### FLAO system test plan in solar tower

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<tr>
<th>Prepared by</th>
<th>S. Esposito, G. Brusa</th>
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<tr>
<td>Approved by</td>
<td>L. Busoni</td>
</tr>
<tr>
<td>Released by</td>
<td>S. Esposito</td>
</tr>
</tbody>
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INAF – Osservatorio Astrofisico di Arcetri  
Largo E. Fermi, 5 - 50133 Firenze - ITALY  
[http://www.arcetri.astro.it/adopt](http://www.arcetri.astro.it/adopt)
ABSTRACT

This document reports a general description of the activities to be executed in the solar tower test to align, set-up and calibrate the LBT First Light Adaptive Optics (FLAO). The testing activity can be divided in two preliminary tasks: (1) system integration in the solar tower and (2) system alignment and two testing phases: (Phase I) closed loop with 200 modes and (Phase II) closed loop test with full set of modes and parameters optimization. Each task is detailed in a separate section and the test schedule, activity responsible and personnel assignment are given in a management section at the end of the document.
## Modification Record

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<td>S. Esposito, G. Brusa</td>
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### Abbreviations, acronyms and symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>LBT</td>
<td>Large Binocular Telescope</td>
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<td>MMT</td>
<td>6.5m MMT telescope</td>
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<td>FLAO</td>
<td>First Light Adaptive Optics system</td>
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<tr>
<td>AGW</td>
<td>Acquisition, Guiding and Wavefront sensing unit</td>
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<td>AO</td>
<td>Adaptive Optics</td>
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<td>W</td>
<td>On axis Wavefront sensing unit</td>
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<td>LBT672a</td>
<td>First Adaptive secondary unit of LBT telescope</td>
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<td>PSF</td>
<td>Point Spread Function</td>
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<td>IRTC</td>
<td>InfraRed Test Camera</td>
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<td>GUI</td>
<td>Graphical User Interface</td>
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<td>TCS</td>
<td>Telescope Control System</td>
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<td>ROI</td>
<td>Region Of Interest</td>
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<td>FoV</td>
<td>Field of View</td>
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<td>RTR</td>
<td>Real Time Reconstructor</td>
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<td>RON</td>
<td>Read Out Noise</td>
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<td>DM</td>
<td>Deformable mirror</td>
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<td>SNR</td>
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<td>WaveFront Sensor</td>
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<td>Strehl ratio</td>
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<td>ADS</td>
<td>ADS International SRL</td>
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<td>IM</td>
<td>Interaction Matrix</td>
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Contents

1 Scope of the document 7
2 Applicable documents 7
3 Introduction 7
4 Requirements for FLAO system solar tower test 7
   4.1 Phase 1 pre-requisites ................................................................. 7
   4.2 Phase II pre-requisites............................................................... 8
5 FLAO system integration in solar tower 9
6 System alignment 9
7 WFS pupil registration 10
8 Test of FLAO system in closed loop, phase I. 10
   8.1 Closed loop with binning = 1.................................................... 10
   8.2 Closed loop with binning = 2, 3, 4.......................................... 11
   8.3 System characterization versus seeing and flux conditions. .................... 11
   8.4 Measurements of interaction matrix using the sinusoidal modulation technique. 11
   8.5 Measurements of interaction matrix using fibers with various core sizes. .................. 12
   8.6 Closed loop test with vibration noise ........................................ 12
   8.7 FLAO system control SW.......................................................... 12
   8.8 TCS mode offloading test........................................................ 13
9 Installation and alignment of IRTC 13
   9.1 IRTC SW requirements .......................................................... 13
   9.2 Measurement of IRTC non common path aberration ..................... 13
10 Operation of FLAO system in closed loop, phase 2 14
10.1 Closed loop with binning 1.................................................................14
10.2 Closed loop test with binning 2,3 and 4 and different photon fluxes.................................14
10.3 Closed loop test with different seeing values................................................15
10.4 System observing modes .............................................................................15

11 Tower test activity management 16

12 References 19
1 Scope of the document

The document describes the various phases of the FLAO system test in the Arcetri solar tower.

2 Applicable documents

See AD list [FLAO_00]

3 Introduction

The FLAO system [R1,R2] test will be performed at the Arcetri Observatory and in particular in the old Solar Tower refurbished to provide a long optical bench of about 15m size. The optical set-up to test the full AO system is reported in [AD13]. The main parts of the FLAO system are the deformable mirror or LBT672 unit [R2, AD2, AD18] and the wave-front sensor or W unit [R1, AD3]. This test plan describes the activity needed to complete a full calibration of the FLAO system and a performance tests. These measured performances will be compared with simulation results [R3, AD1]. Briefly the test can be divided in four phases, two preliminary phases and two testing phases:

1) System integration in the solar tower.
2) Alignment of the full FLAO system including adaptive secondary and WFS unit.
3) Initial closed loop test where the basic operations and procedures are tested and debugged (phase I).
4) Advanced closed loop test where the full range of system parameters is tested together with the complete control SW (phase II). This phase includes a test of the system operational modes.

