# LASSO EXPERIMENT: INTERCALIBRATIONS OF THE LASSO RANGING STATIONS

J.Gaignebet and J.-L. Hatat
J.F. Mangin and J.M. Torre
Observatoire de la Côte d'Azur

W. Klepczxnski and L. McCubin
U.S. Naval Observatory

J. Wiant and R. Rickefs
McDonald Observatory, Texas

## I. LASSO PRINCIPLE — Fig 1–2

Let assume a satellite S fitted with laser retroreflectors associated to a light detector and an event timer. The time scale of the satellite is HS.

Let assume two laser ranging stations L1 and L2 with their own time scales H1 and H2 and their own event timers. (The event timer could be replaced by an intervalometer and a chronometer).

L1 sends a laser pulse towards the satellite at the epoch TE1 in the time scale H1. The laser pulse is detected on board at the epoch TS1, in the time scale HS, and, at its return at the laser station at the epoch TR1 in the time scale H1. The two way flight time tF1 could be expressed in two different manners.

tF1 = TR1-TE1 = tg1+tr1 where tg1 and tr1 are the flight times of the laser pulse from the station to the satellite and from the satellite to the station.

Neglecting aberration and relativistic corrections:

tg1 = tr1 = tF1/2.

In the same way one can define the epochs TE2, TS2, TR2, and flight delays tF2, tg2, tr2.

We can write the following relations:

TS1 = TE1 + tg1 (H1)

TS2 = TE2 + tg2 (H2)

TS2 = TE2 + (H02-H01) + tg2 (H1).

We can deduce:

TS2 - TS1 = TE2 - TE1 + tg2 - tg1 + H02 - H01, TS2 - TS1 = TE2 - TE1 + tg2 - tg1 + H02 - H01,

or

H02 - H01= TS2 - TS1 + TE1 - TE2 + tg1 - tg2.

If the satellite sends by telemetry TS1 and TS2 (HS) or TS2 - TS1 we can compute the time difference between the two time scales H1 and H2.

One can also monitor, from one of the laser station, the behavior of the satellite clock.

TS1 H1 = TE1 H1 + tg1 H1 = TS1 HS + (H0S-H01) H1,

then:

(H0S - H01) H1 = TE1 H1 -TS1 HS + tg1 H1.

## II . DEFINITION OF THE CALIBRATIONS — Fig 3

In the following we assume that the laser ranging stations are provided with event timers. The epochs TE1 TR1 TE2 TR2 TS1 TS2 are related to marks called "reference points". For laser stations this point is defined as the first invariant point of the return path and the last invariant point of the emission path. In general the point is the crossing point of the two axes of the mount. (For some station the two axes are not crossing and a correction computed from the direction of the mount is to be added). In fact the timing is always delayed by optical travel times, cable propagation delays and electronic delays.

Fig. 3 develops the diagram of a conventional laser ranging station and its symbolic representation.

T'E = TE + $\tau$g where $\tau$g = $\sum_1^n \tau$ gn,

T'R = TR + $\tau$r where $\tau$r = $\sum_1^{\circ} n \leq \tau$ rn,

T'E and T'R being the event timer displayed times.

The same kind of relations are true at the level of the satellite but the equations of time synchronization include time differences only. By this the satellite delay t cancels. This is also true when following the on board oscillator frequency. But this delay must be taken into account to know the synchronization between ground and satellite times.

## III. LASER RANGING STATION CALIBRATIONS

The equations leading to the determination of the synchronizations of the clock include for each station two kinds of measurements:

- Time intervals: measurements of the round trip times of the laser pulses at each station:

  The value tg1 - tr1 is the station ranging calibration constant. This constant has to be added to the difference of event timers readings to determine the true flight time of the light from the station to the satellite and back.

- Times TE1 and TE2 and more precisely the difference TE2 -TE1 between two different stations.

