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Invited Paper

In Orbit test result of an Operational Optical Intersatellite Link between ARTEMIS and SPOT4, SILEX

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ABSTRACT

The Semi conductor Inter satellite Link EXperiment, SILEX, consists of two terminals, one terminal embarked on the French LEO observation satellite SPOT4 and one terminal embarked on ESA's GEO telecommunication satellite ARTEMIS. The objective of SILEX is to perform optical communication experiments in orbit and on an operational basis transmit SPOT4 Earth observation data to ARTEMIS, which will relay the data to ground via its Ka band feeder link. SPOT4 was successfully launched on 22nd March 1998. The ARTEMIS launch on 12th July 2001 left ARTEMIS in an orbit with too low apogee, necessitating orbit raising to a circular parking orbit, altitude 31000km, using a large fraction of the chemical propellant on board. The remaining 5000km to GEO stationary orbit will be achieved using the low thrust innovative electric propulsion system necessitating specific attitude control software. The final orbit raising will last about 6 months and the expected lifetime of ARTEMIS after station acquisition is 5 years. While waiting for the establishment of the new attitude control software and the beginning of the final orbit raising maneuvers a test program has been undertaken to characterize the performances of the SILEX system. Testing was performed every fifth day when ARTEMIS was visible over Europe. The test program involves Optical Ground Station acquisition and tracking, inter-satellite link acquisition and tracking, bit error rate measurements and transmission of Earth observation data.

The paper reports on results of the in orbit testing, giving comparisons with predictions. The conclusion of the test program is that the SILEX system has excellent performances qualifying the system for operational use by SPOTIMAGE in parallel with a detailed technological experimentation program involving the two SILEX terminals, ESA's optical ground station on Tenerife, and also NASDA's OICETS, once ARTEMIS has acquired its final orbital position.

Keywords: Free Space Optical Communication. Pointing, acquisition, and tracking. Intersatellite links. Laser. In-orbit test, SILEX, data relay. SPOT4, ARTEMIS

1. INTRODUCTION

The first SILEX optical communication terminal was placed on a 832 km sun synchronous LEO orbit 22nd March 1998 onboard the French Earth observation satellite; SPOT4. While waiting for the counter terminal on ARTEMIS an extensive test program demonstrated excellent performances by acquiring and tracking stars. The ARTEMIS launch on 12th July 2001 left ARTEMIS in an orbit with very low apogee, necessitating orbit raising to a 31000km circular parking orbit using a large fraction of the chemical propellant on board. The remaining 5000km to GEO stationary orbit will be achieved using the low thrust innovative electric propulsion system necessitating specific attitude control software. The final orbit raising will last about 6 months and the expected lifetime of ARTEMIS after station acquisition is 5 years. While waiting for the establishment of the new attitude control software and the beginning of the final orbit raising maneuvers, a test program has been undertaken to characterize the performances of the SILEX system. Testing was performed every fifth day when ARTEMIS was visible over Europe. This paper reports on results of tests involving inter-satellite link acquisition and tracking, bit error rate measurements and transmission of Earth observation data with comparison to predictions. Seven links were successfully established to ESA's optical ground station. The results of these tests are reported in a parallel paper[9]. A list of SILEX acronyms with their meaning is included in figure 2.1. In this paper the term irradiance is used for received power and intensity for emitted power.

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2. TERMINAL DESIGN

The system and terminal design is based on early nineties technology or what could be developed within a reasonable risk at that time. Considering the operational aspect of the mission the terminal equipment is fully redundant without any single point failures except for elements such as structure, telescope, etc. A triple redundancy is implemented for the laser diode transmitter package. The SILEX terminal design is described in numerous publications[1, 2 ,3, 4,d 6, 7, and 8], and only figure 2.1 for layout and acronyms and table 2.1 for the most important features and system parameters is included in this paper.