This document reports a time schedule for the described tasks and the resources needed, in term of personnel, to complete each of the tasks in the assigned time. The FLAO system will be ready for the acceptance test after successful completion of the tasks listed in this document.

4 Requirements for FLAO system solar tower test

The FLAO system test in the solar tower requires that all the FLAO subsystem have been previously integrated, tested and are ready to be installed in the optical bench of the solar tower. Moreover the various control software packages needed for the tests should be ready and installed on the FLAO system control computers. A list of pre-requisites items for phase I and phase II of the test is reported below.

4.1 Phase I pre-requisites

1. The LBT672 functionalities & performance have to be checked in the LBT672a/b acceptance tests [AD18,
AD26, AD19, AD2] so that the “flattened secondary shell, ready for AO test” milestone [AD11] has been reached. The mirror flattening command and the mirror influence functions will be measured during the optical acceptance test [AD2]. The adaptive secondary mirror of LBT namely LBT672a/b will be installed at the top of vertical optical bench in the solar tower [AD24].

2. The W unit1/2 functionalities & performance have to be checked in the W acceptance test [AD3] so that the “W system ready for AO test” milestone [AD11] has been reached. The AGW unit will be attached to the bottom end of the vertical optical bench in the solar tower.

3. An independent mechanical support is provided for an optical interferometer used as external metrology of the secondary mirror. The interferometer will be aligned with the secondary mirror and with the W unit1/2. A 4D interferometer will be used for this task [AD32].

4. The LBT672 hexapod functionality & performance have to be checked [AD42].

5. The retro-reflecting optics together with its support structure has to be checked [AD30]. The full subsystem will be attached to the LBT672 dummy hub.

6. The FLAO system supervisor software has to be installed and running on the AO system workstation [AD8]. The engineering interface software of LBT672 [AD20] and W [AD4] unit have to be installed and running on the AO system workstation.

7. SW for PSF analysis should be available. SW package selection is still to be done. A third party SW (Keck Observatory public routines package) is being considered.

8. The 4D interferometer remote control SW [AD32] should be available.

4.2 Phase II pre-requisites

9. The LBT InfraRed Test Camera (IRTC) [AD28] should be available. This camera will be used for the Solar Tower test to acquire images of the reference source in H and J band after the AO loop correction. This camera will be attached at the bottom of the AGW.

10. The IRTC control software and control computer should be installed and running on the IRTC computer [AD29].

11. The following TCS software, needed to test the AO system functionalities, should be installed and running [AD4, AD14, AD15]:
   a. A dummy instrument application using the AO related commands of the IIF library.
   b. The AOS commands implemented in the TCS.
   c. The mode-offloading control software at least for the offloading-to-hexapod part.
5 FLAO system integration in solar tower

All the components of the FLAO system will be installed in the solar tower. The sequence of installation is the following:

1. LBT672a/b is installed together with the retro-reflecting optics and its supporting structure. The secondary mirror is raised using the tower crane in the solar tower test pipe and bolted to the pipe top flange [AD24].

2. The end of the pipe internal to the tower laboratory is closed using the bottom flange. This flange has a circular optical window that is mounted on the flange prior the installation.

3. The W unit1/2 is transferred from its cart and attached to the lower end of the optical bench using the four cranes located in the lab.

4. The IRTC is mounted in two phases. First the IRTC bottom circular flange is bolted to the AGW [AD38-39]. Then the IRTC is lifted using the cranes and bolted to the flange.

5. In the case that interferometric measurements are needed during the test the 4D interferometer can be mounted after removing the IRTC.

6 System alignment

The alignment procedure of the FLAO system is described in [AD9], and has the following two aims:

1. to position the adaptive secondary so that the axis of the unit is passing from the retro-reflecting optics focal point and the focus of the WFS Unit reference source. This condition ensures that the off-axis aberrations due to the secondary mirror are null. This step assumes that a preliminary alignment of the retro-reflecting optics has been achieved during the previous testing phase [AD17] in which the 4D is used.

2. To position the optical axis of the W unit to be coincident with the optical axis of the secondary mirror. This condition ensures that the geometry of the pupil images on the WFS CCD is the nominal ones and will not be changing when the pupil rotator is operated. This condition will be reached by tilting the WFS board with respect to the translation stages unit.

