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CONCEPTUAL STUDY OF AN OPTICAL APERTURE SYNTHESIS SYSTEM FOR HIGH RESOLUTION ASTRONOMY.

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RÉSUMÉ - Cet article présente le design conceptuel d'un instrument à synthèse d'ouverture optique de type démonstrateur et basé sur l'utilisation de fibres optiques. Après un bref rappel de la technique de synthèse d'ouverture nous présentons des résultats récents ayant permis la conception du système choisi. Le design détaillé par sous ensembles de l'instrument est ensuite décrit.

ABSTRACT - *This paper presents the conceptual design of an optical aperture synthesis demonstrator instrument based on optical fibres. After a brief recall of the optical aperture synthesis techniques we will present recent results which lead to the present concept. We then describe the detailed design of the instrument sub-assemblies.*

1 - PRESENTATION

MATRA MARCONI SPACE has performed and is still performing a number of studies for the European Space Agency on optical aperture synthesis systems. The results obtained in the various relevant domains which have been covered both theoretically and experimentally now allow to propose a complete design for a demonstrator instrument able to perform aperture synthesis imagery. This has been made possible thanks to a collaboration with Philippe ROUSSEL from the European Space Agency, with André LANNES from LAT at Toulouse for the mathematical studies on image reconstruction, with the IRCOM team led by François REYNAUD at Limoges for the studies and experiments on optical fibres and with TPD Delft and the CNRS Service d'Aéronomie team led by Luc DAME for the studies and experiments on Optical Path Difference control.

2 - PRINCIPLE AND PARAMETERS FOR OPTICAL APERTURE SYNTHESIS

This technique aims at obtaining the high optical resolution of a large aperture optical system by using a set of smaller diameter elements separated by large distances, provided that the beams from the various telescopes are added in phase in a common focal plane (Fig. 1).

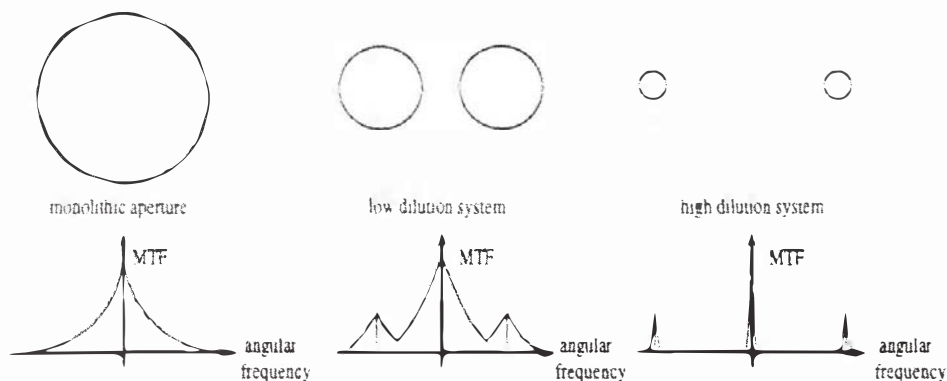


Fig. 1 : aperture configuration and corresponding MTF for a classical optical system and for optical aperture synthesis systems.

In a moderately diluted system, i.e. when the distance between the telescopes is small compared to their diameter the FTM does not present holes and it is possible to recover the object from the image by a simple deconvolution. In the highly diluted systems where the distance between the elements is large compared to their diameter this is no longer possible. In that case the information given by one pair of telescopes in the system is a so called complex visibility which is made up of one modulus and one phase (Fig. 2). This complex visibility is the value of the Fourier Transform of the target object at the angular frequency defined by the distance between the two telescopes.

