VINCI: The first interferometric instrument at the VLTI, its success story, and technical lessons learned

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This is the annotated post-conference version of my presentation. Material that was only presented orally at the conference has been included in these orange boxes.

This talk is about the instrument whose 10 anniversary we are marking with this conference!

Thanks to the many here (and some not here) who helped make the first VLTI instrument a resounding success, allowing the interferometric infrastructure to be tested and verified, paving the way for all of the subsequent instruments.

And, beyond all initial intentions and expectations, a modest instrument which proved itself to produce first-class interferometric data and a large number of scientific results and publications, with a visibility precision that rivals any previous or subsequent optical interferometric instrument, anywhere.

And from which we still have much to learn.......

Here is the abstract for the talk I had submitted but which didn't get completely inserted into the advance program (surely not due to its length ;-)

ABSTRACT

VINCI was the first interferometric instrument implemented at the VLTI, intended primarily as a test and alignment instrument, but which delivered scientific results far exceeding any initial expectations. A very brief overview of the instrument and its operational history is presented.

The talk will then concentrate on some technical issues affecting the instrument, both positive and negative, and some lessons that can be learned. These issues are illustrated in each case using results obtained from analysis of on-sky (and some technical) data sets.

The greatest attention is devoted to the single-mode fiber beam combiner (MONA) which is the heart of the instrument. This device was an improved version of the tried and tested design used in the previous FLUOR instrument. Its parameters fluctuated over time requiring frequent (and troublesome) adjustment in order to obtain a high interferometric efficiency. Polarization mismatch is believed to be mainly responsible for the fluctuating and sometimes poor interferometric efficiency, and this is a general concern in the case of single-mode (guided wave) optical systems accepting both polarizations.

Due to the essentially perfect spatial filtering obtained using single-mode fibers, atmospheric seeing (r_0) had practically no effect on the transfer function (calibration) of the instrument over a single night. Apparent fluctuations in the transfer function are caused in the data reduction stage or are due to changes in the atmospheric coherence time (tau_0) when using an insufficient detector frame rate. This realization can simplify the choice and use of calibrator observations in an instrument benefiting from full spatial filtering.

Due to the exceptionally high intrinsic precision of the measurements, the demonstrated error in raw visibilities (but also in calibrated visibilities) could often be shown to steadily decrease in proportion to the square root of the observing time, rather than reaching a plateau due to systematic error sources as is more often the case. Unfortunately such attainable levels of precision were seldom realized due to the finite duration of observations. A number of conservative approaches in the design of VINCI helped guard against failure of the hardware or data analysis, however these also reduced the observational efficiency of the instrument. For instance, the long scans used in normal observing modes meant that the instrument spent 90% of the time completely off-fringe, leading to this observing inefficiency.

The ultimate test of the instrument's precision can be inferred from fitting calibrated visibilities obtained to the UD visibility function and analyzing the residuals obtained. 155 stars were observed sufficiently to consider, some of which are rather dim or might not be properly fit using a UD visibility function. The better half of this set, 77 stars, all had a median residual which was better than 1.2% of the visibility itself. 19 stars had a median residual better than .7% of the measured visibility.

Some parameters of the hardware were insufficiently characterized, controlled, and/or monitored. Poor knowledge of or means of measuring the effective wavelength of operation led to uncertainty in the spatial frequency assigned to observations whose visibilities had been measured with higher precision. Non-uniformities in the piezo scanning rate are another example of an avoidable hardware fault. Such limitations only became issues once VINCI was employed for generating scientific results that went well beyond its initial design as a test and alignment instrument. From these shortcomings in an otherwise exemplary instrument, some obvious lessons can be learned.

Outline of this talk:

- *Very* brief history and explanation of the VINCI hardware
- Various aspects of the instrument (hardware), its performance and lessons learned, in random order :-)
- *NO* discussion of scientific results (just go to ADS abstract service and type in “VINCI”)
- *NO* discussion of data reduction algorithms and comparisons (that's my other talk!)

Disclaimer/explanation:

- Any reference to data reduction algorithms is only to provide context for discussion of results regarding the performance (or *potential* performance) of the hardware, and the exploitation of the data obtained.
- Any reference to astronomical results (such as fitting stellar diameters) is for the sake of showing goodness-of-fit and analysis of residuals (thus a lower limit on the instrument's precision).

At this point I added a few introductory remarks which hadn't made it into the slides. I mentioned that this entire conference, celebrating the 10 year anniversary of the VLTI, was in fact celebrating the 10 year anniversary of VINCI operating (plans for the VLTI had begun many years earlier, as had been explained in two history talks). So I thought that VINCI's role in the history of the VLTI needed to be accorded its due respect. Even though VINCI had been designated as a test and alignment instrument for the VLTI, its performance had exceeded its design goals and wound up producing many useful scientific results during regular operation over the 3 subsequent years. These were the basis of many dozens of publications.

This unanticipated use of VINCI for “serious” astronomy, is already one lesson that can be learned from the experience. When building a piece of hardware, one's vision of its ultimate utility is always imperfect, and one should never make unneeded sacrifices in its performance or utility simply because those aspects are, at the time, considered of little importance to its designated purpose. Thus some performance aspects of VINCI could have been better assured (at a small cost) or plans could have been made to monitor crucial parameters, but these were missing due to short-sightedness.

The most striking aspect of the VINCI hardware's performance that could be mentioned is certainly the precision with which it is able to measure visibilities, which rivals or exceeds all other stellar interferometers, any time anywhere. It inherited this ability from its design which was based on the successful FLUOR instrument, in which single spatial mode interference between two samples of starlight filtered by an optical waveguide (optical fiber in this case) are each also “photometrically” monitored, so that a precise calibration of the correlated flux to visibility can be assured.

Precision of visibilities is not the only valuable characteristic of an interferometer, and some sorts of serious science can proceed even with interferometers having a poor precision in measurement of visibilities. For instance:

Visibility precision not crucial

- Interferometry emphasizing *spectroscopy*, thus measuring “correlated flux” across a spectrum, not necessarily normalized as visibility. Includes so-called “differential visibility” across spectral lines, or identifying different color/temperature components of an underlying image having different spatial scales.
- Interferometry where *phase* (either differential phase or closure phase) is the main observable.

Visibility precision required

- *Parameter estimation*, such as stellar diameter, ellipticity, limb-darkening. Also binary stars' separation and relative brightness parameters.
- *Nulling*, since this involves measuring a visibility 1-V where V is very close to 1.
- *Imaging*, where the fidelity of any image reconstruction algorithm is dependent on the precision of the visibilities (and phases) that are fed into it.

VINCI was built with no spectral resolution or phase measuring capabilities (left column), but was very successful in attaining precision visibilities. That capability requires single spatial-mode optics plus photometric monitoring, as is obtained using its design (and that of FLUOR) based on feeding the telescopes' light into single-mode optical fibers.

Telescopes,
Relay optics,
Main delay lines
(VLTI infrastructure)

Keys to the success of VINCI hardware:

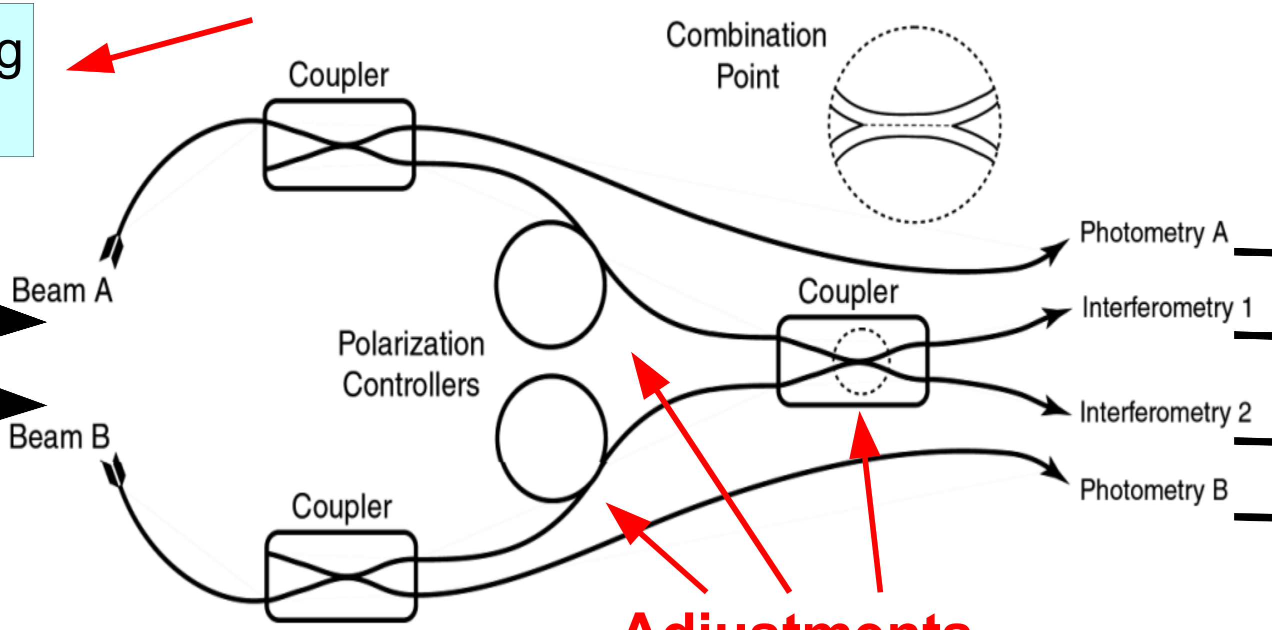
- Simplicity!
- No moving parts (to speak of)
- Based on previous successful design: FLUOR
- Generates 4 data points, just enough to fully interpret fringe, no extra data to confuse the programmers ;-)

Shutters

Only moving parts

Scanning Piezo

Fiber injection optics



Adjustments

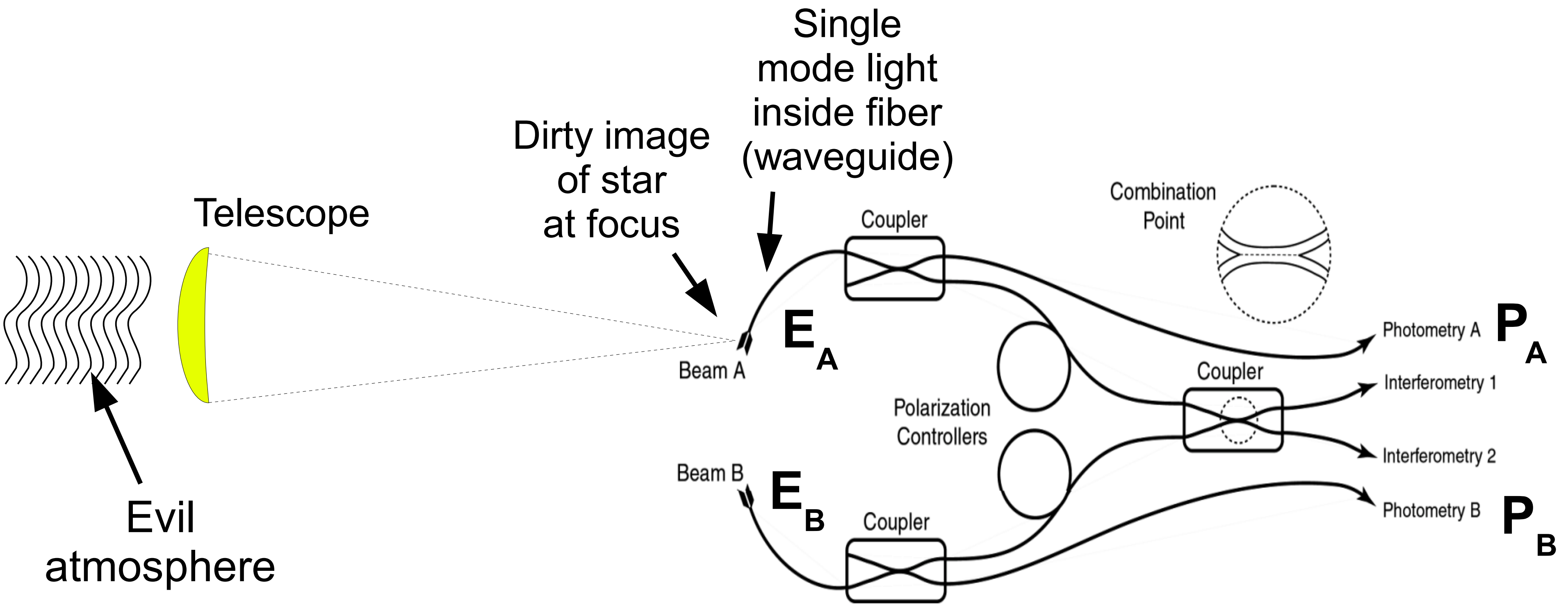
IR Camera (LISA)
(4 pixels used)