	LEO terminal on SPOT 4	GEO terminal on ARTEMIS
Telescope	Afocal cassegrain, common to emission and transmission, Zerodur™ mirrors and structure	
Receiving telescope diameter	250 mm	
Transmitting telescope diameter	250 mm	125 mm
Emitted beam wave front error	λ/14 at 830 nm	
Laser transmitter	GaAlAs diode, 847nm	GaAlAs diode, 819nm
Laser power output set point	60 mW optical at diode level	37 mW optical at diode level
Modulation	NRZ, 50 Mbits/s	PPM, 2 Mbits/s
Beacon beam	None	19 GaAlAs laser diodes, 801 nm bundled fibre coupled
Beacon beam laser output power	NA	Max 900 mW/LD
Beacon beam intensity	NA	8.3 ± 1.9 MW/strd constant in the total divergence angle
Beacon beam divergence	NA	750 µrad
Telecommunication Receiver	None	Slik avalanche photo diode
Acquisition Sensor	CCD (readout at 30Hz)	CCD (readout at 130Hz)
Acquisition Sensor FOV	8.64 mrad x 8.64 mrad	1.05 mrad x 1.05 mrad
Tracking sensor	CCD (readout at 1kHz, 4kHz, and 8kHz)	CCD (readout at 4kHz, and 8kHz)
Tracking Sensor FOV	0.238 mrad x 0.238 mrad	
Quadrant Detection sensor	Four centre pixels of the TS	
Fine Pointing and Sensor Control Electronics	Based on Digital Signal Processor and Field programmable arrays	
Point Ahead Mechanism	Two mirrors, Piezo electric actuators, capacitive position sensors	
Fine pointing assembly	Two mirrors, Electromagnetic actuators, inductive position sensors	
Coarse Pointing Mechanism	Direct driven stepper motor, 200 steps, each step divided in 32000 micro-step	
Thermal stability of optical enclosure	+/- 0.2°C	
Optical bench	Sandwich of carbon fibre reinforced epoxy, all units on isostatic mounts	