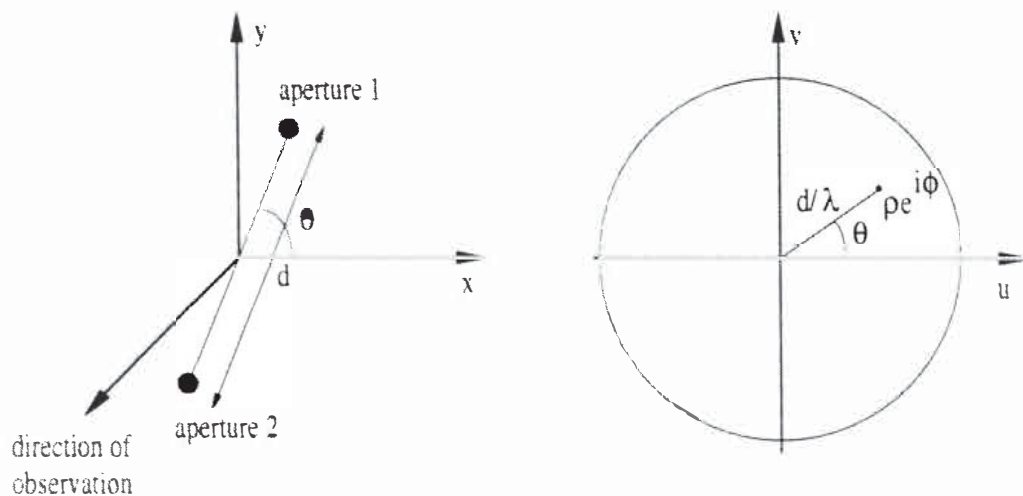


Fig. 2 : visibility $pe^{i\phi}$ given by a pair of apertures.

To perform good imaging one must thus have a good coverage of the Fourier plane by the measurement points and one must have proper modulus and phase data for those points.

3 - IMAGING WITH MODULUS AND PHASE CLOSURE DATA ONLY

A set of N apertures will give $N(N-1)/2$ complex visibilities. We see that in order to properly cover the Fourier plane in a single measurement we would need a lot of simultaneously cophased apertures. This would result in a very complex recombination scheme in the focal plane. It is in fact very difficult to design a focal plane with more than five or six apertures. In fact it starts being difficult above three.

If we make a set of independent measurements and if we want to measure the phase with a few nm accuracy we will need to reference all phases to a common zero. This can be made quite easily if the phase reference is the object itself. If the system uses another reference like a bright point like star the knowledge of the angle between the reference and the target for the various measurements must be obtained with an accuracy in the nanoradian range (a nanoradian on a few meter will give an Optical Path Difference of a few nm). As this is not realistic it is thus desirable to be able to accept an arbitrary phase bias between those independent measurements.

So the simplest situation for the system conception is if one is allowed to work with simple triplets of apertures and arbitrary phase biases between the reconfigurations of the system.

A.Lannes from LAT has indeed proven that this is possible. But what is even more important is that we do not even need to measure the three phases given by the triplet but that the simple closure phase value is enough. The closure phase relationship can be described as follows : if we consider a triplet of telescopes 1, 2 and 3, the phases given by each pair of telescopes can be written as $\Phi_{12} = (\phi_1 - \phi_2)$, $\Phi_{23} = (\phi_2 - \phi_3)$ and $\Phi_{31} = (\phi_3 - \phi_1)$. The closure phase is the value $\Phi_{12} + \Phi_{23} + \Phi_{31}$. This value is equal to zero for a perfect point object and has a given value for a given resolved object. In this functioning mode called "weak phase imaging" the instrument gives all modules data but only a third of the phase data.

A property of this phase closure is very interesting : the OPD difference between the arms has only to be maintained within the temporal coherence length to have a correct measurement. In fact the real value of the needed OPD control ultimately depends on the needed accuracy on the measurement of the modulus. This modulus will decrease when the OPD is not 0. However this decrease is not very fast especially if the scientific measurements are made after spectral dispersion where the amplitude of the fringes is not very sensitive to the OPD variation near 0 because of the long temporal coherence length.