+ K band filter

MONA Beam combination unit
(Figure lifted from papers by P. Kervella; thanks)

VINCI was inspired by the design of FLUOR from several years earlier, using same beamcombination optics based on optical fibers and X-couplers

- Forcing starlight into single-mode fiber selects only one spatial mode of starlight = perfect *spatial filtering*
- Light entering each fiber given by a single field quantity: $\mathbf{E}_\mathbf{A}$ and $\mathbf{E}_\mathbf{B}$.
- The intensities $\mathbf{I}_\mathbf{A} = |\mathbf{E}_\mathbf{A}|^2$ and $\mathbf{I}_\mathbf{B} = |\mathbf{E}_\mathbf{B}|^2$, are sampled by the photometric pick-offs $\mathbf{P}_\mathbf{A}$ and $\mathbf{P}_\mathbf{B}$


Single mode light inside fiber (waveguide)

Dirty image of star at focus

Telescope

Evil atmosphere

$\mathbf{E}_\mathbf{A}$

$\mathbf{E}_\mathbf{B}$

$\mathbf{P}_\mathbf{A}$

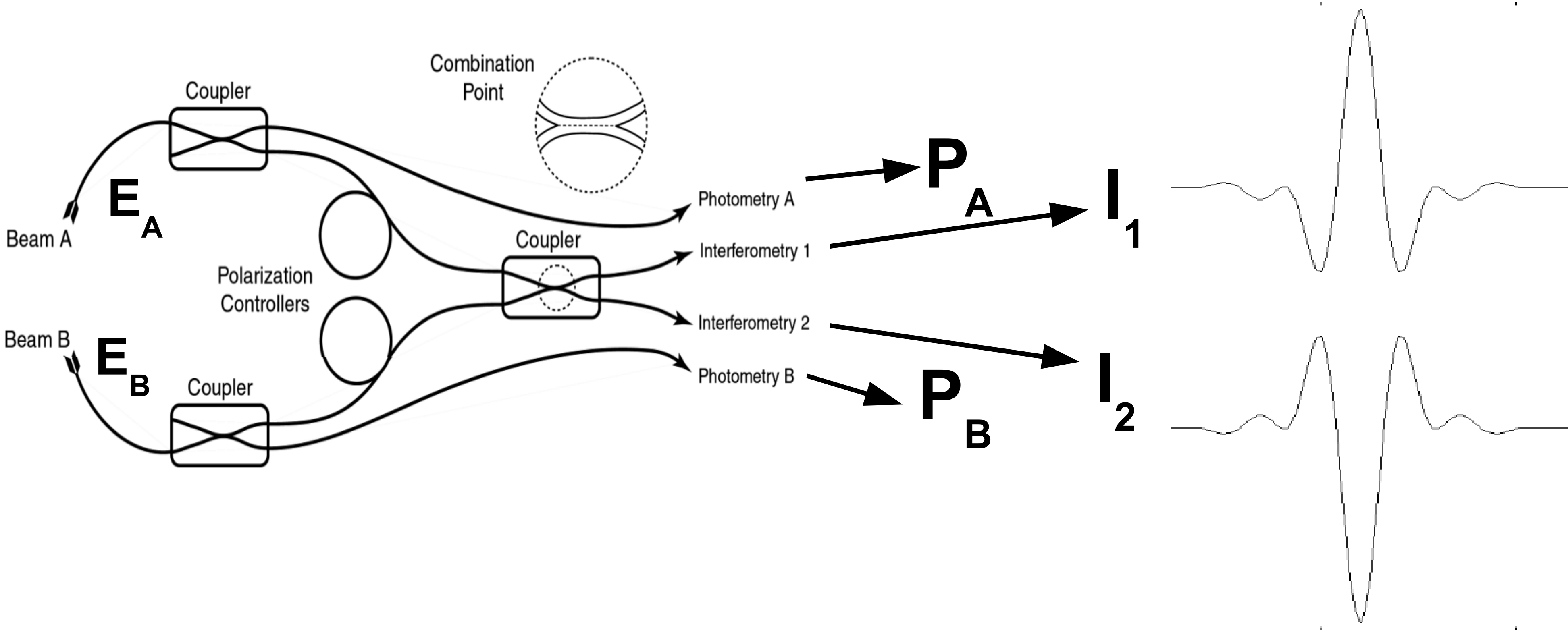
$\mathbf{P}_\mathbf{B}$

The interferometric outputs have intensities $\mathbf{I}_1 = |\mathbf{E}_1|^2$ and $\mathbf{I}_2 = |\mathbf{E}_2|^2$ which are a result of interference between $\mathbf{E}_A$ and $\mathbf{E}_B$:

$$\mathbf{E}_1 = \mathbf{s}_{1A}\,\mathbf{E}_A + \mathbf{s}_{1B}\,\mathbf{E}_B$$

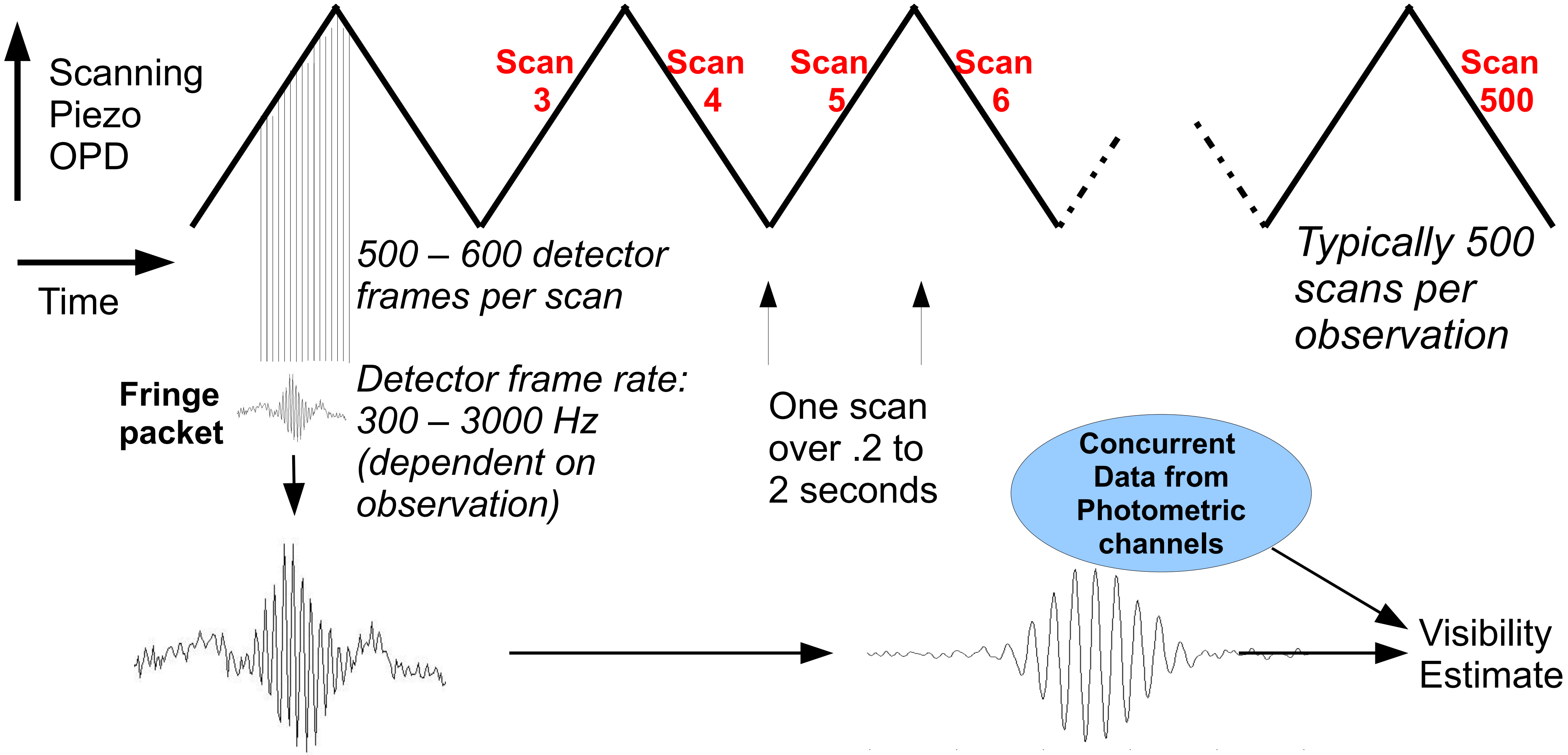
$$\mathbf{E}_2 = \mathbf{s}_{2A}\,\mathbf{E}_A + \mathbf{s}_{2B}\,\mathbf{E}_B$$

$\mathbf{I}_1$ and $\mathbf{I}_2$ each include both a “photometric” contribution from $\mathbf{I}_A$ and $\mathbf{I}_B$, and an interferometric signal due to any correlation in the inputs' electric fields: $<\mathbf{E}_A\ \mathbf{E}^*_B>$ which appears in opposite phases in the two interferometric outputs.