Table 2.1: Main SILEX system parameters and design features

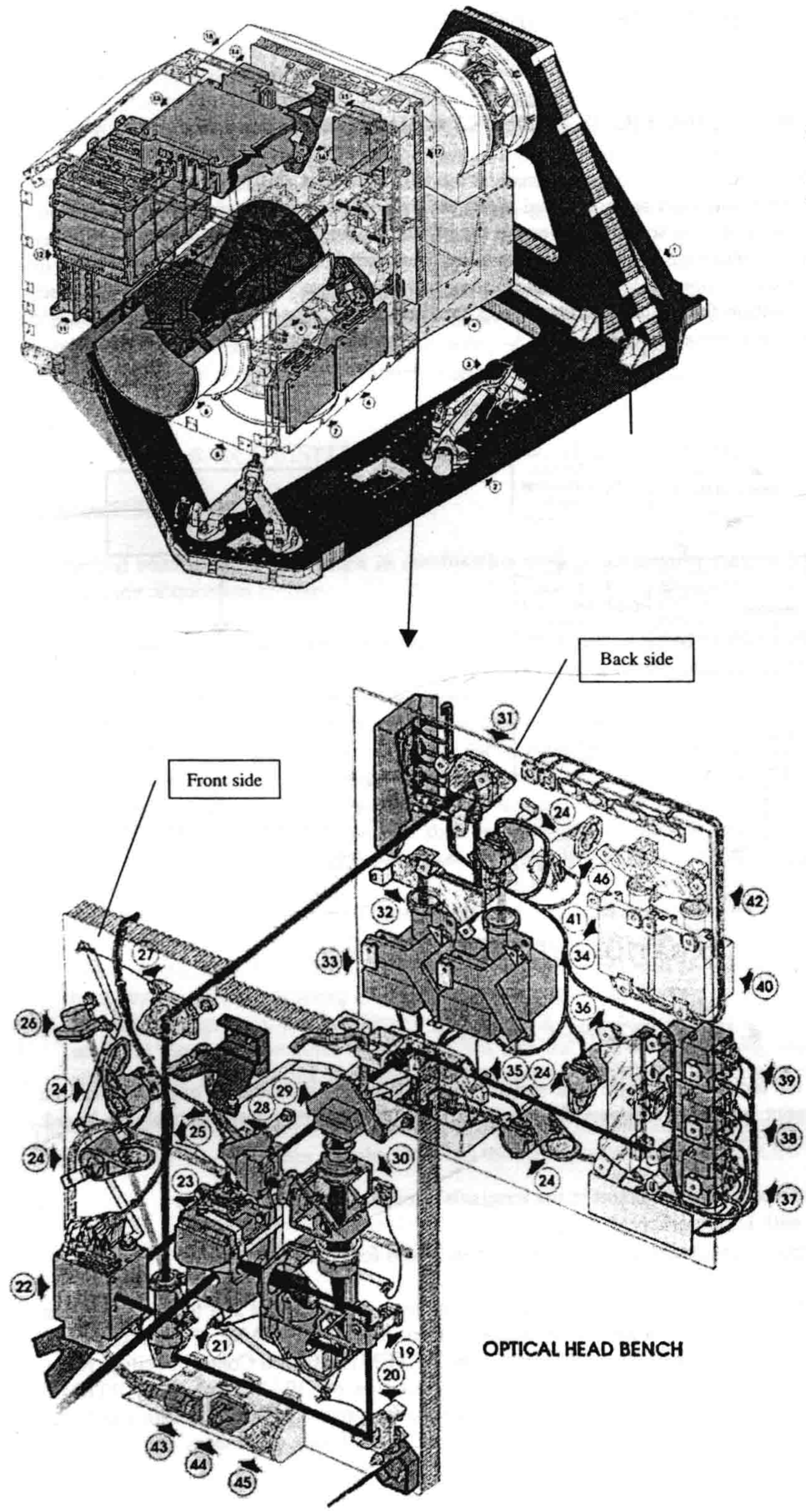

Figure 2.1: the SILEX terminal

1	CPASB	Coarse Pointing Support Bracket
2	ASIFS	Aerial Spacecraft Interface Structure
3	LLD	Launch Lock Devices
4	CPM	Coarse Pointing Mechanism
5	MPCS	Mobile Part Carrying Structure
6	FPDE 1	Fine Pointing drive Electronics, A
7	FPDE 2	Fine Pointing Drive Electronics, B
8	BAFFLE	Telescope Baffle
9	TA	Telescope Assembly
10	PADE	Point Ahead drive Electronics
11	TEMP	Telecom Electronics of the Mobile Part
12	FPSCE	Fine Pointing Sensors and Control Electronics
13	MTCE	Mechanism and Thermal Control Electronics
14	ADPEM2	Acquisition Detector Proximity Module, A
15	ADPEM1	Acquisition Detector Proximity Module, B
16	OHBAD	Optical Head Bench Attachment Device
17	OHB	Optical Head Bench
18	OHTH	Optical Head Thermal Hood
19	FSM	Field Separator Module
20	FOM 1	Folding Mirror
21	BCM	Beam Combiner Module
22	PAM	Point Ahead Mechanism
23	FPM	Fine Pointing Mechanism
24	FFM	Flip Flop Mechanism
25	OHHAR	Optical Head HARness
26	RCC	Retro-reflecting Corner Cube
27	FOM 2	Folding Mirror
28	AS 2	Acquisition Sensor, B
29	AS 1	Acquisition Sensor, A
30	ALM	Acquisition Lens Module
31	TF	Tracking Filter
32	FBT	Fixed Beam translator
33	TS 1	Tracking Sensor, A
34	TS 2	Tracking Sensor, B
35	ANA	ANAmorphosor
36	TRM	Transmitter Redundancy Module
37	LDTP1	Laser Diode Transmitter Package
38	LDTP 2	Laser Diode Transmitter Package
39	LDTP 3	Laser Diode Transmitter Package
40	RFE 1	Receiver Front End , A*
41	RFE 2	Receiver Front End , B*
42	RRM	Receiver Redundancy Module*
43	BH	Beacon Head*
44	RL 2	Return Link*
45	FOM4	Folding Mirror*
46	FFM	Flip Flop Mechanism*
	PASTEL	Passager Telecom= LEO terminal
	OPALE	Optical Payload=GEO terminal
	FFP	Far Field Pattern