  In this case:

  $TE1 = T'E1 - \tau g1$ and $TE2 = T'E2 - \tau g2$,

  $TE2 - TE1 = T'E2 - T'E1 + \tau g1 - \tau g2$.

Therefore, it is enough in order to keep the same accuracy of the time synchronization to determine $\tau g1 - \tau g2$.

**NB.**: it has to be noted in that application of laser ranging to the time domain that we use directly the flight time without consideration to the medium crossed. The index correction necessary for range determination is not useful in time synchronization.

# IV. CALIBRATION DETERMINATIONS

## A: Ranging Calibration ($\tau g$ - $\tau r$)

Several methods have been developed within the laser ranging community.

### a) Target ranging

A target at a known distance is ranged by the station. The flight time from the reference point to the target and back is computed taking into account the meteorological parameters at the time of each session.

$\tau g + \tau r = T'R - T'E + \tau g - \tau r$.

### b) Simple and double two way flight time, Fig 4

Simple ranging:

$\tau g + \tau r = T'R - T'E + \tau g - \tau r$

Double ranging:

$2(\tau g + \tau r) = T''R - T''E + \tau g - \tau r$

which allows us to determine

$\tau g - \tau r = T''R - T''E - (T'R - T'E)$ round trip time

$T''E$ and $T''R$ being the event timers displayed times for the double ranging.

$\tau g - \tau r = T''R - T''E - 2\,(T'R - T'E)$ ranging calibration constant:

c) Measurement of optical and electronical delays

This method let determine a value of the correction with good approximation but must be verified by a global method as some delays are rather tricky to determine.

d) Co-location

The co-locations do not by themselves measure the value of the ranging calibration constant. However they are the only way to verify that the measurements are consistant within to stations.

### B: Lasso Intercalibration ($\tau g1$ - $\tau g2$) Fig. 5

The two methods are:

**a) Co-location**

Two co-located stations use the same time scale and range on the same target, it allows to determine the Lasso intercalibration constant. In practice most of the laser stations are not mobile and cannot be co-located.

**b) Calibration station**

The method requires a common reference for the different stations. This common reference is a highly mobile laser ranging station able to be set up next to the stations to be intercalibrated. The method is in fact a double co-location with a common station. This allows the determination of $\tau g1$ - $\tau gC$ and $\tau g2$ - $\tau gc$ and taking out $\tau gc$, $\tau g1$ - $\tau g2$.

Principle of the measurements Fig. 6

Two sessions will be organised ranging at the target T in the following configurations :

Session 1 :

The calibration station LC ranges the target, recording in its own time scale HC, the emission time T'E(C,C,C) the return time T'R(C,C,C) and the return time at the station to be calibrated L1 and with an additional delay h1C (delay of the link from station 1 to station C) T'R (C,1,C). At the same time L1 records the return in its own time scale T'R(C,1,1).

Session 2 :

The station to be calibrated L1 ranges the target. L1 and LC record the epochs T'E(1,1,1) T'R (1,1,1) T'R(1,C,1) T'R(1,C,C).

The format of these times is a follow :

T' Time displayed at the event timers

E/R Emission or return time

C/1 Emitting station

C/1 Receiving station

C/1 Event timer

We could express these times as follows: Fig 7

$$
\begin{aligned}
&Session1: \\
(1)T'E(C,C,C) &= TE(C,C,C) + \tau gC \\
(2)T'R(C,C,C) &= TE(C,C,C) + \tau rC + \tau gC + \tau rC \\
(3)T'R(C,1,C) &= TE(C,C,C) + \tau r1 + \tau gC + \tau r1 + h1C \\
(4)T'R(C,1,1) &= TE(C,C,C) + \tau r1 + \tau gC + \tau r1 + (H01 - H0C) \\
&= TE(C,1,1) + \tau r1 + \tau gC + \tau r1
\end{aligned}
$$

$$
\begin{aligned}
&Session2: \\
(5)T'E(1,1,1) &= TE(1,1,1) + \tau g1 \\
(6)T'R(1,1,1) &= TE(1,1,1) + \tau r1 + \tau g1 + \tau r1 \\
(7)T'R(1,C,1) &= TE(1,1,1) + \tau rC + \tau g1 + \tau rC + h1C \\
(8)T'R(1,C,C) &= TE(1,1,1) + \tau rC + \tau g1 + \tau rC + (H0C - H01) \\
&= TE(1,C,C) + \tau rC + \tau g1 + \tau rC
\end{aligned}
$$

