as the associated differential Doppler shift (also called "fringe rate"), the correlator hardware must be capable of tracking these rapidly-changing quantities with high precision. Typically, the Mark IIIA correlator is capable of tracking the high-level model to (average) picosecond precision in delay, and (average) micro-radian precision in Doppler phase.

As part of the data-taking process, several calibration signals are continuously injected through the entire data-acquisition system and embedded in the radio-star data stream. These calibration signals are used to monitor the performance of the acquisition equipment and to calibrate the relative phases of the various oscillators that are used to translate the individual "window" signals from RF to base-band. These calibration signals must be extracted by the correlator and applied to the data prior to the estimate of the value of $r_g(t_0)$.

3. HARDWARE SYSTEM

3.1. Overview

The Mark IIIA processor, like the Mark III processor, is based on a straight-forward modular concept utilizing one hardware correlator module per baseline track-pair, where a tape track contains the data from a single RF "window". Thus 14 modules are required to process one baseline of 14 tracks. Each module operates as a completely autonomous unit, but all are controlled by a common overseeing computer. The module performs the functions of de-coding the two data streams (one from each station forming the baseline), buffering and correctly aligning the data streams to remove the effects of recorder jitter before rotating and cross-correlating the data streams.

In the Mark IIIA system, up to 5-stations (10 baselines) of 14-track data may be correlated through the ensemble of 140 identical correlator modules. Software-selectable signal-path selection allows considerable freedom with regard to configuring the correlator for processing other types of data. For example, up to 5 baselines of 28-track data may be processed simultaneously; or all polarization combinations from a 3-station 14-track (7 tracks/polarization) may be processed with suitable software commands.

3.2. The Mark IIIA Correlator Module

Figure 2 show a simplified block diagram of a single Mark IIIA correlator module and its interfaces to the tape recorders and external control computer. The signals from the reproduce heads are amplified, equalized and passed to "bit synchronizers", which re-construct the data and associated clock streams. Decoders built into the processor module detect the synchronization bits in the serial format and separate the radio source data streams from embedded time, parity, and auxiliary data. One of the

radio-source data streams is buffered by a fixed delay and then multiplied by 3-level approximations of the sine and cosine functions, while the other data stream is buffered by a programmable delay before the two data streams are cross-correlated. The cross-correlator processes 32 lags per quadrature channel, with 32-bit accumulators in each lag.

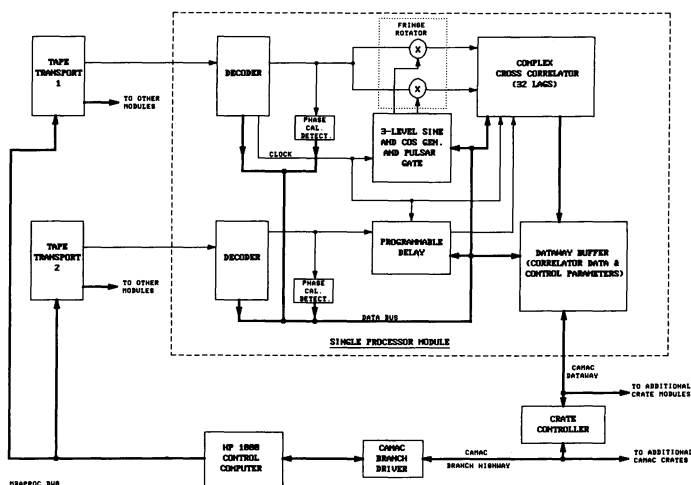


Figure 2. Simplified Block Diagram of Mark IIIA VLBI Processor

Normally each processor module is allowed to accumulate several seconds of data before being read by the control computer. More rapid service can take place and may be desirable for special processing. Because the data-playback tape drives must run continuously (i.e. they cannot perform rapid start/stop like computer tape drives), the correlation results from each integration period must be internally buffered until the control computer can read them out, while correlation continues in a steady continuous process.