*Equipment for GEO terminal only

3. ON-GROUND PREDICTIONS VERSUS IN-ORBIT RESULTS

The SILEX on-ground verification philosophy is based on mathematical models correlated with tests allowing to predict worst case in orbit performance[6]. In orbit test results are compared to the on ground worst case performance predictions established in the performance documentation, the so-called Pdocs in figure 3.1. The worst case philosophy is justified by the operational nature of the SILEX mission, but it is very penalizing, e.g. Pastel is designed to be within its performance specification in the practically impossible case that all three reaction wheels on SPOT4 turns at speeds coinciding with a structural resonance within the terminal. Considering the limited testing performed so far one should not assume that the worst case has been reproduced in orbit.

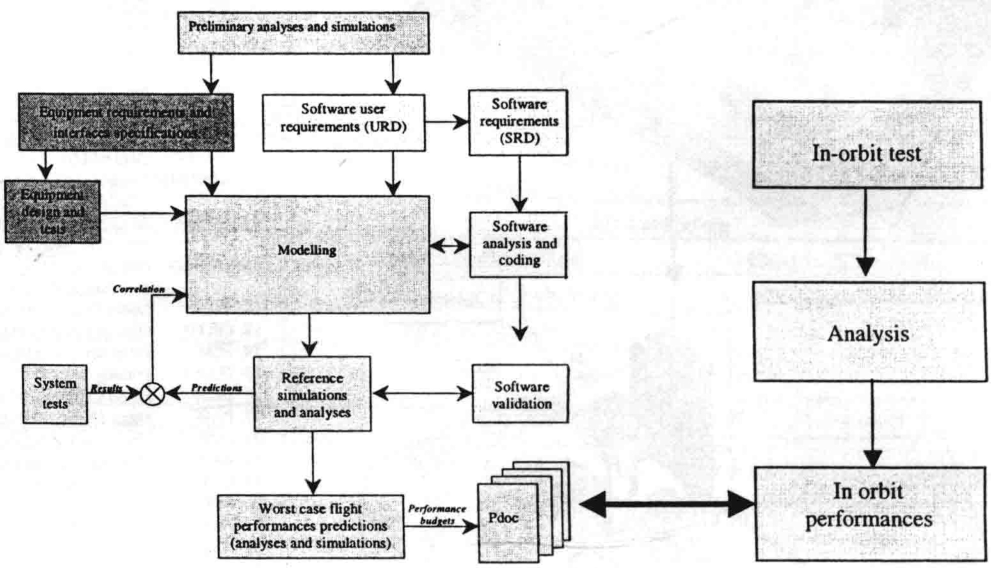

Figure 3.1: The SILEX on ground and in orbit verification approach

4. OPERATIONS CONCEPT

The SILEX operations concept is that the terminals provide their service without operator intervention over 24 hours, i,e all pointing calculations and management including recovery from any failures are performed autonomously on board. The following operations must be done every 24 hours:

- Update of parameters of the orbital models resident in the terminals after ranging of the satellites
- Calibration of on-board time with UTC
- Programmation of communication sessions in terms of start and end dates for communication

The GEO terminal can support two users in an interleaved way, i.e. it has its own orbital model and those of two user satellites (e.g. SPOT4 and NASDA's OICETS) on board. User requests from e.g. SPOTIMAGE, Toulouse, France (responsible for the commercialization of the SPOT data) are directed to the ARTEMIS Mission Control Facility, Redu, Belgium, which establishes the operations schedule, and coordinates the operation of OPALE with the ARTEMIS operations Centre, Telespazio, Fucino, Italy, that operates ARTEMIS, and the operation of PASTEL with the Pastel Mission Control Centre, Redu, that operates Pastel Via the SPOT4 Operations Center, Toulouse, France.