The alignment procedure is considered completed when:

1. the two mentioned axes are coincident with an error less then 1-2 arcminutes. This is to ensure the proper optical configuration of the WFS.

2. the total $\omega f$ error seen at the WFS location should be not larger then the initial DM best flat figure. In any case it should be less then $120\text{nm RMS}$. 
7 WFS pupil registration

The pupil registration procedure has the aim of adjusting the following quantities: pupil centering, diameter, relative distance, focusing, and clocking. These quantities define the pupil geometry and have to be checked with the values measured at the W unit acceptance test [AD3].

8 FLAO system closed loop tests, phase I.

After completion of the two previous steps, the testing of the FLAO system can start. The initial operations are aimed at setting-up the system in such a way that an automatic measurement of the system interaction matrix can be done. To do that, the following basic requirements have to be fulfilled:

1. Computation of the FLAO system correction modal base (in terms of mirror commands). These modes are obtained using the LBT672a/b optical influence functions measured during the secondary optical acceptance test [AD2]. The system modal base will be obtained as a set of linear combinations of these influence functions that approximates a set of Karhunen-Loève polynomials.

2. The FLAO system control SW should be able to issue a command to the LBT672 and to sequentially take frames with the WFS CCD.

3. Slope null SW. A SW procedure should be able to measure a set of WFS slopes when the LBT672 is set to a fixed commanded position.

4. Dark frame SW. A SW procedure should be able to measure several frames of the CCD47 and CCD39. The average of those frames will be used for dark counts subtraction for the acquired CCD47 images and when calculation the WFS signals.

8.1 Closed loop with binning = 1.

The aim of this first test is to check the operability of the main HW components and SW procedure. This first test will be done using the WFS CCD with no binning (binning = 1) and with high photon flux. The measurement of a low order interaction matrix (IM) is performed using about 200 modes. The IM acquisition is done using the classical modal push-pull method. Data reduction SW is used to analyze these measurements and to identify the reconstruction matrix for the first 200 modes. After achieving a reconstruction matrix, a test of the AO system in closed loop is done. In this case, the loop is closed with no external disturbance.

The system performances are analyzed using the technical viewer (TV) of the WFS Unit [AD4]. This camera can be configured to measure a 32x32 pixels ROI so that a fast frame rate (40fps) can be achieved for temporal analysis of the system performance. A possible configuration to measure the system PSF using the TV requires having (1) the red
dichroic on the filter wheel #1 so that most of the light above 600 nm is transmitted to the wavefront sensing arm leaving a small fraction going into the TV arm, (2) a high-pass filter on filter wheel #2 (TV arm) cutting light below 600nm-700nm, to avoid flooding the TV CCD with blue (less corrected) light. The achieved SR and FWHM will be measured.

8.2 Closed loop with binning = 2, 3, 4.

After a successful closed loop operation with binning = 1 the system operation will be tested in a preliminary way, with binning =2, 3, 4. This is done in order to identify possible problems in the operation with higher binning. This problem solving activity will be done as much as possible in parallel with other system tests. The test will require the acquisition of a system interaction matrix for each binning. A closed loop test will also be performed and the achieved results will be analyzed.

8.3 System characterization versus seeing and flux conditions.

A characterization of the system behavior as a function of photon flux and seeing conditions will be done. In this case phase perturbations for different seeing values will be introduced by using the feature of uploading in the secondary control electronics a given time history for each one of the actuators [AD18]. The SW procedures to optimize system gain, binning, tilt modulation and number of corrected modes will be tested for the first time at this stage. SR, FWHM, modal disturbance attenuation and modal transfer functions will be measured and compared with numerical simulations.

8.4 Measurements of interaction matrix using the sinusoidal modulation technique.

The measurements of the interaction matrix (IM) will be repeated using the sinusoidal modulation technique. This test will be done by measuring interaction matrices with about 200 modes as done in the test previously described. The measurement will be done initially with binning = 1. The closed loop results will be compared with those previously achieved to identify possible problems of the technique especially related with data reduction SW. This technique should provide:

1) a better SNR in the IM measurements of high order modes. This is a relevant point for the secondary mirror given the small amplitude applicable for high order modes (around 50nm).

2) a considerable reduction in the IM measurement time. The reduction in time depends on the number of simultaneously measured modes, previous measurements on P45 showed that 10 modes can be measured simultaneously [R4].
8.5 Measurements of interaction matrix using fibers with various core sizes.