The information from the module is transmitted through a CAMAC controller and branch driver to the controlling computer. The "tape time" information in the data is used by the computer to control the speed of the tape drives so that they are kept mechanically synchronized to within the limits of the internal buffers of the correlator module. Typically, tape synchronization is maintained to within a few hundred bits on the tape, corresponding to <1.0 mm of physical tape position. (bit density on the tape is 33,000 bits/inch/track).

Following correlation, the data from all frequency channels of an observation are combined in software "fringe" processing, which implements the bandwidth synthesis algorithm to estimate group-delay. Also estimated at the same time are delay rate, correlation amplitude, and fringe phase.

Table 1 lists the basic Mark IIIA module characteristics. Each correlator module contains approximately 350 integrated circuits, including a dedicated microprocessor. The equivalent processing power of a single Mark IIIA module is estimated to be about 1 Mflops/sec. The improved internal modelling allows use of the Mark IIIA correlator for processing data collected by orbiting spacecraft, where potentially very large values of delay rate and acceleration must be dealt with. In fact, the Mark IIIA correlator was used to process the first successful space-based astronomical VLBI experiment in August 1986 (Ref 3).

<u>Module I/O</u>	- X data & clock (8 Mbits/sec max, from 16-way selector)
	- Y data & clock
	- CAMAC dataway to/from computer
<u>Correlator</u>	- 32 complex lags
	- 32-bit accumulation registers (updated every data bit)
<u>Rotator</u>	- 32-bit phase register (1.5 nanoradian quantization, updated every data bit)
	- 0.9 milliHz phase-rate quantization (updated every 5 millisecc)
<u>Internal data buffering</u>	- 20,000 data bits (5 millisecc at 4 Mbit/sec)
<u>Integration period</u>	- Software adjustable from 5 millisecc to 16 sec (@ 4 Mbits/sec)
<u>Phase calibration</u>	- 2 1-channel (complex) special-purpose correlators

Table 1 - Mark IIIA Correlator Module Characteristics

4. RADIO-ASTRONOMY PROCESSING CAPABILITIES

The Mark IIIA correlator also provides a full range of radio astronomy processing capabilities, where the needs are often somewhat different. In particular, observable quantities such as delay and delay rate are generally of less interest than correlation amplitude and fringe phase. Spectral-line observations, requiring many additional lags in the correlation processing, are also a standard part of radio-astronomy observations, as are observations of pulsars, where correlation must be gated on and off rapidly and at precise intervals. The facilities for processing these types of observations are included within the Mark IIIA correlator.

5. POTENTIAL SYSTEMATIC ERRORS IN THE GROUP-DELAY ESTIMATE

5.1. Instrumental Sources of Error

Table 2 shows estimates of known estimated worst-case systematic errors in the group-delay estimate due to various instrumental effects in observations spanning an RF bandwidth of 400 MHz (some of the listed

effects will increase for a smaller spanned-bandwidth; none are likely to decrease for a smaller spanned-bandwidth). Most of the potential errors are <10 picoseconds, although a few are potentially larger and merit some comment. In any case, it is unlikely that all, or even many, of these instrumental errors will be simultaneously significant.

Antenna flexure can physically move the focus point of the antenna away from its modelled location. For small antennas (<15-20 meters), this effect is generally believed to be <15 picoseconds, but for large antennas (>25 meters) the effect may be increasingly large, due particularly to gravitational loading deformations and, generally to a lesser extent, to environmental effects (differential temperature, wind loading, etc). Even in the cases where flexure may lead to systematic biases in group-delay measurements, their effect is often diminished in final geodetic solutions by being absorbed into estimates of other parameters, most notably site elevation; this is particularly true for azimuth-elevation mount antennas where such delay-estimate errors tend to be azimuthally symmetric, and so will primarily affect the local elevation estimate of the site. As methods become available for more accurate modelling of large antenna structures, the effects of antenna flexure errors will undoubtedly be significantly reduced.