We know that $\tau$gC = $\tau$rC = $\tau$C and $\tau$g1 = $\tau$r1 = $\tau$1 and the difference $\tau$1 - $\tau$C could be accurately measured (difference of the position of the two reference points related to the target).

From these relations we could compute the ranging calibration constants and their difference ($\tau$gC - $\tau$rC) - ($\tau$g1 - $\tau$r1). In the case of the calibration station: $\tau$gC - $\tau$rC = 0 - Fig 8 - we will determine immediately $\tau$g1 - $\tau$r1.

For the Lasso intercalibration $\tau$gC- $\tau$g1 different methods could be used:

1) Direct measure of the difference H01 - H0C of the time scales of the two co-located equipments. Inaccuracy arises by the fact that the internal delays of the event timers are not taken into account.

2) Use of known delay links between the two time reference points of the event timers. These reference points are in most of the cases the input of discriminators for the emitted and received signals. As these links are simple cables the measurements of their delays are quite simple. In practice we have two cables. Each cable carries the signal from one of the station to the second one in one direction only. The difference in their delays h1C - hC1 must be known.

3) Use of the same cables to intercalibrate the two fixed stations

$\eta 1C = \eta 2C \; \eta C1 = \eta C2$

We consider that the cables with delays $\eta 1C$ and $\eta C1$ are part of the calibration station.

4) Use of the same cables for all the co-locations to carry the 1Hz and 5MHz signals. When the event timers have been started they need the 5MHz only. The 1Hz line could be used to time tag pulses at both event timers. At the end this will allow to determine H01 - H02 in the conditions used during the calibration session.

From equations 1 to 8, which are not fully independent, we could determine: the ranging calibration constant of station 1 $\tau r1 - \tau g1$, the gap between the two time scales H01 - H0C, the Lasso calibration constant $\tau g1 - \tau gC$.

N.B. : In the case of the calibration station the event timer has 4 channels and two inputs (Emission/Reception). We have implemented an emission delay Fig.3 $\tau' g$ which allows us to monitor the stability of the equipment. By conception the ranging calibration constant of the calibration station is equal to zero Fig. 8.

This delay is designed to be as stable as possible with an optical fiber link. As noted hereupon the ranging calibration is zero. The emission and reception paths are common after the reference point.

The difference of return levels could introduce some error. To minimize it we use very short laser pulses (13ps), light attenuators and constant fraction discriminators.