Generation of data stream by VINCI

Triangular wave OPD scanning over range ~200 microns



Scanning Piezo OPD

Time

Scan 3

Scan 4

Scan 5

Scan 6

Scan 500

500 – 600 detector frames per scan

Typically 500 scans per observation

Fringe packet

Detector frame rate: 300 – 3000 Hz (dependent on observation)

One scan over .2 to 2 seconds

Concurrent Data from Photometric channels

Visibility Estimate

Raw fringe from interferometric channel

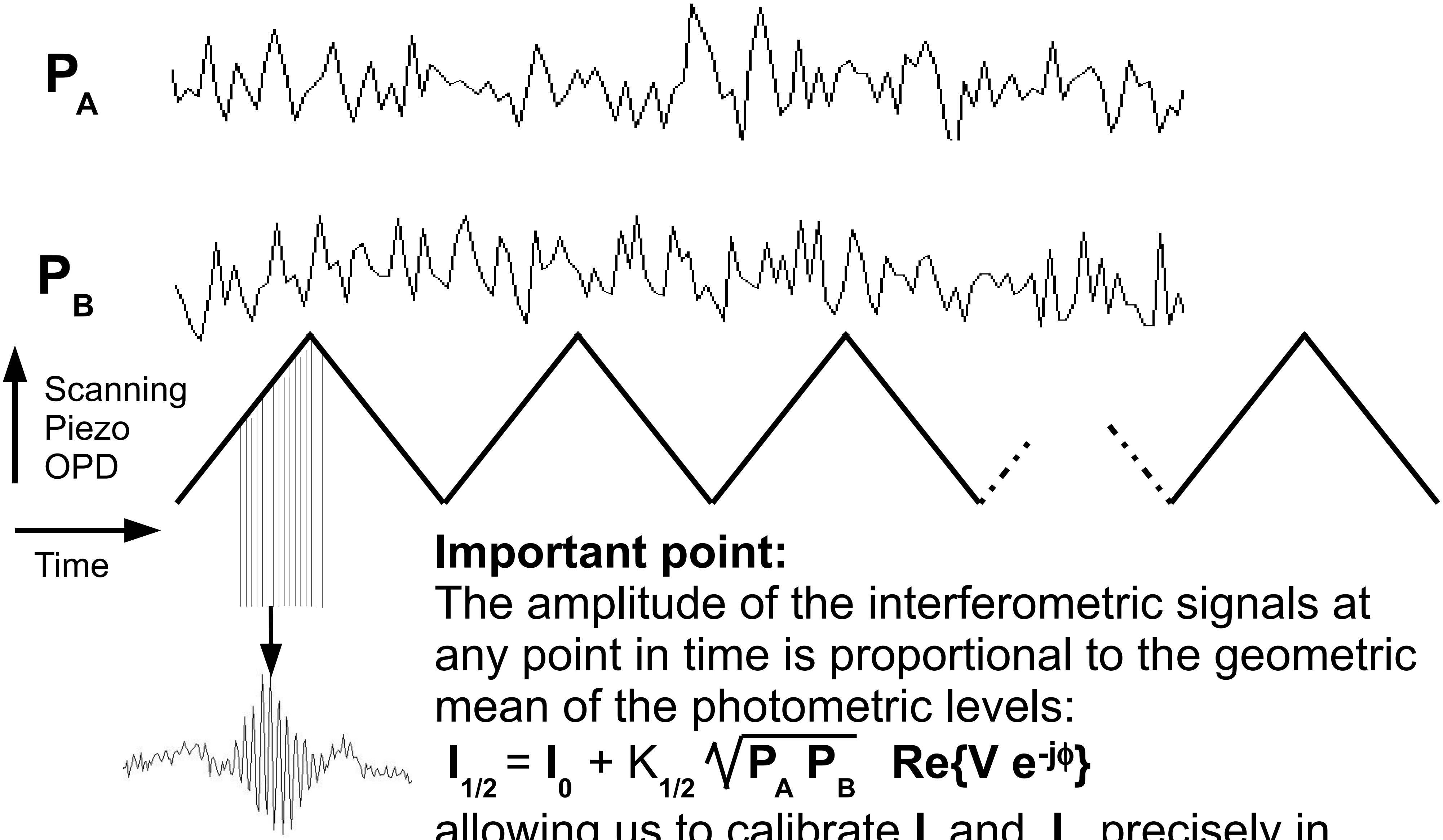
5 detector readings per fringe cycle

About 50 detector frames for entire fringe packet

90% of scan is off-fringe

Filtered fringe with “photometric noise” removed

Concurrent recording of sampled "photometry" P_A and P_B



Important point:

The amplitude of the interferometric signals at any point in time is proportional to the geometric mean of the photometric levels:

$$\mathbf{I}_{1/2} = \mathbf{I}_0 + K_{1/2}\sqrt{\mathbf{P}_A\,\mathbf{P}_B}\;\mathbf{Re\{V\,e^{-j\phi}\}}$$

allowing us to calibrate $\mathbf{I}_1$ and $\mathbf{I}_2$ precisely in terms of the visibility V and applied phase ϕ!

Precision of VINCI visibilities in practice

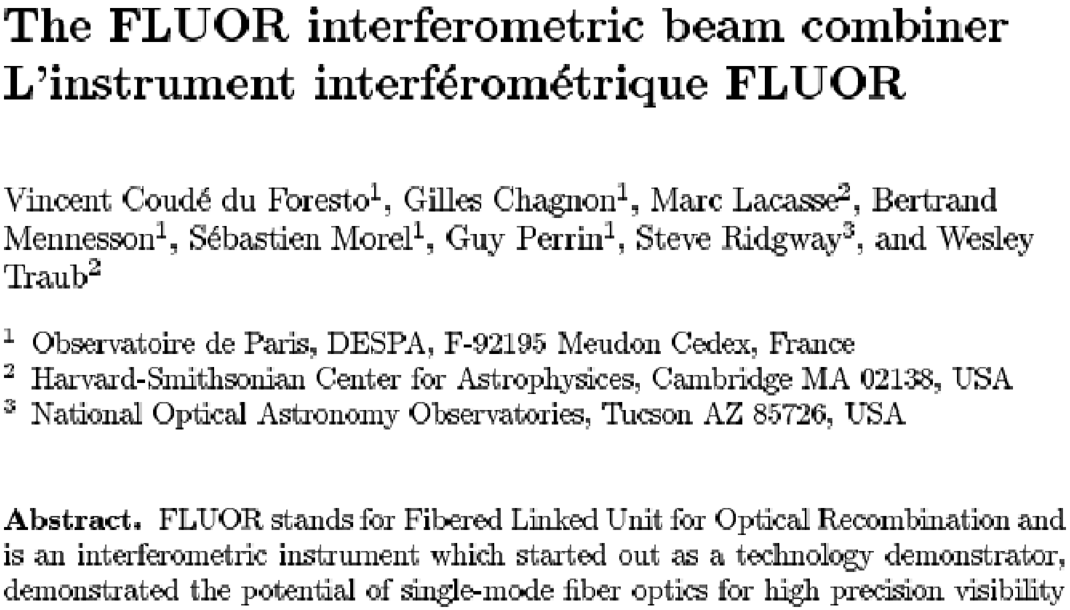
Using over 15,000 observations (or “observation blocks”) performed over 3 years of regular operation, the diameter of the observed stars has been fit blindly by a computer. Of the 155 stars which had been thus fit, we choose to concentrate on the half which have the best fit to a Uniform Disc (UD) visibility curve. Therefore this filters out stars which (for one reason or another) cannot be reasonably fit by a UD curve or which are so dim that their visibility errors are exaggerated. Taking only this subset does not significantly bias the subsequent analysis inasmuch as each star is fit by many (between about 10 and 800) visibility points, so any arbitrary subset of stars could be used to gauge the precision of the visibilities obtained (but we have now eliminated stars which would not be fit properly for reasons which VINCI isn't responsible for).

We find that the residuals of the VINCI calibrated visibilities with respect to the UD fit, $\Delta V = V_{\mathbf{measured}} - V_{\mathbf{expected}}$ expressed as a fraction of the full visibility, thus $|\Delta V| / V$, had a median value of no more than 1.2% for each of these 74 stars. This median error level thus includes the calibration error, highlighting the underlying precision of the instrument, on-sky, through the atmosphere, under real-world observing conditions. Although probably not appreciated at the time of this observing, the intrinsic precision of the instrument appears to have been quite a bit better than 1%, but most observations only consisted of 500 scans, typically taking 10 minutes, as the observational efficiency of VINCI was poor (90% of the time it was scanning away from the fringe packet) and the wisdom of recording more scans (over a longer period, or using shorter scans) was not appreciated.

FLUOR

While it is widely appreciated now, this understanding concerning the precision attainable with single-mode optics and separate photometric monitoring of the guided waves was originally demonstrated by FLUOR in the early 90's, and revolutionized the precision of stellar interferometry! FLUOR was employed on the IOTA interferometer and was largely copied by VINCI.

Missing from the author list is Jean-Marie Mariotti who had died at the time of this publication :-(



The FLUOR interferometric beam combiner
L'instrument interférométrique FLUOR

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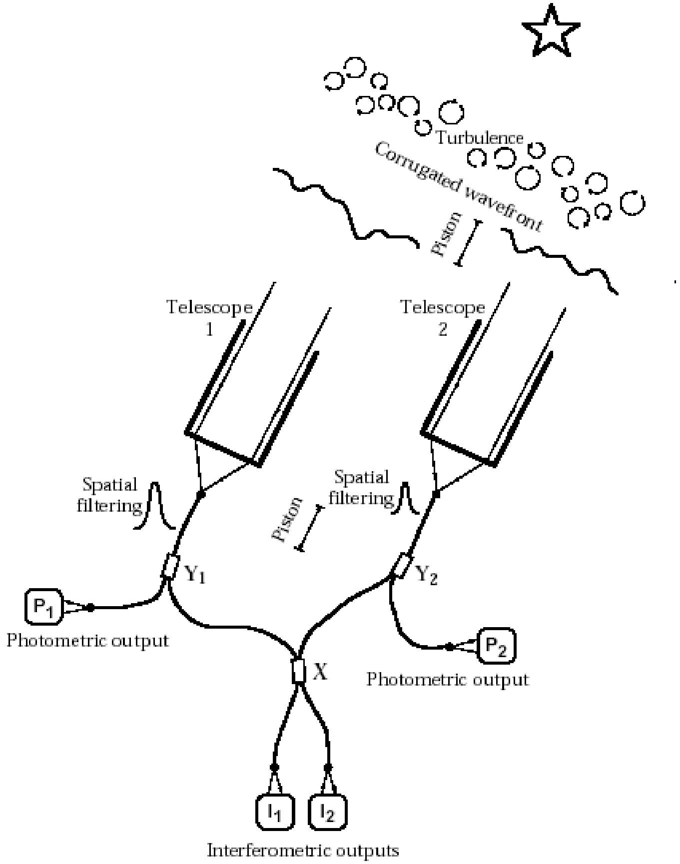
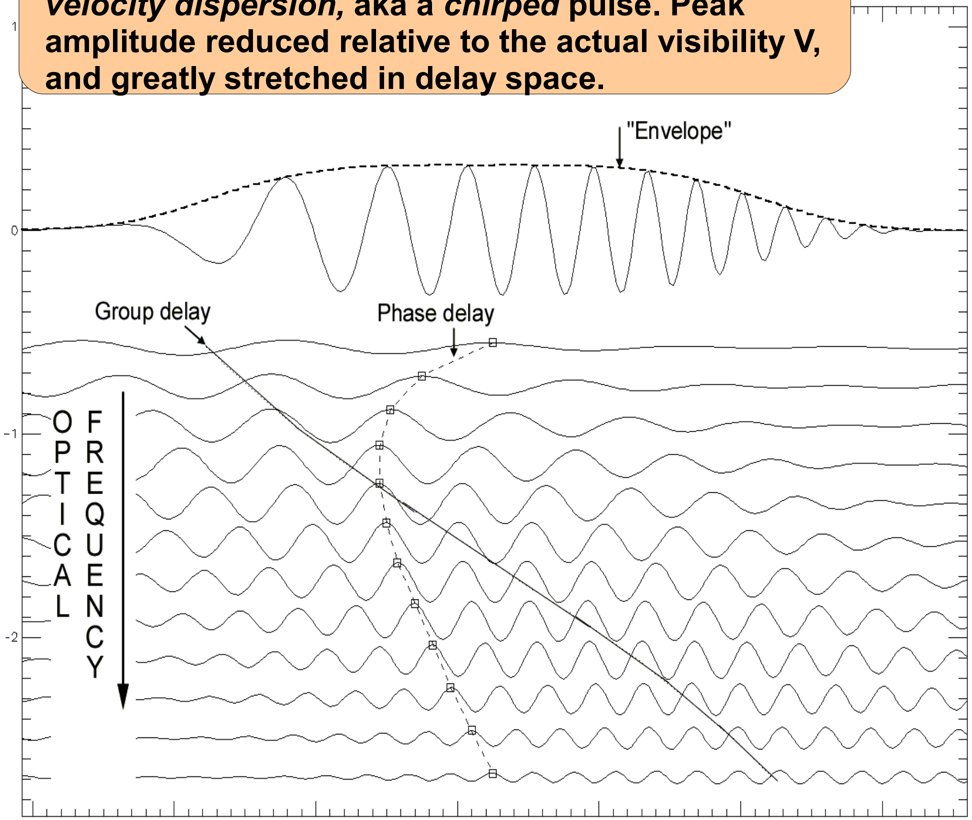
Abstract. FLUOR stands for Fibered Linked Unit for Optical Recombination and is an interferometric instrument which started out as a technology demonstrator, demonstrated the potential of single-mode fiber optics for high precision visibility