Another important point of optical aperture systems is the choice of the object to be used for the control of the OPD. Even if we want to control the OPD within a few λ it will be very difficult to perform this by a pure metrology of the internal optical paths inside the array and by a simultaneous control of the absolute pointing direction of this array (for a 4 meter array we would still require sub arcsecond absolute pointing). Thus an external reference object has to be used. Two solutions are possible : either use a reference star or the target itself

If a reference star is used, we have seen that the OPD bias between this star and the target at each telescope level does not have to remain stable within a few nm during an exposure. However we need a split field system to send the light from this star inside the system. It looks therefore easier to use the target but as this target is not a point there will be values of the baseline where the amplitude of the interference signal is very low so that the OPD control will be difficult. It has also been shown by A.Lannes that this drawback is not too catastrophic as indeed the amplitude is very low for these baselines so that an error on its measurement or on the measurement of the phase closure has a low impact on the image reconstruction process.

4 - PRESENTATION OF THE DEMONSTRATOR

The aim of a demonstrator is to prove the chosen concept by performing imaging of objects. It must also use techniques which are considered as best candidates for a future full size high performance system. Considering the future trends for space instruments the emphasis has been put on high modularity and low cost. This led to the choice of optical fibres for the transportation of the beams as their use is compatible with focal planes using integrated optics. This results in very small size elements which can be produced in large quantities at a low cost. Nevertheless except for the fibre part the design proposed here below could be used for a free beam system with minor modifications.

The specifications for our demonstrator are given in the table below :

| parameter | specification | comments |
|-----------------------------------------------|--------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| number of apertures (and Fourier coverage) | 3 | To cover the Fourier plane the array must be able to rotate. In addition 4 different arrays are needed if the relative position of the telescope are fixed or this position must be modifiable. |
| maximum distance between the telescopes | 4 m | Compatible with a non deployable structure within AR5 fairing |
| useful waveband | 0.4 to 1.8 μm | See the discussion below |
| beam transfer technology | optical fibres | See the discussion below |
| telescope diameter | 30 cm | This has an impact on the limiting magnitude but could be adapted and has no direct influence on the design presented here |
| OPD control reference | target | See chapter 3 for the discussion on this point |

The choice of optical fibres today limits the useful waveband but this should evolve in the future. The used fibres are monomode polarisation maintaining fibres. These fibres have a non null dispersion which has to be compensated for so that the phase is the same for all wavelength at their output. The present experiments have shown that this is possible for a waveband width around 350 nm. The chosen wavelength range will thus be covered by the use of four fibre links.

To properly cover the Fourier plane with triplets the chosen option is to use four triplets on a circle and nine rotations of $\Pi/9$ of this circle (Fig. 3). This can be made by having effectively four triplets or by having only one which is reconfigured three times. In the latter case we have less telescopes but we must have a way to perform the reconfiguration and the total measurement time is multiplied by 4 compared to the solution with four triplets. If we consider that a basic element is not too expensive the baseline approach should be to use four independent triplets making simultaneous measurements.



Fig. 3 : Configuration with four triplets and 9 rotations and the corresponding frequency coverage.

5 - BLOCK DIAGRAMME OF THE DEMONSTRATOR

The block diagram (Fig. 4) shows the main functions to be performed by the various sub-systems of the demonstrator.