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5. INTERNAL CALIBRATIONS

Three internal calibrations are possible:

- Laser diode calibration to verify and reset the laser diode power output and modulation depth
- Global bias calibration to calibrate bias and gain of the Point Ahead Mechanism by means of the Tracking Sensor grid
- CCD calibration by pointing a dark area of the sky to verify dark currents.

In addition to these calibrations performed upon ground request, an automatic calibration of co-alignment between Emission path and tracking path is performed just before each communication session.
All three calibrations have been performed regularly on the LEO terminal since the launch in March 1998 in order to monitor health and trends of the terminal[8]. A series of calibrations of the GEO terminal was performed after the launch indicating stable performances with respect to on ground measurements.

6. ACQUISITION, TRACKING, AND POINTING PERFORMANCES

6.1 Acquisition scenario

The limited beacon beam divergence in combination with an uncertainty cone of 5,4 mrad (full angle, 3σ) has lead to the following acquisition process.

- Both terminals point in open loop towards to counter terminal based on on-board orbital models
- GEO scans the uncertainty cone with the beacon beam by deflection of the FPA. The scanning parameters (area scanned, scanning speed, and overlap) are tuned to ensure a minimum illumination duration of LEO. This duration allows for both terminals to perform their acquisition operation including time for mode automaton reconfiguration in case of transient illumination before the useful signal presence.
- LEO is illuminated by the beacon beam and detects the direction of the incoming light on the acquisition sensor and directs its telecom beam towards GEO by actuating the FPA so as to receive the incoming light first in the field of view of the Tracking Sensor and then in the centre of the tracking sensor, the so-called QD sensor and by applying an adequate point ahead angle to the transmitted beam using the point ahead mechanism. This process is referred to as rallying.
- GEO receives and detects the telecom beam from LEO and stops scanning and correct its line of sight
- Once both terminals point in closed loop towards each other, the GEO terminal remains in rallying mode (tracking based on the most illuminated pixel on the tracking sensor) with its beacon beam pointed towards LEO in order to be robust to transient pointing errors in the initial acquisition phase.
- The initial acquisition step performed with the FPA is off-loaded, so as to align the telescope axis with the counter terminal direction. Hereafter GEO enters the fine tracking mode (tracking based on centroiding of the four centre pixels of the TS) and point its communication beam towards LEO, where after the beacon beam is turned off.

The timeline for the acquisition can be seen in figure 6.1.1. Link establishment between GEO and the Optical Ground Station follows the same steps, i.e. the OGS has the same performances as the LEO terminal.