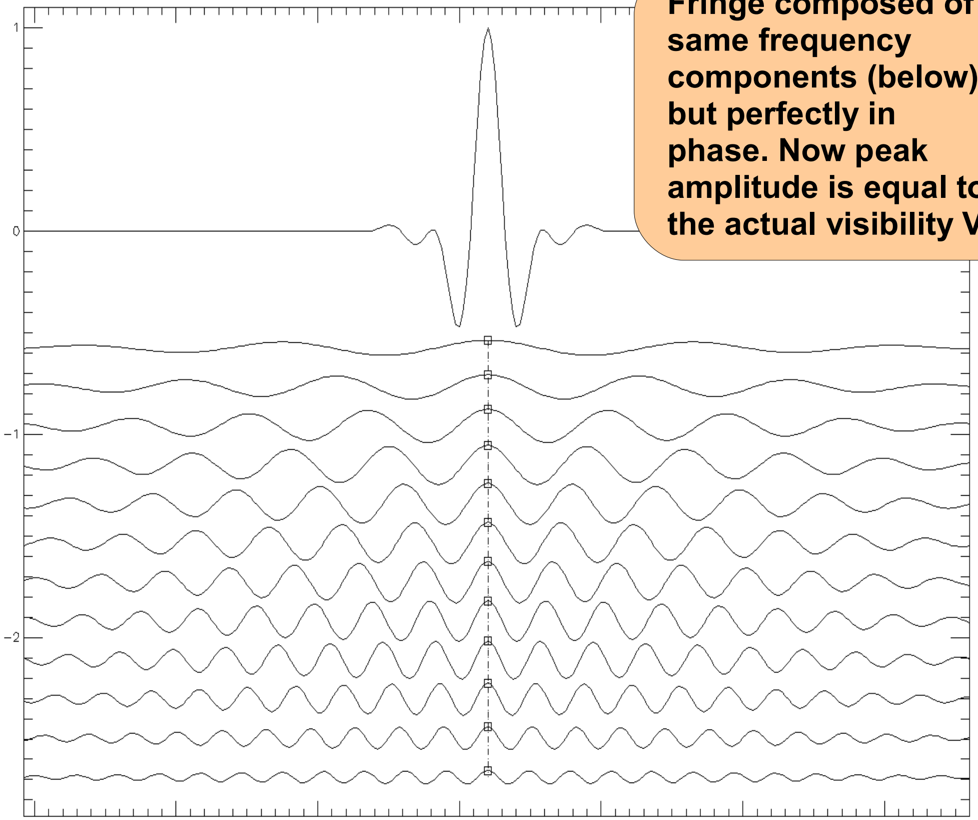


Dispersion problem

Because optical fibers have a great deal of chromatic dispersion (both due to the glass and due to the waveguide properties) the fringe in FLUOR was excessively extended in delay-space. This required long scans to acquire the entire fringe power, and also required an estimator of visibility that was insensitive to that dispersion.



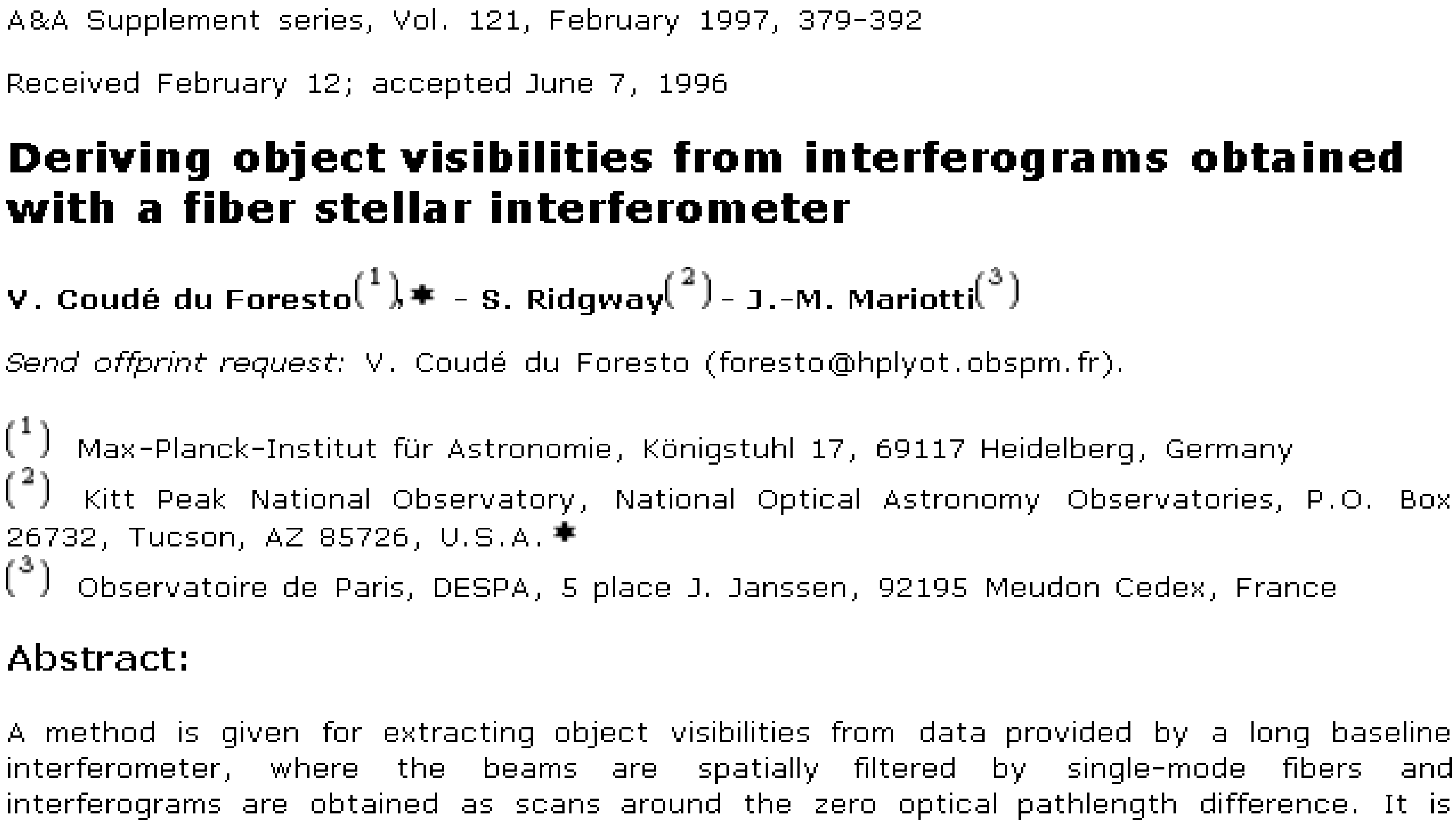
Fringe in delay-space subject to severe *group-velocity dispersion,* aka a *chirped* pulse. Peak amplitude reduced relative to the actual visibility V, and greatly stretched in delay space.



Fringe composed of same frequency components (below), but perfectly in phase. Now peak amplitude is equal to the actual visibility V.

Dispersion problem

Solution for FLUOR involved an algorithm which didn't look at the amplitude of the fringe (which has been reduced by dispersion) but the total “energy” in the fringe (band-limited). This algorithm was also used for VINCI data .....



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Deriving object visibilities from interferograms obtained with a fiber stellar interferometer

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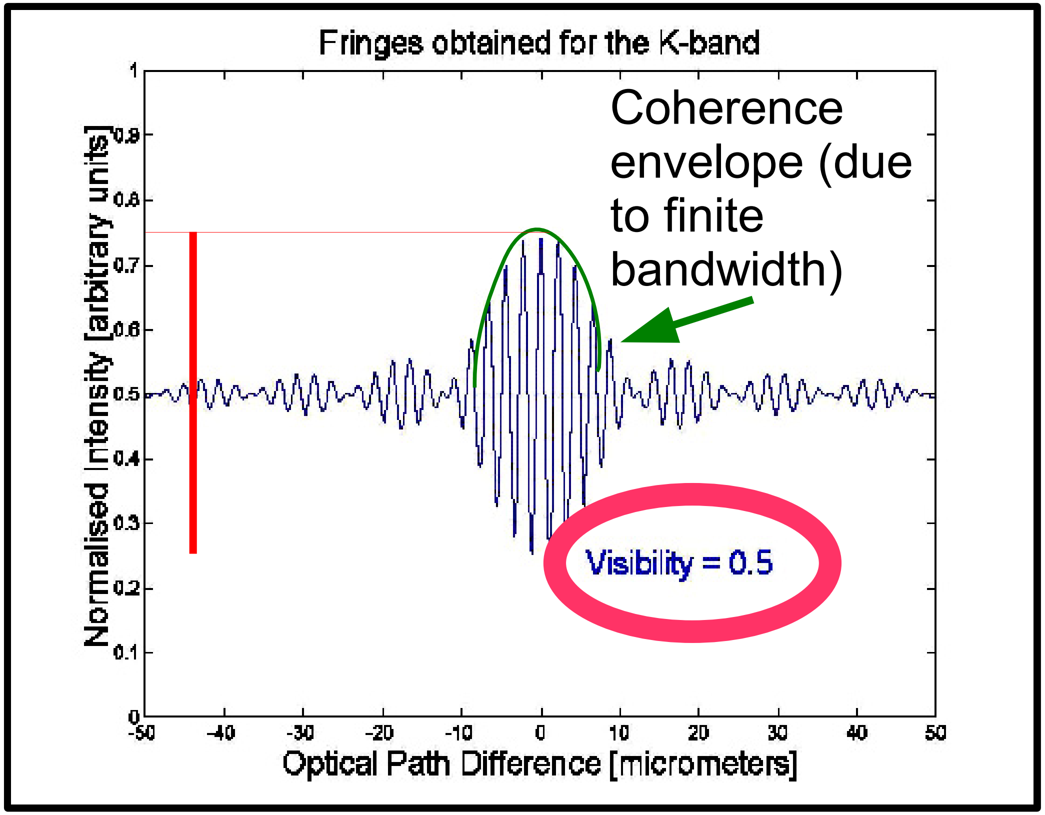
Abstract:

A method is given for extracting object visibilities from data provided by a long baseline interferometer, where the beams are spatially filtered by single-mode fibers and interferograms are obtained as scans around the zero optical pathlength difference. It is

Dispersion problem: not with VINCI!

With the construction of VINCI, careful attention was placed on cutting the fibers to the exact same length and other measures to reduce (with great success!) dispersion in the fringe. This had two benefits, which were not quickly appreciated:

- There was (essentially) no reduction of the amplitude of the fringe packet below the actual visibility (except for the interferometric efficiency)
- The energy of the fringe was compact and could reasonably be scanned through in < τ_0



Coherence envelope (due to finite bandwidth)

Visibility = 0.5

Visibility estimators designed for the dispersion problem that wasn't

The official VINCI data reduction software was based on incoherent integration, that is, measuring the energy in the entire fringe to obtain an estimate of $|V|^2$ with an added term due to detector noise which had to be subtracted. Incoherent estimators have the following characteristics:

- Robust (insensitive to dispersion or position of the fringe energy within a long scan)
- Suffer at low visibilties due to sensitivity to background subtraction (and what's more, a small visibility is a *very* small squared visibility!
- Sensitive to the actual bandwidth of the fringe (which must therefore be defined by a spectral filter, only).
- Suffer a 3 dB noise penalty (as is well known in communications theory) since they are sensitive to noise both in phase and in quadrature phase to the fringe phase. Thus 1.4 x larger error bars.