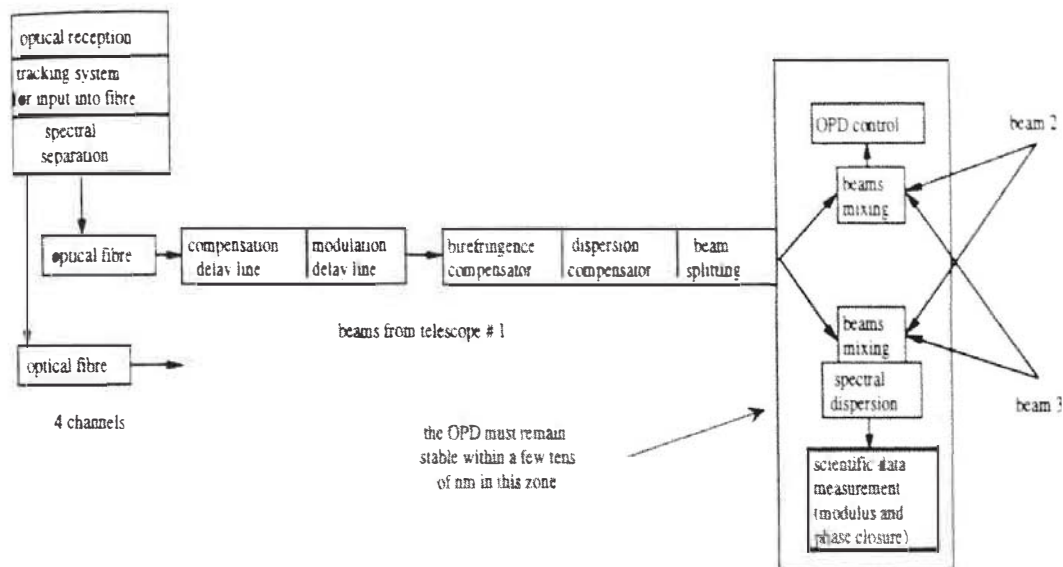


Fig. 4 : Block diagram showing the main functions of the demonstrator.

The beam is received at one aperture. It must then be fed into the fibres so that a tracking system is needed. This is followed by a spectral separation because one fibre is only able to carry a waveband width of 350 nm. The signal is then sent along the fibre to the recombination hub. Along the fibre we have the delay lines on two of the three beams. The modulation delay line is justified by the control and measurement approach which is described later. At fibre output we have a system to compensate for the birefringence (as the optical length of the fibre is not totally the same for the two polarisation modes) and a system to compensate for the dispersion. These systems are static, i.e. they are adjusted only once on ground.

A choice has been made at that level to separate the part dedicated to the OPD control from the scientific part. This is justified by the fact that there is a spectral dispersion in the scientific part so that there is less signal available in each spectral element and the use of a large bandwidth makes the acquisition and control of the OPD near zero easier.

In the OPD control box the three beams from the three telescopes are mixed by pairs and focused on single pixel detectors (the beams at fibre output are collimated).

In the scientific measurement box the beam from each telescope is spectrally dispersed. Then for each spectral element the beams from the three telescopes are mixed and focused on a single pixel detector.

We will now describe the design of the various elements of the above chain.

6 - RECEIVING TELESCOPE AND FIBER INPUT SYSTEM

A possible system is shown in Fig. 5.

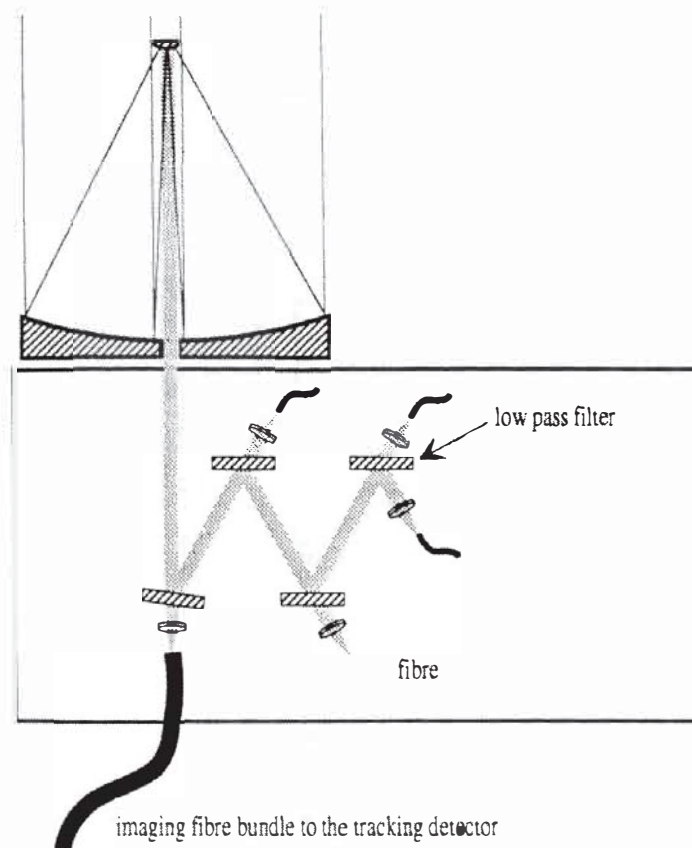


Fig. 5 : Reception and fibre launch system.