	Max over 400 MHz
<u>Antenna, Feed, Waveguide</u>	(psec)
Antenna flexure	50
Multiple reflections	7
Dispersion	2
Polarization impurity (20db)	5
<u>RF-IF Signal Processing</u>	
Image rejection	2
Receiver saturation	14
Harmonic responses	2
Phase variations across band	3
VC residual 10kHz	1
Spurious signals	7
<u>Calibration System</u>	
Multiple reflections	7
Temp coefficient (6ps/degC)	12
Phase-cal 5-kHz sidebands	1
<u>Data Recording System</u>	
Sampling-epoch error	2
	RSS= 55

Table 2 - Instrumental Sources of Group-Delay Errors

The other two major contributors to potential systematic errors, namely receiver saturation and instrumental temperature coefficients within calibration equipment, are generally smaller than the worst-case values listed in Table 2. Receiver saturation is a rare occurrence with modern high dynamic-range receivers, and generally only occurs in the face of severe man-made interference. And, generally, calibration electronics are temperature-controlled to ~1 degC, so that errors due to that source are below 10 picoseconds.

5.2. Data-Processing Sources of Error

Table 3 lists potential sources of worst-case systematic errors due to processing with the Mark IIIA correlator system and the subsequent software "fringe" processing to estimate a group-delay value for each observation. Clearly, the most significant of these is due to a non-symmetric loss of data, either in time or frequency. The partial or full loss of a data channel (i.e. frequency "window") due to faulty equipment or defective recording can be particularly troublesome, due to the fact that there may be unmodelled and uncalibrated phase dispersions in the RF receiving system, usually due to multiple reflections in the receiver and phase-calibration injection system. It is possible in principle to remove most of this effect by making observations on a strong radio source, measuring the dispersion, and then applying the necessary corrections to all of the data, under the assumption that the observed dispersion is time invariant. In practice, the magnitude of dispersion is usually small, and these added measurements and complications in the data reduction are neither undertaken or necessary.

<u>Correlation</u>	Max over 400 MHz (psec)
Phase-cal error (0.1 deg)	1
Modelling errors	
Software (0.001 deg)	.01
Firmware/Hdwre (0.01 deg)	.1
Lo-el atmos accel (1 deg)	7
Truncation effects (0.1 deg)	1
<u>Fringe processing</u>	
Approximations (.2 deg)	2
Non-symmetric loss of data (2 deg)	14
	RSS= 16

Table 3 - Data-Processing Sources of Group-Delay Errors

References:

1. T. A. Clark et al, 'Precision Geodesy Using the Mark-III Very Long Baseline Interferometer System', IEEE Transactions on Geoscience and Remote Sensing, GE-23, 438-449 (1985).
2. A. R. Whitney, 'The Mark III Correlator: Design, Operation, and Productivity', Proceedings of IAG Symposium No. 5: Geodetic Applications of Radio Interferometry, 152-162 (1982).
3. G. S. Levy et al, 'Very Long Baseline Interferometric Observations Made with an Orbiting Radio Telescope', Science, 234, 187-189, (1986).

DISCUSSION

Eubanks: What is the nature of the low elevation atmospheric acceleration error source?

Reply by Whitney: At low elevations, the acceleration in phase due to the atmosphere can be very large, and if the correlator model does not track these variations, then systematic group delay errors can be introduced.

Treuhaf: Does the non-symmetric loss of data error show up in the formal errors which come out of the Mark III correlator?

Reply by Whitney: No. It is often smaller than the 14 psec reported, but is not included in the correlator formal error.

Bauersima: Do you intend to reconstruct the form and the size of satellites by observing them by VLBI methods after they've been illuminated by radar?

Reply by Whitney: Initially, at least, this work will be done using the Lageos satellite, which is quite smooth and nearly symmetric, and should be quite good for these sorts of observations. Other existing and future satellites of the Lageos type should also be quite suitable.