Various people appreciated the improved quality of the VINCI data and employed estimators described by terms including coherent integration, wavelet transform, and fringe-fitting. However this was a case of the hardware success that VINCI was outstripping the imagination of the astronomers who were married to a tried-and-true algorithm, despite its shortcomings.

A note regarding FLUOR

The one question that there was time for after the talk (which already went over-time!) was more of a comment, in which one person protested that FLUOR is happily in operation and does not have the excessive dispersion I had depicted in the previous slides. I acknowledged that this was the case, but only because the hardware of FLUOR currently in use has been revamped, with the original fiber beam combiner replaced with one in which the fiber lengths have been carefully matched (as was done in the construction of VINCI).

The current state of FLUOR was beside the point, in that I was pointing out a lesson. Namely that the algorithm which had been invented to obtain precision visibilities from the original FLUOR hardware, and which did well given that hardware limitation, had persisted (in the VINCI data reduction algorithm) when it was no longer required. It wasn't quickly (or thoroughly) appreciated that with VINCI (especially at the faster scan rates) the entire fringe packet was recorded *coherently* inasmuch as VINCI scanned through the power due to the fringe in less than τ_0 (whereas the dispersive FLUOR hardware spread it out over much longer than τ_0).

Another outdated (?) concept: the wild fluctuating transfer function and need for painstaking visibility calibration.

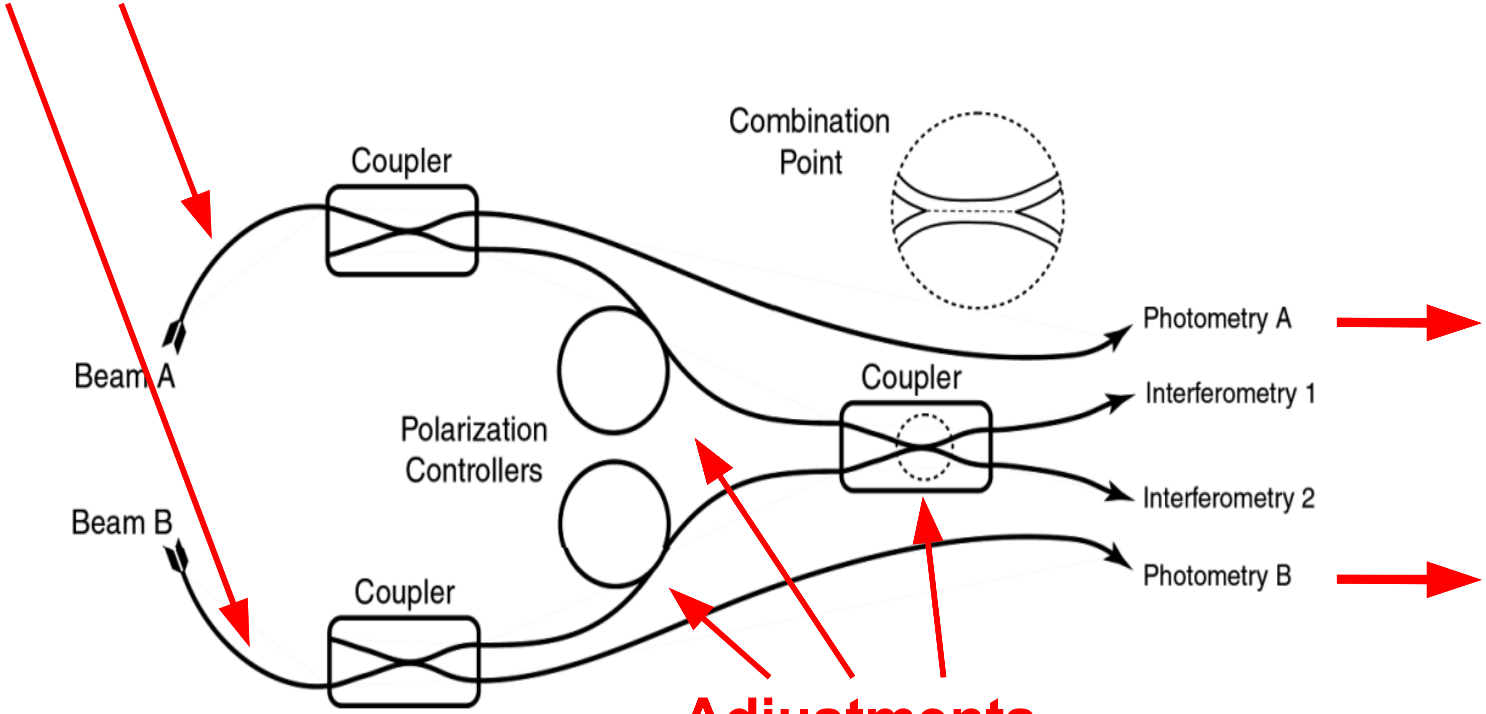
There were many reasons that older interferometric hardware (and algorithms) delivered a ratio of raw visibility to the actual visibility (*calibration*, or *transfer function*) that was troublesome and unstable. The transfer function had to be carefully calibrated for each science observation by observing a star which had to meet some or all of the following criteria:

- Closely spaced in time (thus right before and/or after the science observation).
- Similar color or spectrum compared to the science target.
- At the same air-mass (elevation) or even very close on the sky.
- Having a known (and preferably small) diameter fitting the UD visibility curve (ideally unresolved). **<--- Still true**

Calibrator observations often take the same amount of time as the actual science targets, cutting the observing efficiency by 50% even though a claimed feature of single-mode inteferometry is a constant interferometric efficiency!

Stability of the transfer function over at least a single night (unless something "happens") routinely observed with VINCI.

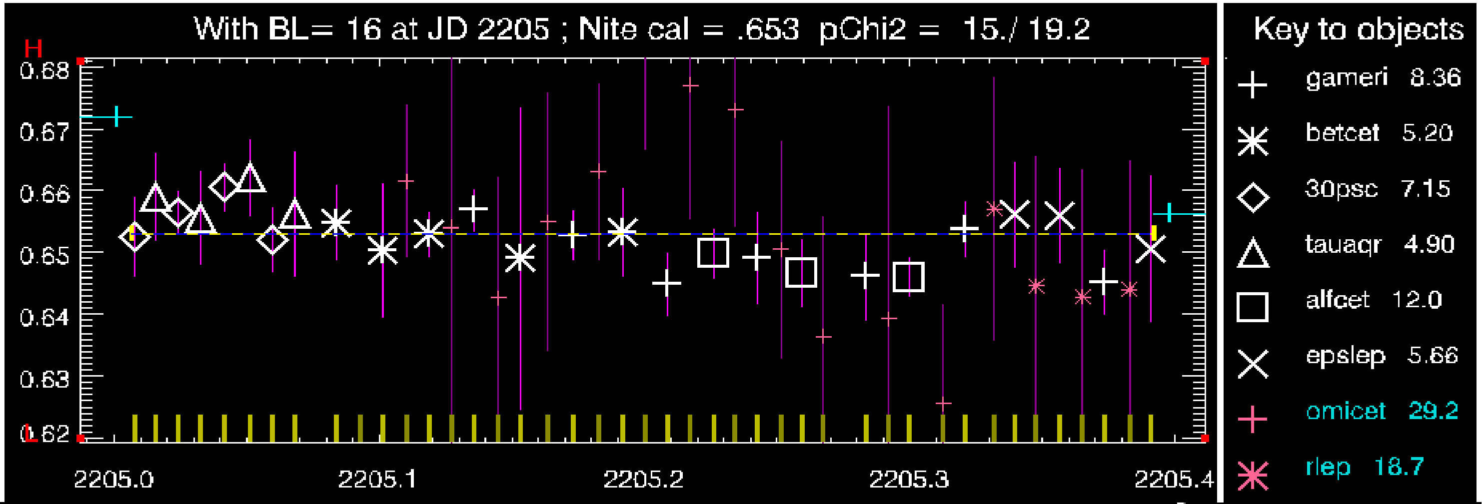
Rationale:
Light inside the waveguides is single-mode, having no memory of the turbulent atmosphere that it had passed through just a few nano-seconds ago. The effect of the atmosphere (τ_0 and r_0) is simply to *reduce* the coupling of light into the fiber and to cause that coupling to *fluctuate*.

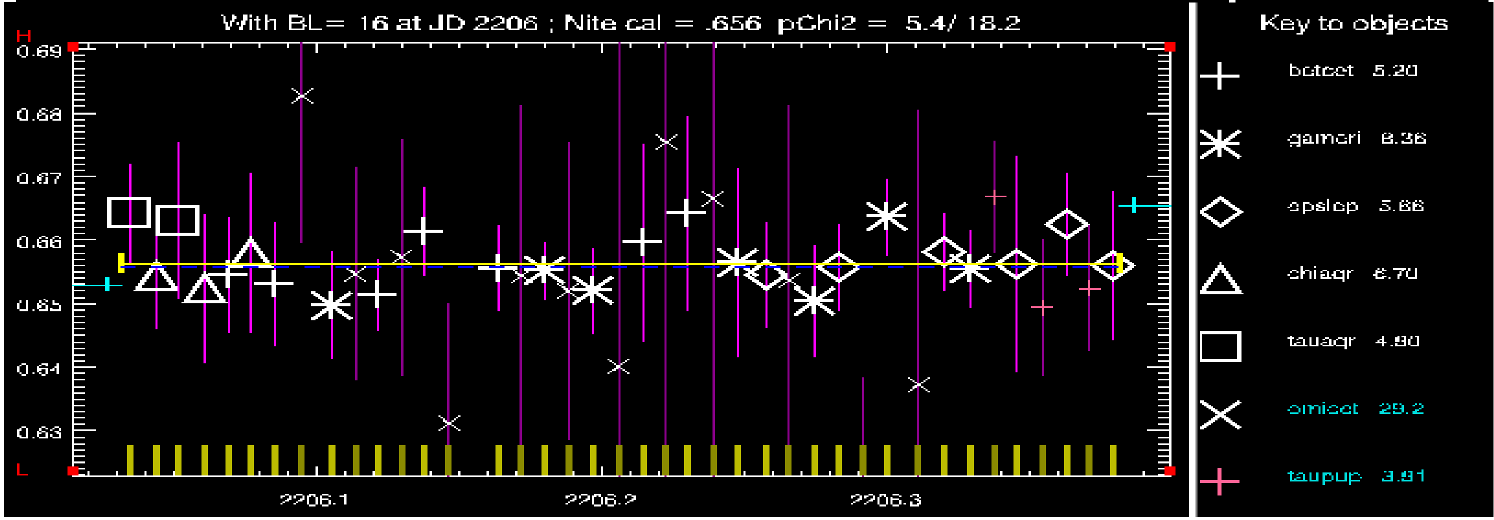


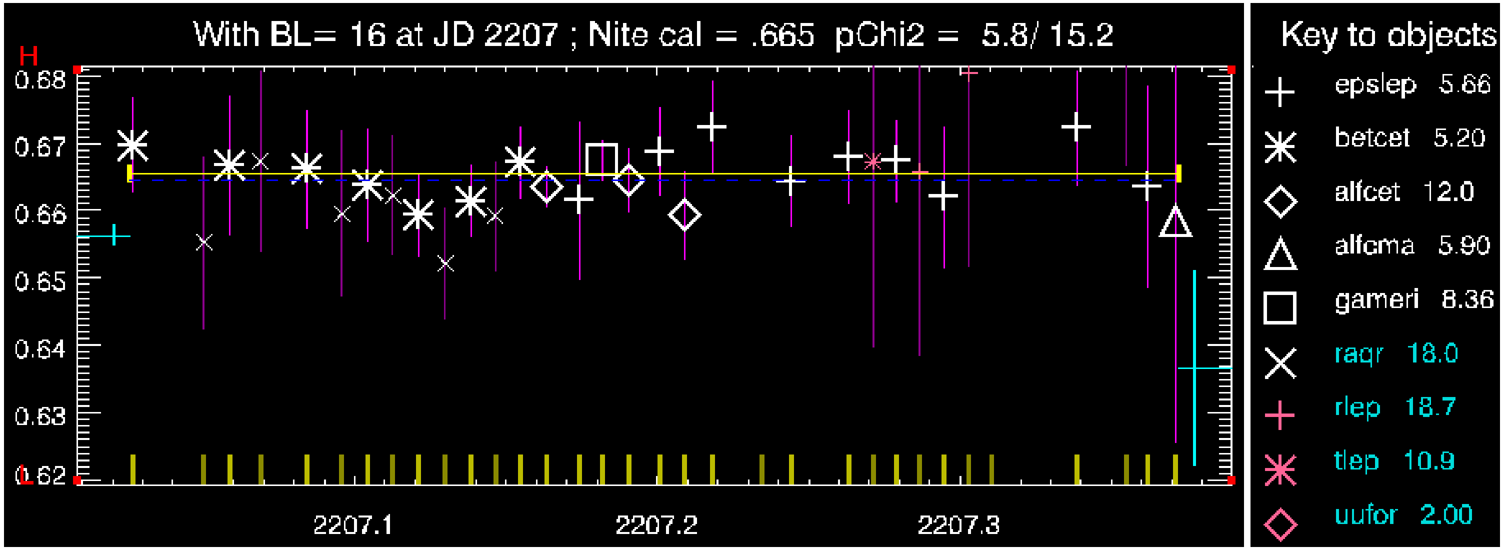
Adjustments

All required information to take into account, right here!