It starts with an afocal telescope. This telescope does not need to have a wide field because it is only used on axis for the measurement. Its field of view therefore is only defined by the needed size of the acquisition and tracking fields. A pointing accuracy in the arcsec range can be expected from the spacecraft carrying the instrument so that this arcsec field is found on the telescope. The telescope thus could have a parabolic primary and a parabolic or even spherical secondary. Its manufacturing is not a critical point.

The non useful spectral part of the beam is selected with a low or high pass spectral filter to be focused on the tracking detector. The useful beam is then transmitted and the four parts of the spectrum are selected by a set of three filters and focused on the four optical fibres.

This focal plane must be stable at the $0.1 \mu\text{m}$ level so that the tracking performed on the detector is valid for the launch into the monomode optical fibres having core diameters in the 3 to $5 \mu\text{m}$ range. However this focal plane is a purely passive one with the size of a large matchbox (typical beam diameter is 10 mm) so that this looks perfectly possible.

7 - FIBRE, DELAY LINES AND CORRECTIONS

We will describe here the delay lines implemented on the fibre as well as the system to compensate for the birefringence and the dispersion (Fig. 6). All the concepts presented here have been designed, manufactured and tested by IRCOM Limoges in the framework of the ESA OAST study.

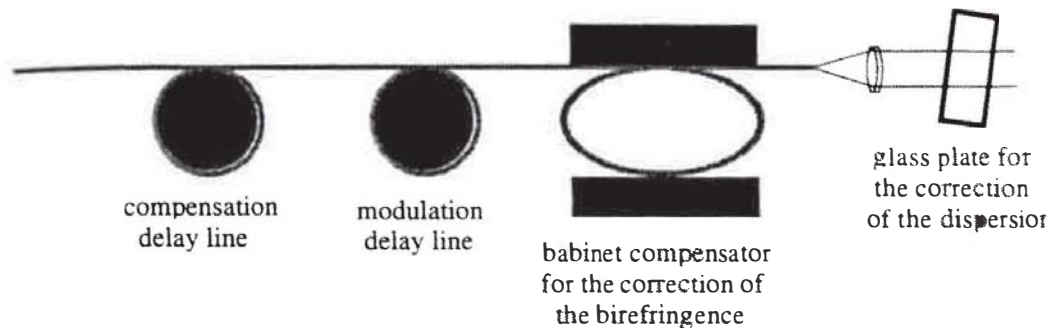


Fig. 6 : Delay lines and correction of the birefringence and dispersion effects.

The optical delay is obtained by stretching the fibre which is coiled around a cylindrical piezo actuator. Such delay lines have been tested and allow to obtain an OPD control accuracy in the nm range. The maximum possible delay amounts to 2% of the fibre length which allows a few mm range with a few meters of fibre. The OPD range needed for acquisition depends on the pointing accuracy of the array. With a 2 mm OPD we can compensate for a large one arcmin pointing error together with a 0.8 mm internal OPD difference.

The compensation of the birefringence is made by a simple compression of a fibre coil. This has been tested on 25 m long fibres and the shown component is 5 cm long in reality.

The dispersion is compensated in air by a simple glass plate with the required thickness.

8 - FOCAL PLANE

At the entrance of the focal plane the beam from each telescope is split into two parts, one of which is sent to the so called OPD control layer and the other one to the scientific data acquisition layer. The splitting can be done either spectrally using a dichroic plate or on the whole waveband with a beam splitter. The ratio of the flux needed in each layer is not defined here and will depend on a fine analysis of the available flux in a real system.

As the OPD control is made in a separate layer the optical paths which are not common have to remain stable in the tens of nm range. Once again the size of the proposed focal plane (a few cm) and the fact that the optical paths only contain passive components make this a realistic assumption. As an example a length variation of 15 nm over 10 cm on an INVAR plate with a coefficient of thermal expansion of $1.5 \cdot 10^{-6}$ is obtained for a temperature variation of 0.1°C which is easily achievable.