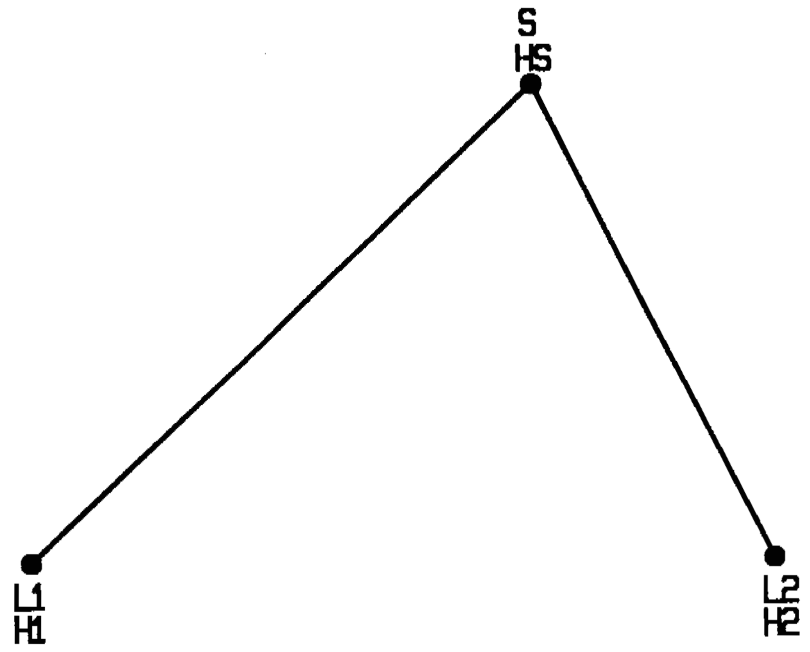

S
HS
L1
H1
L2
H2

Fig 1

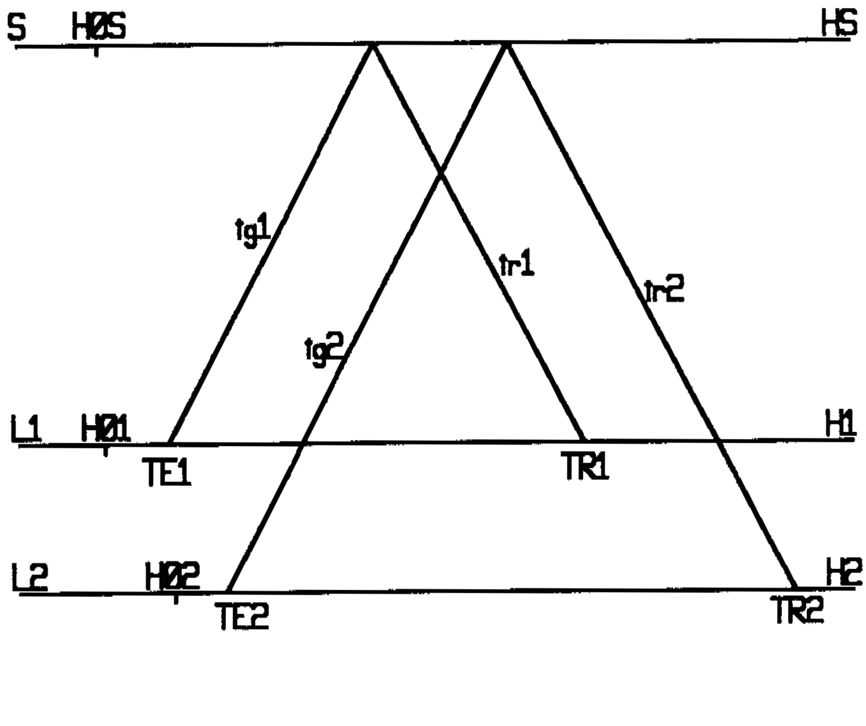

S
HØS
HS
tg1
tr1
tr2
tg2
L1
HØ1
H1
TE1
TR1
L2
HØ2
H2
TE2
TR2

Fig2

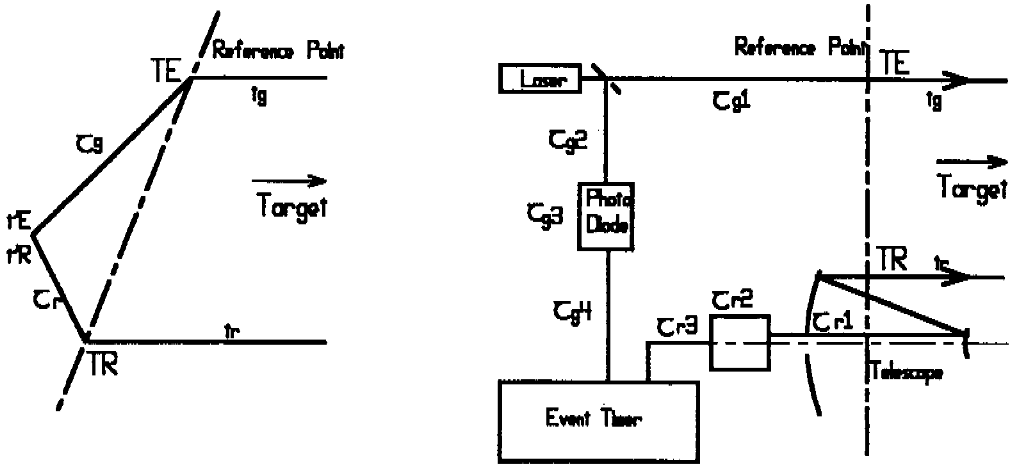

Reference Point
TE
tg
τg
Target