The relationship between the WFS signal and a given wave-front aberration depends in the case of the pyramid sensor, on the size of the corrected PSF as seen by the WFS. A test will be done to compare the closed loop performance obtained with different interaction matrices, the increased PSF size will be simulated by varying the reference source size. The compared cases are:

1. IM measured with a fiber generating a diffraction limited source.
2. IM measured with a fiber generating a resolved source.

In case 2 the resolved source will have a size approximately equal to the expected size of the WFS PSF when the system is in closed loop. The test will be done in particular for the low photon flux cases where the difference between diffraction limited and correction limited PSF can be large.

8.6 Closed loop test with vibration noise

A test of the closed loop performance of the system in presence of vibration will be done. The test will require implementing a Kalman filter control scheme for tip and tilt, the computation required by this filtering will be performed by the secondary DSPs as in the case of the wave-front reconstruction. The time history used for the closed loop test will be modified to add a tip tilt disturbance with a PSD matched with tip tilt vibration PSD measured at the LBT telescope and the results achieved with and without vibrations disturbance will be compared. This will provide a useful tool to counteract vibrations eventually present at the LBT telescope.

8.7 FLAO system control SW

Phase I of the testing will provide the opportunity to debug the FLAO control SW. At the end of this phase we assume that most of the upgrades will be completed and most of the bugs identified and fixed. After completion of the testing phase the control SW should be able to set-up and configure the AO system automatically. In particular after receiving the following input parameters r0, v0, star magnitude the system should be able to:

1. startup all the system HW and SW, in particular the adaptive secondary mirror (DM) and the W unit (WFS).
2. Configure the two units (DM and WFS) to be ready to start adaptive optics operation: after input of the initial parameters r0, v0, photon flux, the system configuration for DM and WFS will be calculated using look-up tables created using numerical simulations. The look-up tables will allow computing the optimal system gain, tilt modulation, CCD binning and integration time after definition of three initial parameters like r0, v0 and photon flux (or star magnitude).
3. Save diagnostic data like CCD frames, WFS slopes and mirror commands as a function of time. In case of fast
frame rate the data set could be decimated to allow the acquisition of a continuous stream of data. The continuous acquisition of data should be possible at least at 200 Hz.

Some preliminary testing of the telescope TCS control of the AO system should occur at this time; this control should be achieved using a dummy instrument GUI. At this stage both IIF commands and AOS software should be fully tested.

8.8 TCS mode offloading test

A test of the offloading mechanism for low order modes will be done. A low order mode drift will be introduced by placing an offset in the WFS signals. This offset will produce a low order mode accumulation on the secondary mirror. Alternatively the tilt drift could be introduced by slowly translating the WFS stages. The offloading mechanism should compensate the accumulated drift by moving the hexapod. A verification of the effect of the offloading mechanism on the PSF quality will be performed as well.

9 Installation and alignment of IRTC

After positive completion of the AO system test the IRTC camera [AD28, AD29] will be mounted in the solar tower and aligned with the FLAO system.

9.1 IRTC SW requirements

Before starting the installation process of the camera the control SW should be tested. In particular the following capability should be checked:

1. Ability of saving a continuous set of frames with a short exposure time. The IRTC SW should be able to receive commands issued by the supervisor SW of the AO system.

2. The filter wheel should be controlled with commands issued by the supervisor SW of AO system.

The maximum frame rate at which continuous frames can be saved should be checked at this point.

9.2 Measurement of IRTC non common path aberration

After installation and alignment of the IRTC some measurements will be done to find the shape of the secondary mirror that gives the best performance in terms of SR and FWHM on the camera. A list of possible techniques to be applied is:

1. Phase diversity

2. Curvature sensing

3. Temporal modulation of low order modes.
The SR on the IRTC should be better then 80%.

10 FLAO system closed loop tests, phase 2

In this second test phase the system will be mainly operated by using the complete control SW, including AO supervisor [AD4] and TCS simulation software. Access to the engineering GUI of W unit and LBT672 should be reduced as much as possible. Log of all encountered errors in operating the AO system should be kept for later analysis.

10.1 Closed loop with high photon flux

The second phase will start with measurements of system interaction matrix that includes all the 672 system modes. The system performances will be measured first with high photon flux using the images taken in H and J band with the IRTC. As before PSF SR and FWHM will be measured and compared with results obtained with numerical simulations. At this stage the system performance will be optimized against the pupil registration. In particular the system performance will be optimized in terms of

1. pupil relative positions, via adjustment of camera lens translation stage.
2. pupil mask (or valid sub-aperture mask), via signal thresholding.
3. pupil images alignment with CCD pixel grid axes, via pyramid rotation.
4. Actuator grid rotation with respect to CCD pixel grid, via re rotator adjustment.
5. Pupil magnification, via adjustment of camera lens focus.