The method chosen for the OPD control is a synchronous detection scheme. The beams are collimated and superimposed beams and then focused on a single pixel detector which detects a signal depending on their relative phase shift. The modulation delay line which we have seen before is used for high frequency modulation of the OPD. Tests of this method have been performed by the Service d'Aéronomie and it looks as the most promising one for both acquisition and control.

The OPD control layer of the focal plane is shown on Fig. 7.

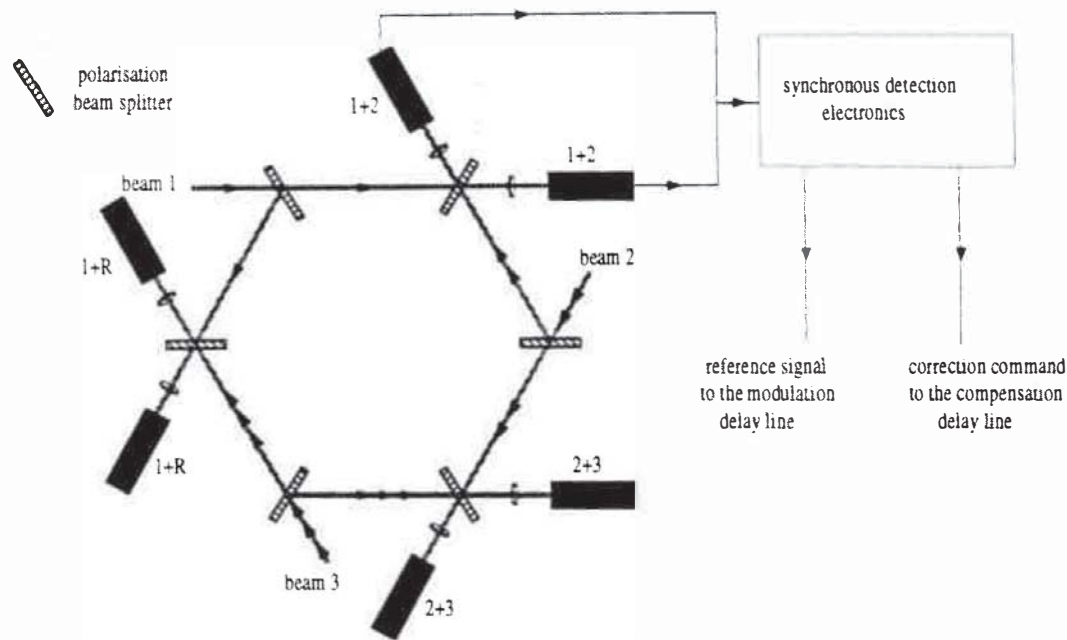


Fig. 7 : OPD control layer in the focal plane.

The input beams from the fibres are polarised. They are split by polarisation and combined two by two in collimated beams prior to be focused on single pixels detectors. When the system is functioning only two controls are needed as well as two delay lines. However a redundancy is easily obtained by putting a delay line on all fibres and by having the capability to control any of the three pairs. In this case all channels are identical and the failure of the control of one channel does not prevent the system from working properly. The detection of the 0 OPD position is made by synchronous detection. The modulation delay line modulates the OPD by a fraction of λ at a high frequency (a few 100 Hz) and the detector output is sent to the synchronous detection electronics which gives a maximum signal at the 0 OPD position. The error signal is used to control the compensation delay line. During the acquisition phase the OPD is scanned over the required range (2 mm in our example), when the detected signal is over a given threshold the "white light" brightest fringe is finely searched and the system is then locked for a continuous control on this position.

A complete sequence including acquisition and control has been tested by service d'Aéronomie. The obtained results enable to predict the OPD control performance of the system knowing the available flux at detector level.

In the scientific layer it is assumed that the beams are spectrally dispersed. For each spectral element the three beams from the three telescopes are then combined in a scientific data acquisition module. One of these modules is shown in Fig. 8.