tE
tR
τr
tr
TR
Laser
Reference Point
TE
τg1
tg
τg2
Photo Diode
τg3
Target
TR
tr
τr2
τg4
τr3
τr1
Telescope
Event Timer

Fig 3

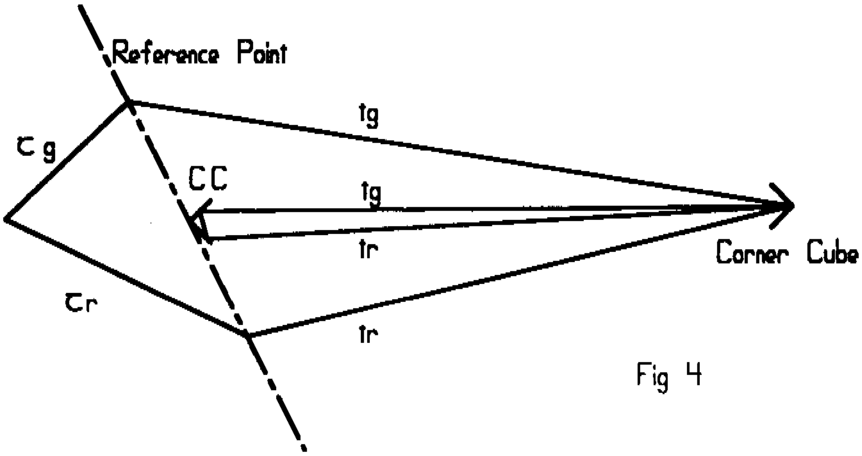
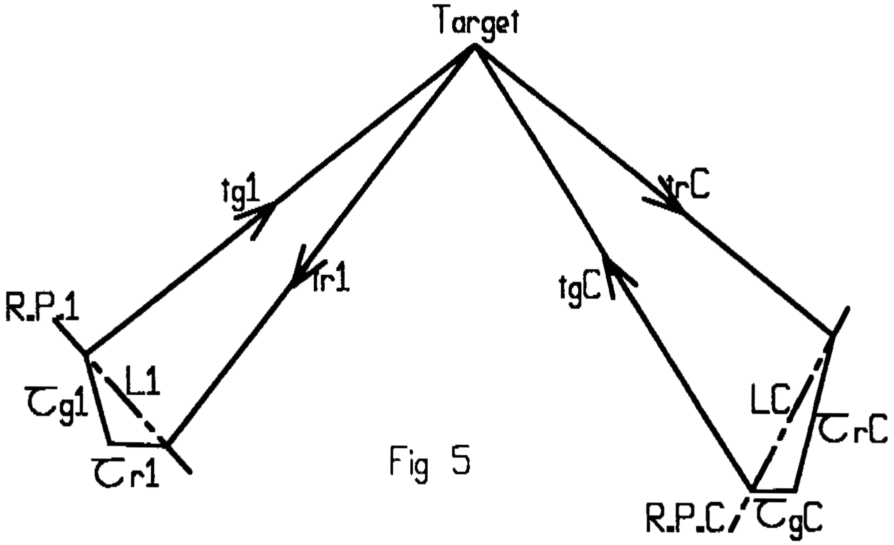
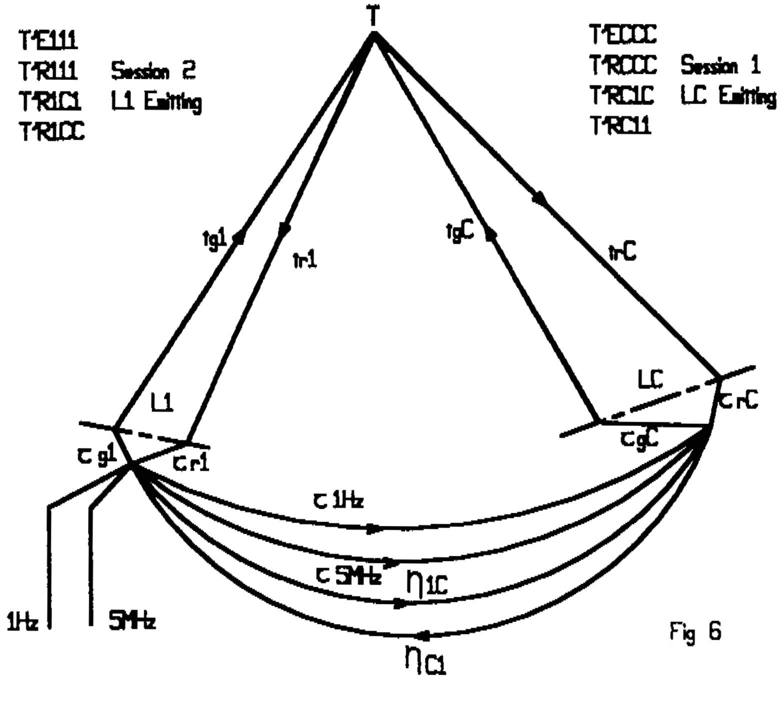