Shown here: “calibration solutions” from each star (white symbols) for each of 3 consecutive nights. The raw visibility of the observation is divided by the expected visibility (according to that star's UD diameter, solved using VINCI data) to get an estimate of the calibration, leading to a single calibration for the whole night (white line). TF changes each night due to operators' adjustments.







This isn't to say that recalibration is never needed!
In addition to hardware changes (frequent with VINCI), variations in the TF may be experienced due to the visibility estimator in response to:

- Change in the *depth* of photometric fluctuations as r_0 decreases (or at lower elevations).
- Change in the *speed* of photometric fluctuations as τ_0 decreases.

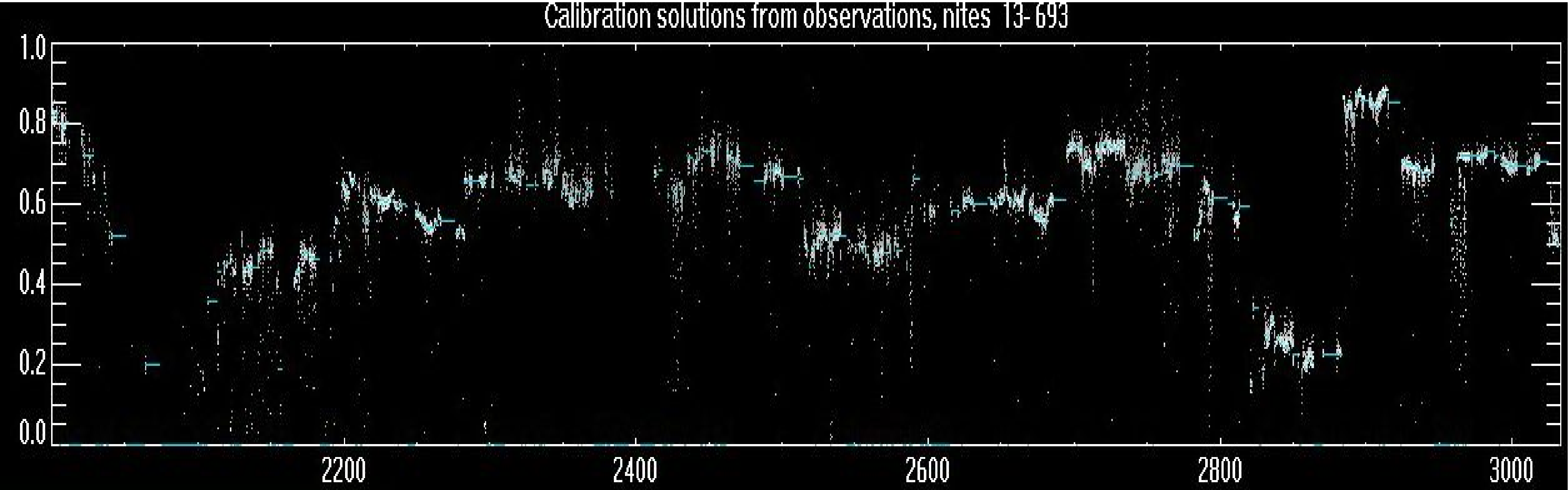
However these are a function of the estimator, not the instantaneous interferometric efficiency, and can be minimized (or at least flagged) by a clever algorithm.

Also:

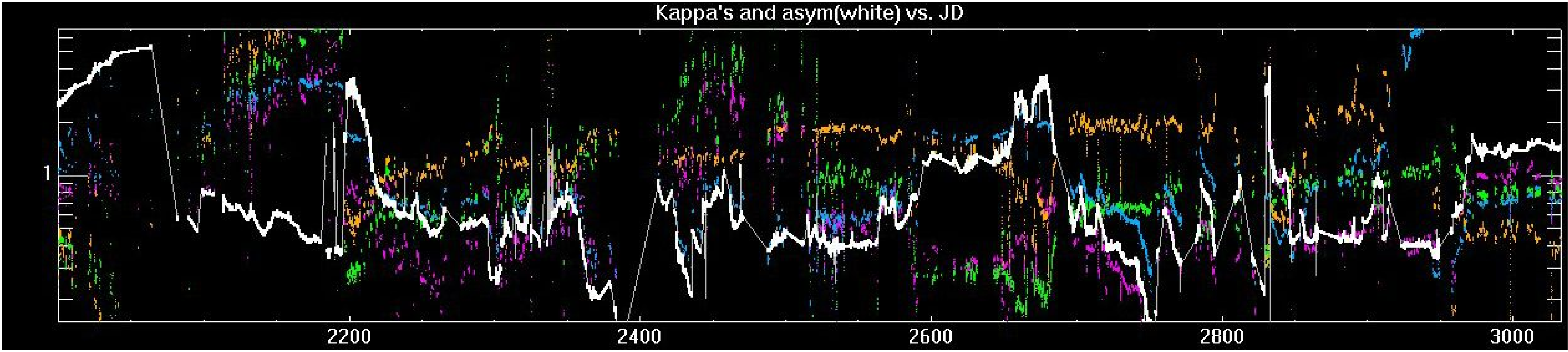
- There will be an expected (and calculatable) reduction in the detected (not underlying) visibility whenever the detector frame time is not MUCH less than τ_0 (smearing of the phase during one detector readout). Hardware fringe-tracking can eliminate this even for long detector exposures (why we like fringe-tracking!) but not if the residual OPD jitter rms level changes (as it will, with changes in τ_0) if this isn't taken into account. (But this wasn't a problem with VINCI)

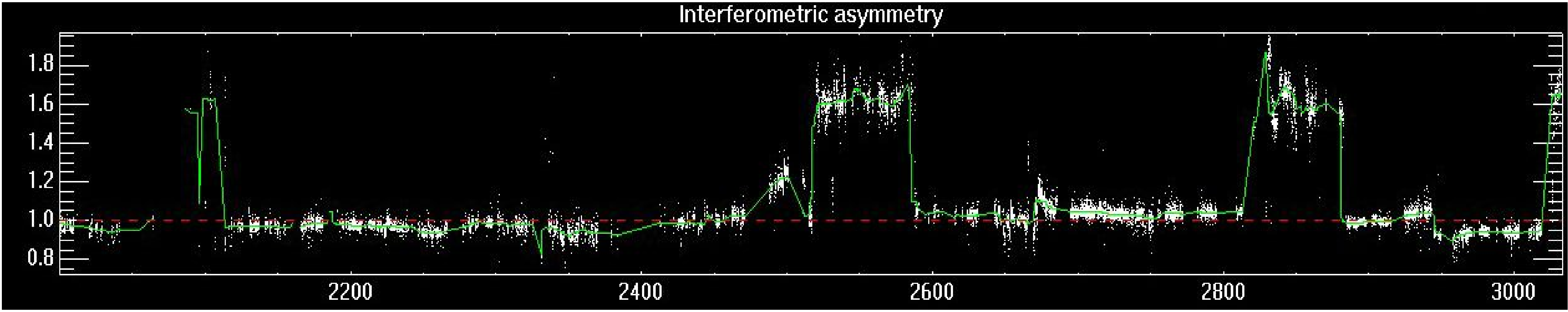
VINCI benefited in these regards by using small r_0-sized telescopes (siderostats) so that the depth of photometric (input coupling) variations were kept within limits. Much worse performance was obtained when using VINCI with the 8 meter UT's (no adaptive optics!), especially when reduced using coherent estimators (in these cases incoherent estimation may have been superior, albeit subject to TF variations).

The TF of VINCI did vary greatly (from about .2 to .85) over its 3 years of regular observations, but always due to hardware (mis-) adjustments or accidents.

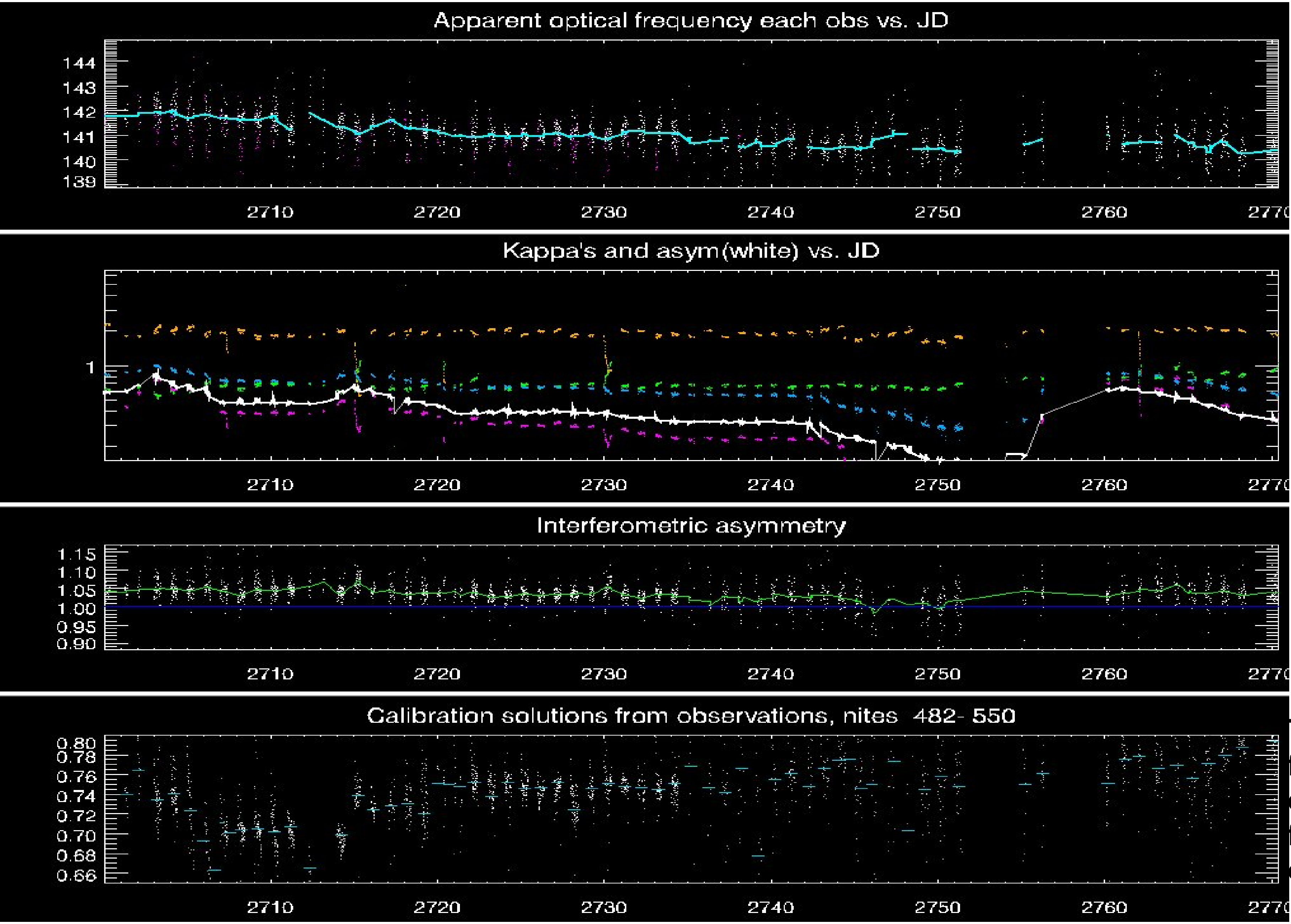


The calibration changes in VINCI could always be ascribed to nightly readjustments of the beamcombiner, which are also evident in changes in the kappa coefficients (and the photometric asymmetry which is derived from them), and the interferometric asymmetry (these can be measured with no knowledge of the star or atmospheric conditions).