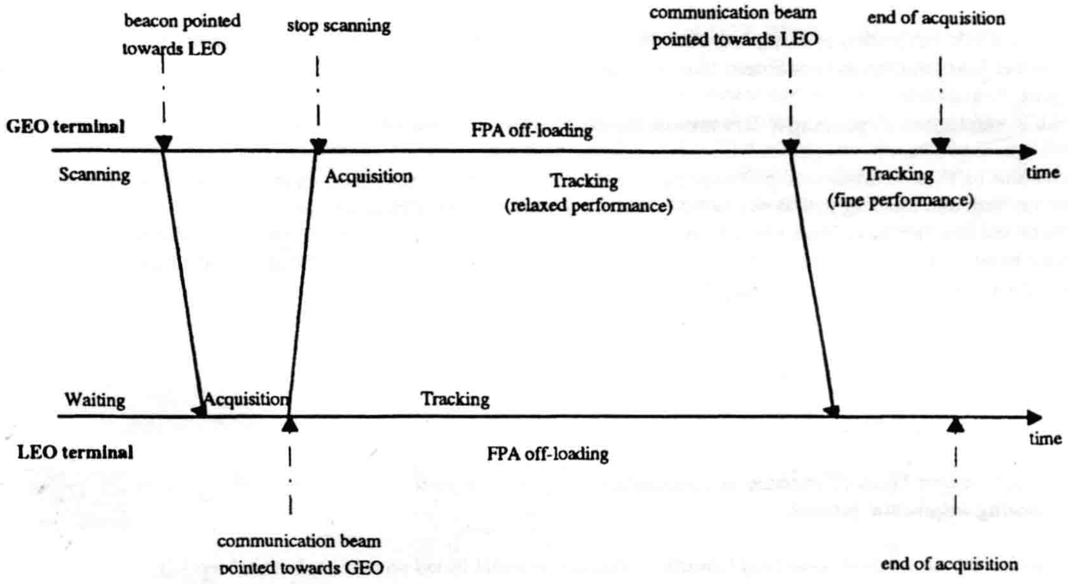

Figure 6.1.1: Time line for acquisition

6.2. Acquisition performances

Over a period of two months 26 acquisitions between PASTEL and OPALE have been successfully performed without any failures. Figure 6.2.1 indicates the first detected direction of the Geo terminal. The open loop pointing error of the LEO terminal is exceptionally small.

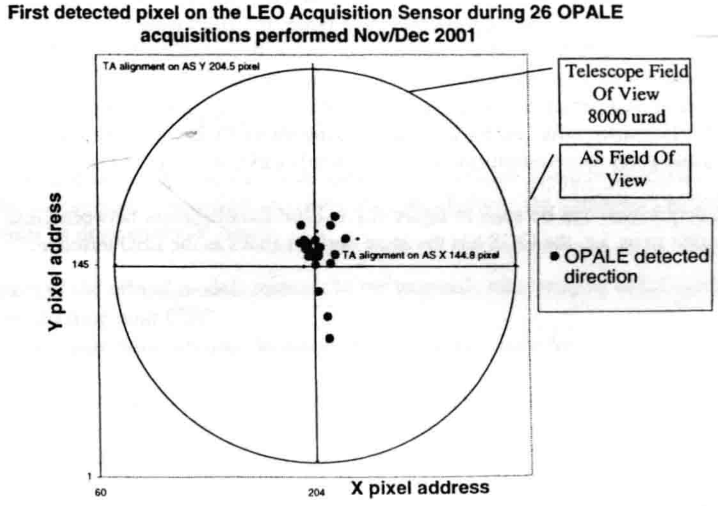

Figure 6.2.1: First detected OPALE direction on PASTEL's acquisition sensor

Figure 6.2.2 indicates the first detected direction of the Pastel by Opale. The open loop pointing error of Opale is considerable, though within the worst case expected and all acquisition attempts were successful. The relatively large error may well be due to the lower accuracies of attitude control and orbit determination in the non-nominal orbit. It is possible to increase the scanned area to cover the complete telescope Field of View in order to maintain a close to one probability of acquisition if the same error is present once ARTEMIS is geo-stationary. The average scanning time with the present scanning parameters is 68 second.