Reference Point
τg
tg
CC
tg
tr
Corner Cube
τr
tr

Fig 4



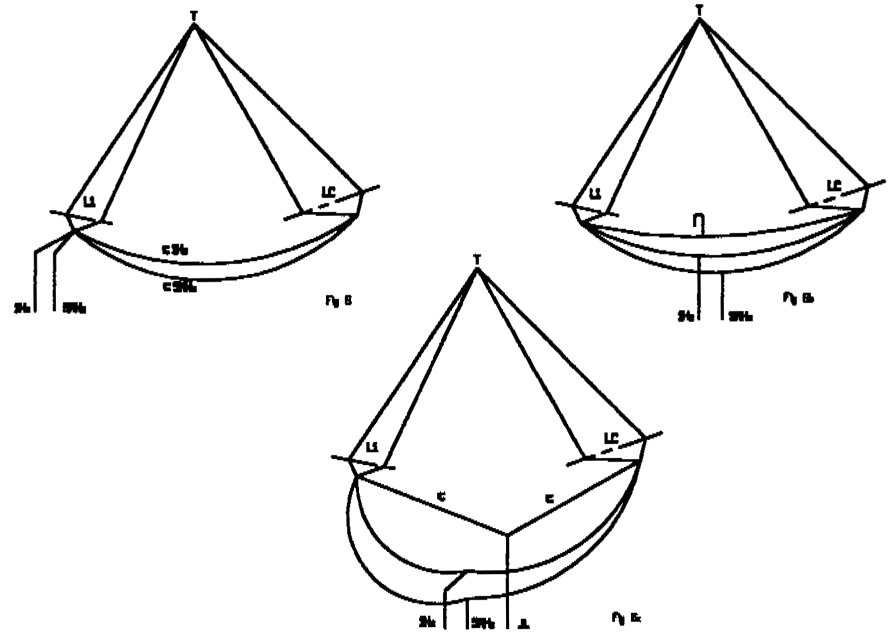
Target
tg1
tr1
tgC
trC
R.P.1
L1
τg1
τr1
LC
τrC
R.P.C/τgC