The optimization of pupil registration will be done with binning = 1 that is the WFS mode with the maximum sampling on the pupil. Points 2 and 4 will be repeated for the different binning values. At this point the achieved SRs in H band at high photon flux in the seeing condition described in [AD1] should be better then the baseline values. After achieving this result the test will be done with the other binning values. The achieved results in terms of SR should be equal or better then the baseline values stated for binning 2, 3 and 4 [AD1].

10.2 Closed loop test with different photon fluxes

The reference source of the FLAO system will be used to produce different illumination of the WFS. In such a way the different photon fluxes or star magnitudes will be simulated. The closed loop performance will be measured for all binning 1,2,3 and 4 and various photon fluxes or counts level on the CCD39. The number of counts corresponding to a given star magnitude will be estimated by considering the measured optical efficiency of the WFS and detector QE. The telescope optical efficiency is assumed to be 0.9^3=0.73. The system performance will be optimized using:

1. the CCD39 binning;
2. the system integration time;
3. the tilt modulation;
4. the AO system overall gain;
5. modal gain control or number of corrected modes.

As seen in the simulation this optimization will require adjusting the parameters listed above for the four binning values. This requires measuring four interaction matrices including all the 672 system modes. Moreover these matrices will be measured for several values of tilt modulation. Assuming to measure a minimum of four amplitudes of modulations [AD1] the minimum required number of interaction matrix measurements is sixteen. The WFS slope null vector will be measured in the different binning and modulation configurations as well. The optimization of the number of modes will be done by inverting interaction matrices of different initial number of modes as required.

10.3 Closed loop test with different seeing values

This test will be done measuring the system performance as a function of the initial seeing conditions in terms of r0 and v0. In this test the system will be initially configured based on the system look-up tables. The different seeing values will be introduced by using the already mentioned feature of the secondary to load a different time history for each one of the actuators. The optimization of tip tilt modulation, system gain and modal gains will be done in a similar way to the previous tests, i.e. using the numerical simulation results. The achieved performance will be compared with the numerical results [AD1].

10.4 System observing modes

After completion of the test described above the closed loop performance data will be used to update the system look-up tables. After updating the system tables a validation of the system automatic configuration algorithm will be possible by selecting input parameters that require to the configuration algorithm some interpolations between the measured values. The observing modes to be tested are briefly defined below:

1. Field Stabilization Mode (FSM). In this mode only tip-tilt is corrected using the W sensor tilt measurements.
2. Automatic Configuration modE (ACE). In this mode the reference star co-ordinates, the star magnitude and the r0 and v0 parameters will be provided to the system and the AO supervisor will select the AO system configuration to achieve the best SR. Basic configuration parameters are: integration time, number of sensor sub-apertures, number of corrected modes, tip-tilt modulation amplitude. The AO supervisor will configure the AO system using some pre-computed look-up tables.
3. Interactive Configuration modE (ICE). In this mode the reference star co-ordinates the star magnitude the r0
and v0 parameters are provided to the system and the AO supervisor will still configure the AO system however the user can change some configuration parameters among pre-defined values. Adjustable parameters are: integration time, binning, number of corrected modes, tip-tilt modulation amplitude.

Validation of automatic configuration requires measuring the system performance in closed loop. These performances will be compared with the performance achieved by the system using a manual configuration. The performance validation will be done on a set of 3-5 different fluxes spanning the range of magnitude $m_R = 0-18$ (TBC).

### 11 Tower test activity management

The schedule for the described test is reported in the Gantt chart of Figure 1. The estimated total duration of the test is 141 working days. The start and finish date are 25/03/2009 and 07/10/2009 respectively.

![Figure 1 The Gantt chart reporting the different tasks of the solar tower test of FLAO. Phases are reported in black brackets, milestones are marked as green diamonds.](http://www.arcetri.astro.it/adopt/)
management elements of these tasks are summarized in Table 1.

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<td>IRTC installation and alignment</td>
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Table 1 The main five phases of the FLAO system test in the solar tower. The central area in light gray reports the percentage of duty for each person participating to the test. Total FTE required per person and per phase is reported. Days left free for each person in the test period are reported too. Finally the two last columns on the right report the personnel specific role and the percentage of time required.

Table 1 reports the percentage of time that each person is working for each phase, the total FTE per person is also reported. The total FTE spent for the test is found to be 3.55. One FTE is assumed here to correspond to 230 working days, after subtraction of Saturdays, Sundays, national holidays and personal holidays (30 days per year). The test total time is of 6 months so that the maximum workload for each person is 0.5 FTE. The assigned workload for each person seems to be compatible with assignments from other projects.
12 References