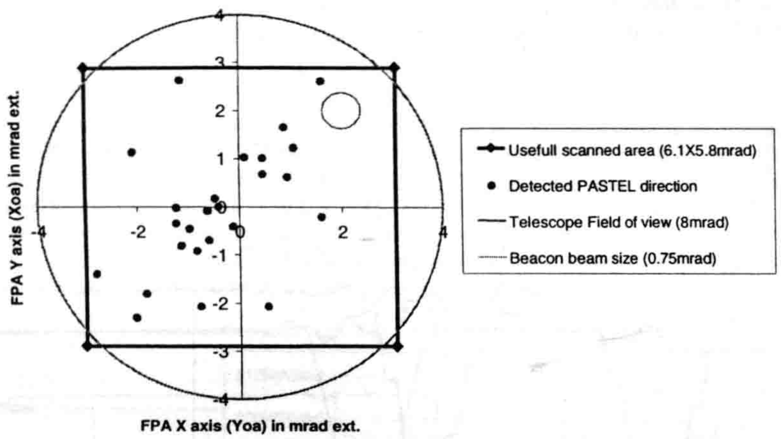

Figure 6.2.2: Useful scanned area versus PASTEL detected direction during 26 PASTEL acquisitions

6.3 Rallying Performances

The first step in the rallying process is to deflect the incoming beam onto the small FOV tracking sensor. If the first deflection misses the TS a second reading on the AS is used to generate a second FPA step command. Any failure in this process will make the LEO terminal go back to waiting scrutinizing its AS and the GEO terminal will resume scanning at the point in the pattern where it would have been if the scan had not been interrupted by a false alarm. False alarms have indeed been observed on the LEO terminal when it is illuminated transiently by the GEO beacon beam and also on the GEO terminal from the Earth background due to an initially too low detection threshold on the Acquisition Sensor. The terminals mode transition design has proven adequate to cope with the so-called twinkling effects.
During in-orbit testing the rallying from the AS to the TS is demonstrated to be highly accurate; the transition is always done in only one step and the spot arrives directly on one of the four center pixels or the adjacent pixels on the TS. All the Sirius acquisitions of Pastel over almost 4 years and the 26 Opale-Pastel acquisitions are plotted in figure 6.3.1 It confirms a highly stable alignment of the optical bench and stable performances of the Fine Pointing Assembly.

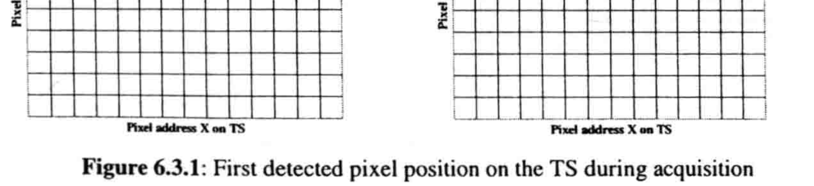

Figure 6.3.1: First detected pixel position on the TS during acquisition

The cooperative process between the Fine Pointing Assembly and the Coarse Pointing Assembly to align the telescope axis with the incoming light can be seen in figure 6.3.2. The example is the GEO terminal, which has the biggest open loop pointing error to be off-loaded. The CPM could not be tested in gravity, which means that this was never tested end-to-end on ground. The in-orbit measurement is fully in line with the simulations on ground.