Fig 5



T
T'E111
T'R111 Session 2
T'R1C1 L1 Emitting
T'R1CC
T'ECCC
T'RCCC Session 1
T'RC1C LC Emitting
T'RC11
tg1
tr1
tgC
trC
L1
LC
τg1
τr1
τgC
τrC
τ 1Hz
τ 5MHz
η1C
ηC1
1Hz
5MHz


Fig 6



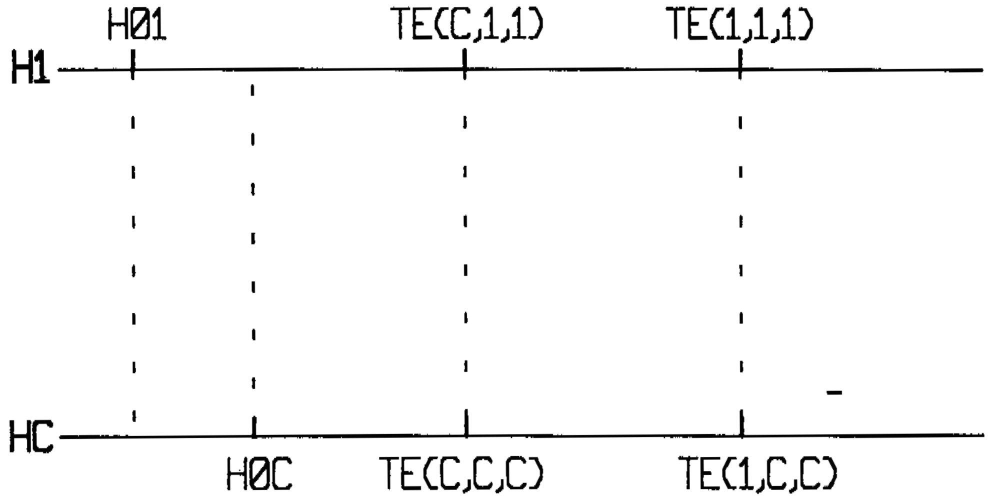


Fig 7

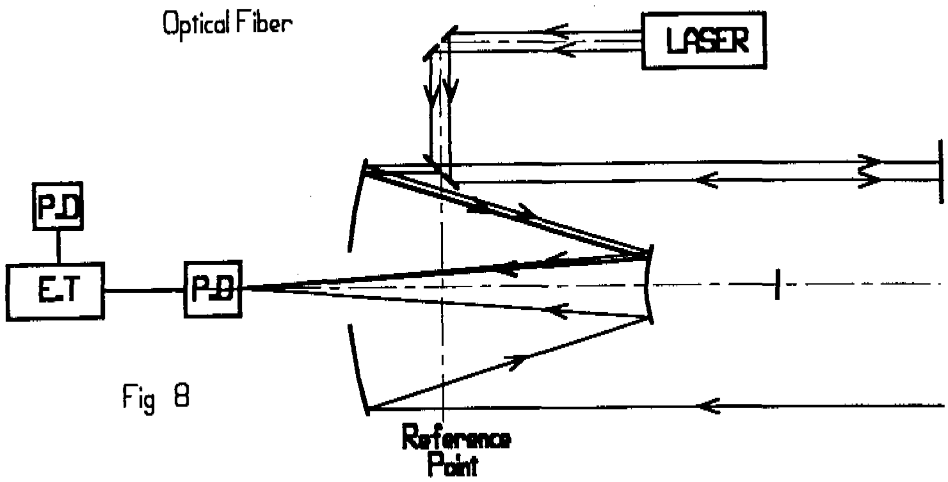



Fig 8