Kappa's and asym(white) vs. JD


Interferometric asymmetry

70 days in the life of the VINCI beamcombiner (MONA)



Effective optical frequency, decreasing by 1% over 40 days

Photometric asymmetry goes bad over 40 days (white) and Kappa coefficients in colors

Transfer function (TF) computed from each observation

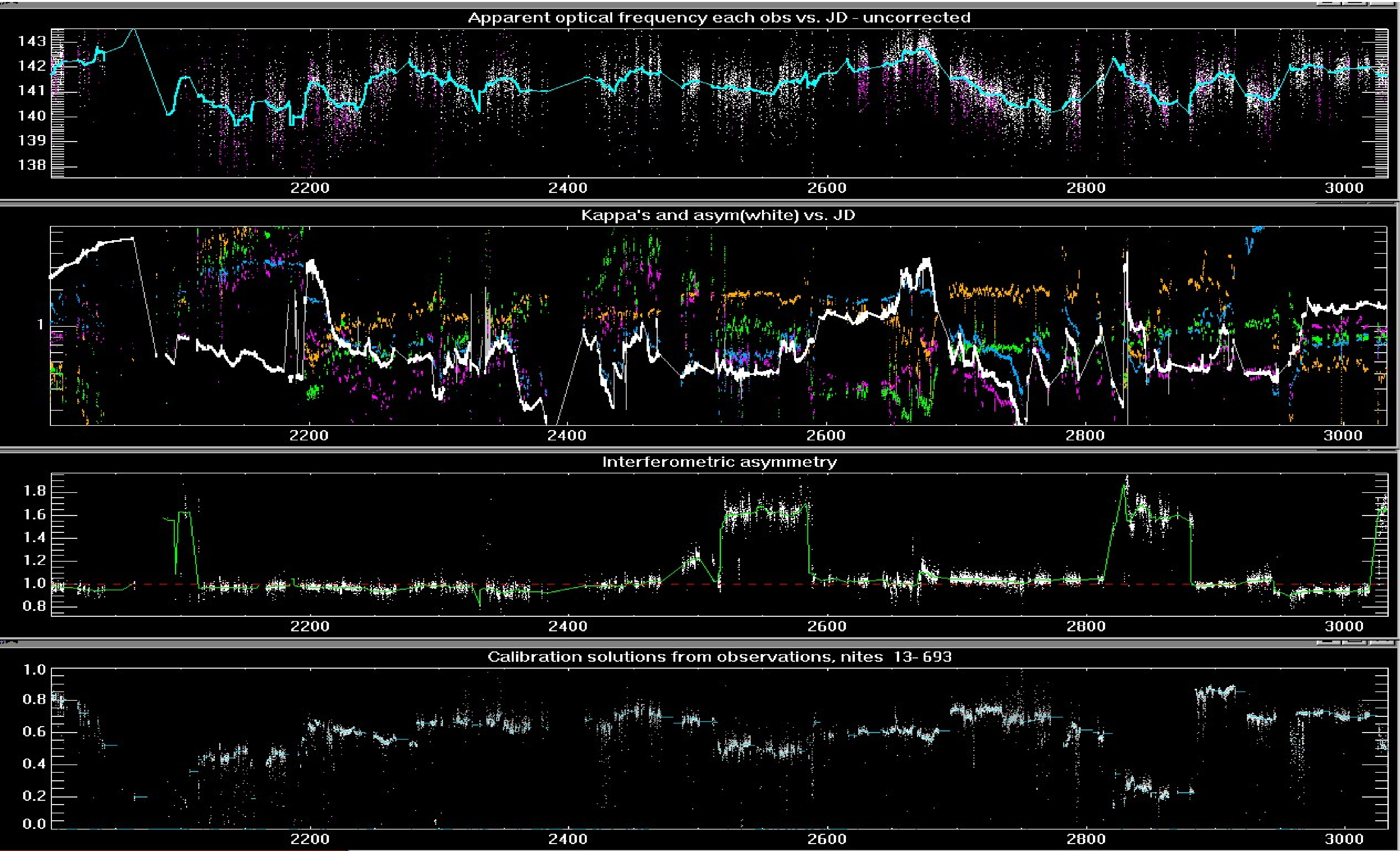
Intervention to boost TF

-- Good period, steady TF ---

Deteriorating performance

Major Intervention!

Diagnostics to detect variations in the VINCI beamcombiner (MONA) using ~18,000 on-sky observations over 3 years of regular operation (2001 - 2004)

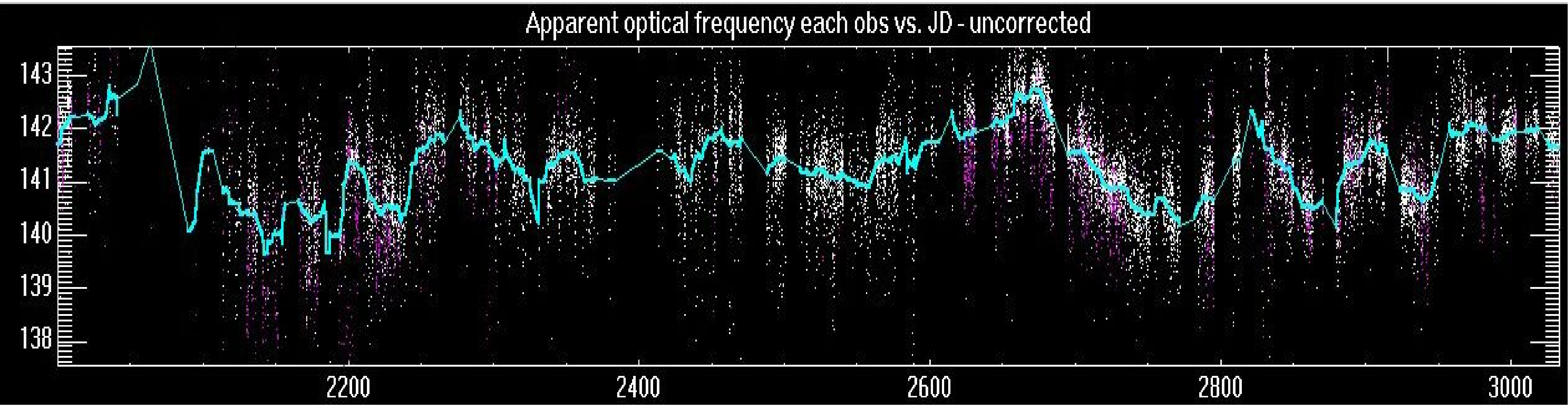

Apparent optical frequency each obs vs. JD - uncorrected

Kappa's and asym(white) vs. JD

Interferometric asymmetry

Calibration solutions from observations, nites 13- 693

Note the changes in the effective wavelength of the interference, detected through coherent integration of the fringe (essentially using the instrument as a fourier-transform spectrometer). This is on top of small variations between observations due to the color of stars.



This is something that should have been at least measured and taken into account, since it changes the spatial frequency of an observation at a particular baseline, and will lead to a different diameter interpretation of visibilities over this range of almost 2%. Such details hadn't been thought of when VINCI was designed merily as a test and verification instrument!

So why wasn't the interferometric efficiency of the beamcombiner (almost) 100% all of the time?
Three reasons:

- Polarization
- Polarization
- Polarization

While a single-mode optical system will interfere perfectly, most “single-mode” systems are *dual mode* if they accept 2 polarizations (of one *spatial* mode). With VINCI having a 3-D optical configuration, polarization control was entirely empirical, based on maximizing the TF. Full interference with 2-polarization interference requires:

- No rotation of the axes of polarization
- No relative phase shift between them.

Requirements, again:

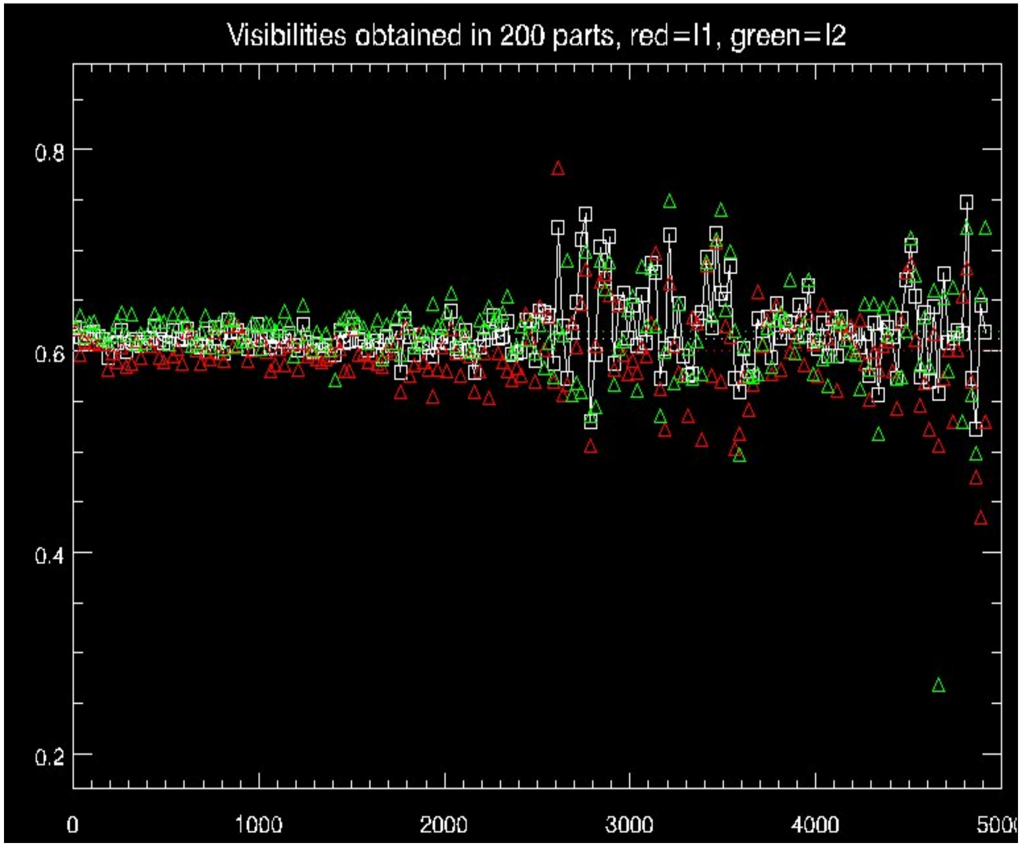
- No rotation of the axes of polarization
- No relative phase shift between them.