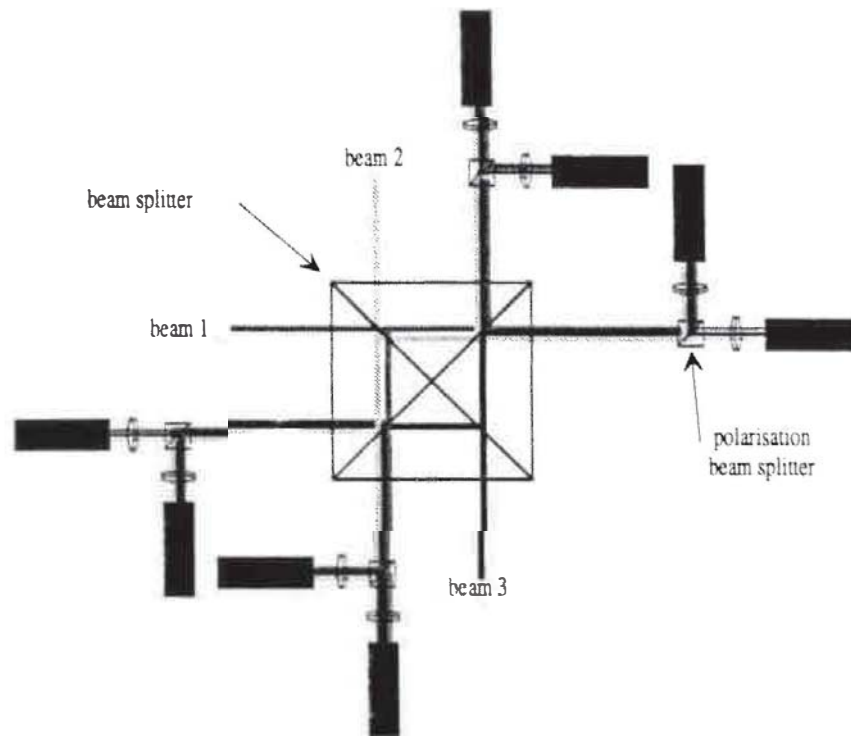


Fig. 8 : Scientific data layer in the focal plane. The three beams are combined on all detectors.

In each module the three beams are combined on a set of mono pixel detectors by use of a 50/50 beamsplitter and polarisation beam splitters. When the two used modulation delay lines are modulated at two distinct frequencies, the signal obtained here contains information at three frequencies (ν_1 , ν_2 and $\nu_1 - \nu_2$). It is then possible to directly measure the closure phase after various filtering processes. As pointed above this phase closure is directly measured so that the result is not dependant on a phase bias on one of the beams

One must not be afraid by the apparent complexity of the presented focal plane. On one hand all the shown detectors are simple photodiodes which can be operated with a simple amplifier and on the other hand all the modules are identical so that the final assembly remains a simple operation.

9 - OPERATION

We will give here a very brief overview of the operation of the system. We will consider that we have four arrays of three telescopes and we want to have a Fourier plane coverage similar to the one presented in chapter 4. The operation of each triplet will be the same.

The triplet is pointed towards the chosen target with an accuracy of a few arcsec. The search for the fringes is made by scanning the delay line over its whole range until a signal is found (the pointing error gives an external OPD error around 0.5 mm and the remaining delay line range is used for the internal OPD compensation), the system is then locked on the white light fringe. The three modules and the phase closure corresponding to the triplet configuration are acquired. The system is then rotated about the line of sight by $2\pi/9$ and another similar measurement is performed. After 9 measurements for the four triplets all data are available and the image can be reconstructed. Then a new target is chosen.

10 - CONCLUSION

Thanks to the development of LAT image reconstruction method we have been able to present a possible design for a demonstrator optical aperture synthesis system with the following features

- the dimensional stability and OPD control accuracy are in the order of the wavelength which is about a hundred times easier than what was ordinarily foreseen for such systems
- all elements are of a very small size and completely modular so that a reasonable cost can be foreseen

Such systems are therefore now perfectly within reach of our present technical capabilities.