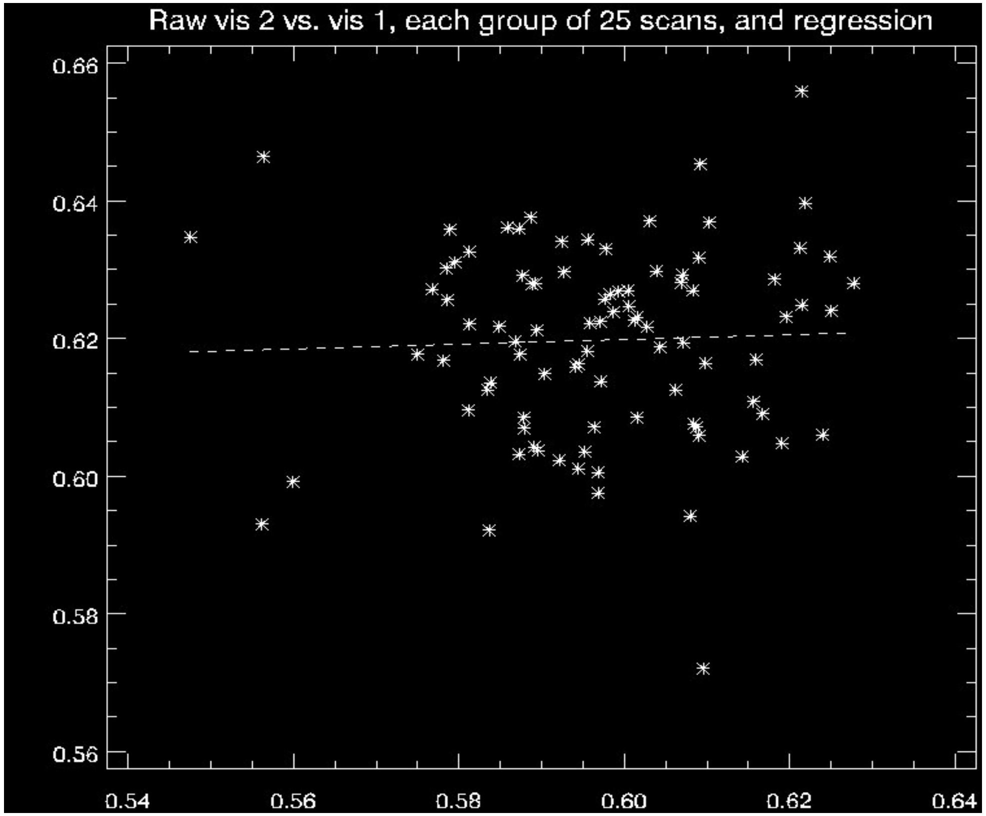
These cannot be easily met using waveguide optics. A planer beamcombiner such as PIONIER can meet the first requirement if built with X and Y separate (no skew angles). Even then, the phase requirement is difficult or impossible to get right, requiring separation of the polarizations before detection so that the two phases are detected independently.

OR to separate the polarizations before entering the waveguide and then having single-polarization systems.

But at least VINCI would have a stable TF due to a constant polarization offset, except for some rare nights where the hardware was seen to be relaxing after an adjustment!

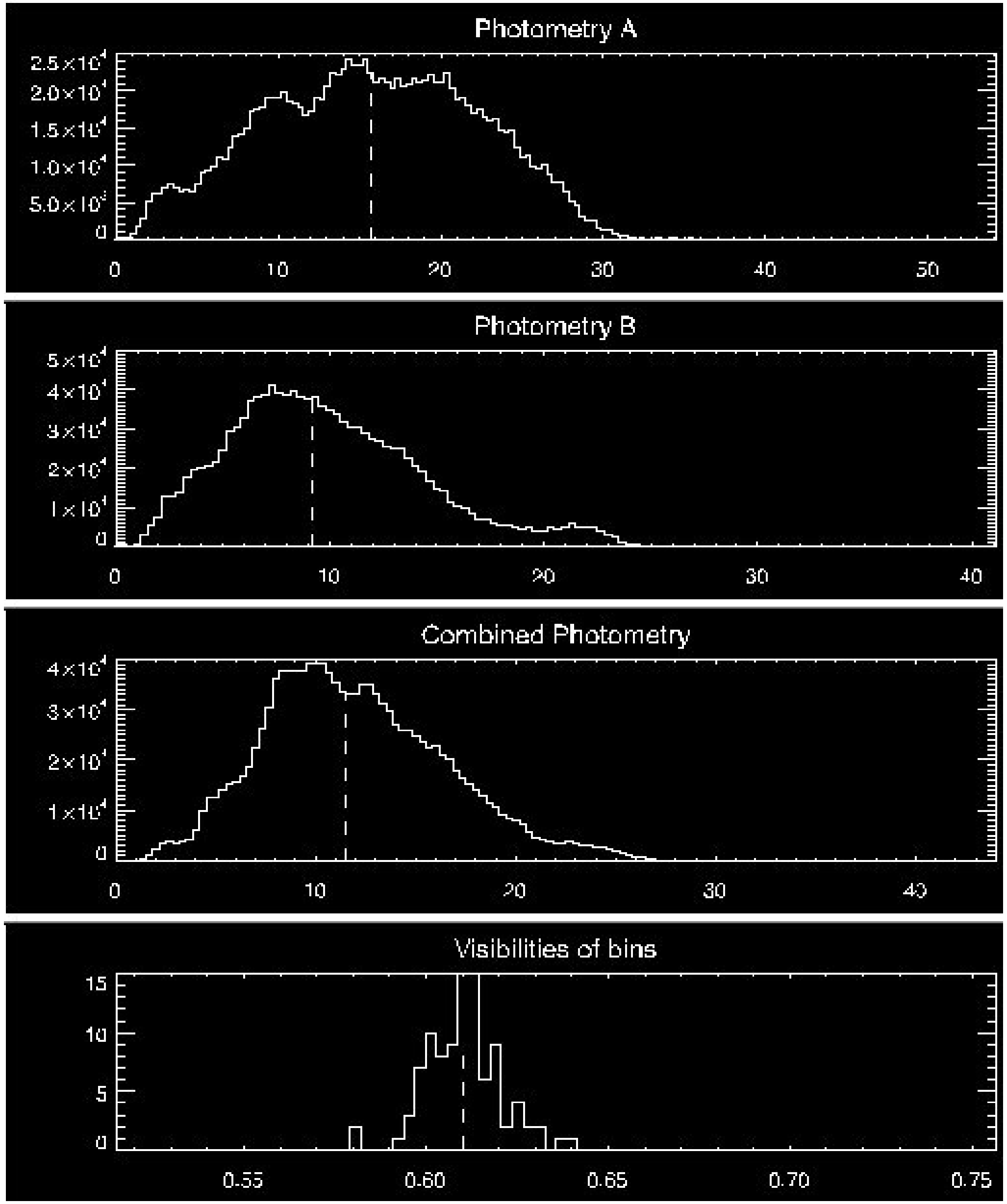
Consistency of interferometric efficiency seen in visibility results, regardless of changes in atmosphere (or, more likely, the fiber-injection hardware!). One long observation of Sirius, first half is good, 2nd half poor.



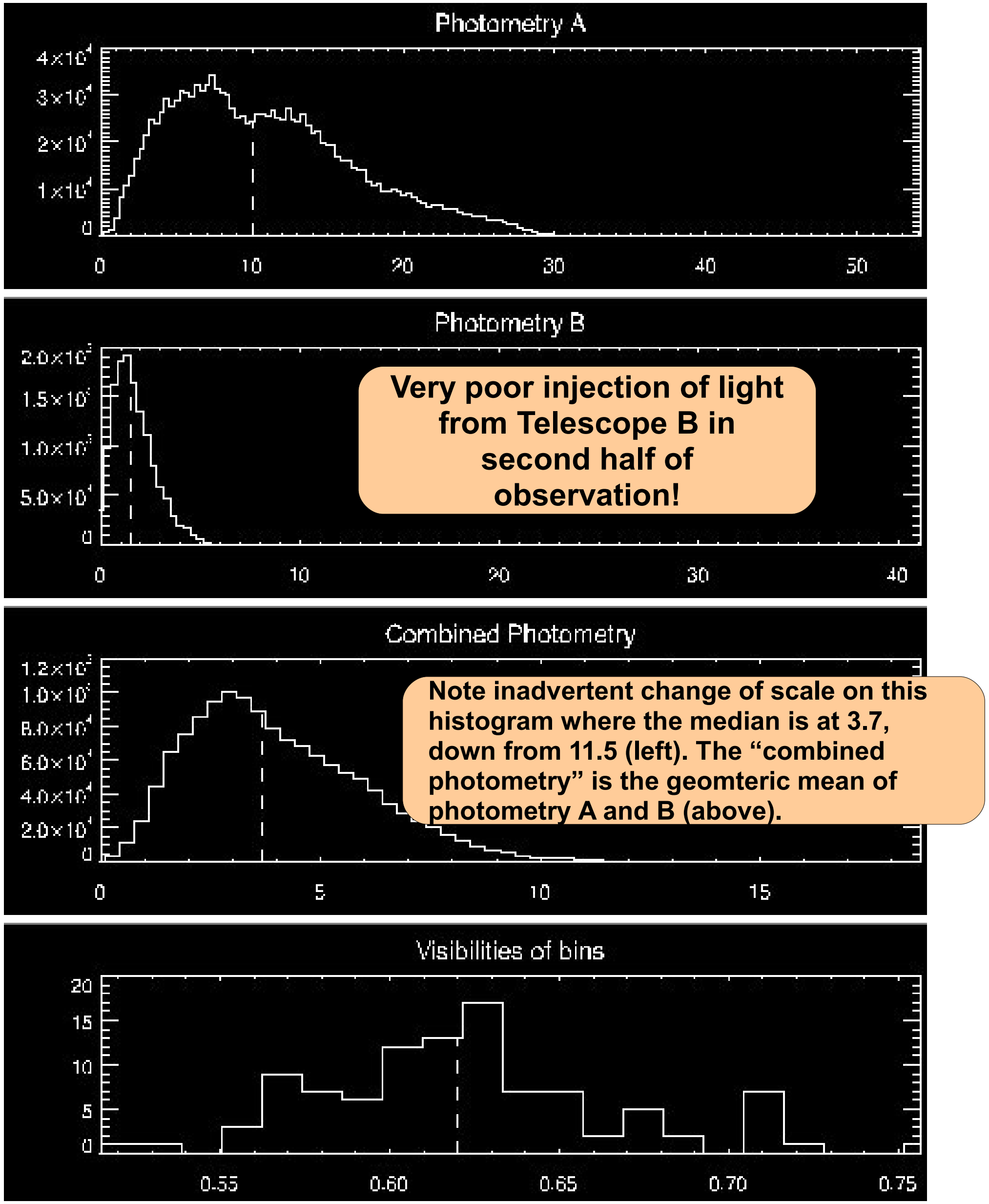


On the right, we plot the visibility found in each group of 25 scans using only the #1 or #2 interferometric channel over the first 2400 scans. Can see that fluctuations in visibility due to uncorrelated (detector) noise, not “atmosphere” etc.

Consistency between visibilities found during first half (good) and second half (poor photometric injection), but with much greater rms error (as you'd expect).



Scans 0 - 2400



Very poor injection of light from Telescope B in second half of observation!

Note inadvertent change of scale on this histogram where the median is at 3.7, down from 11.5 (left). The "combined photometry" is the geomteric mean of photometry A and B (above).

Scans 2400 - 5000

The end