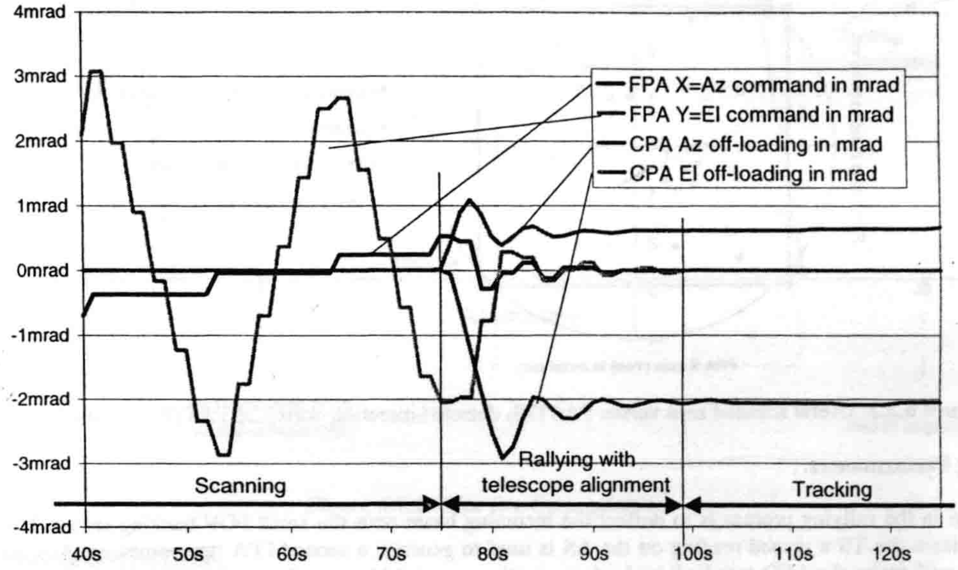

Figure 6.3.2: The cooperative process between FPA and CPA aligning of the telescope axis

The irradiance of the two terminals during the pointing convergence can be seen on figure 6.3.3

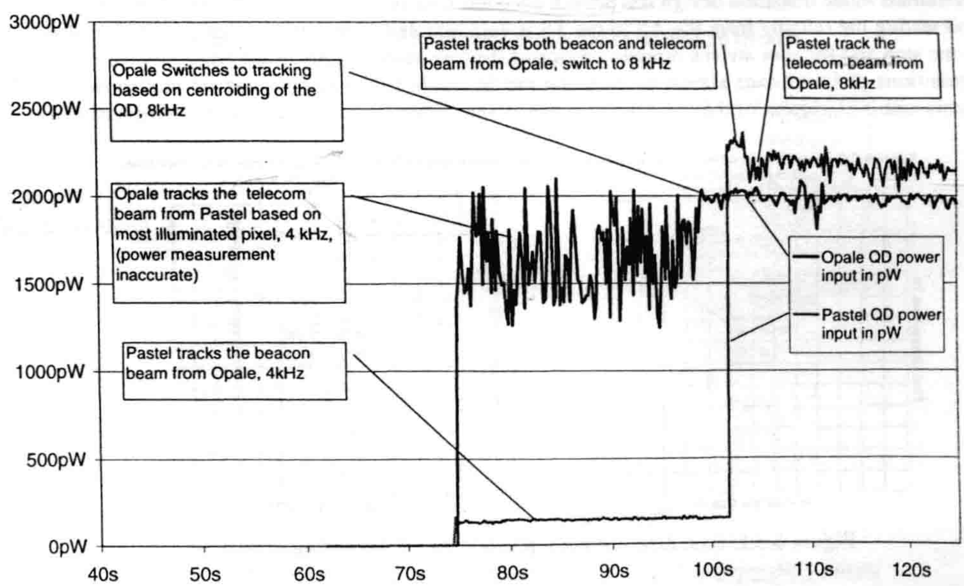

Figure 6.3.3: Received power on the tracking sensor during acquisition and pointing convergence

6.4 Beacon intensity

The beacon beam Far Field Pattern is expected to be flat with and emitted intensity of 8.3±1.9MW/strd in the total divergence of 750μrad. The flatness is confirmed by in orbit measurements by a highly stable irradiance of Pastel during rallying and the mean intensity derived is identical to that expected; 8.3MW/strd.

6.5 Tracking and pointing performances

The tracking performances of terminal A can be characterised by observing the output of the QD sensor or by observing the irradiance of terminal B, which characterises the sum of the tracking and pointing error of terminal A. The terminals provide the QD sensor output, received power and measured tracking error, at 8kHz in a dedicated downlink (the LEO data is sent via the optical link). Unfortunately at the time of writing the LEO data has not been decoded due to a problem with the demodulator in the ground segment, nevertheless these data has been spied at 50Hz.

Figure 6.5.1 shows the intensity emitted by the LEO terminal derived from the received power of the GEO terminal sampled at 8kHz. The average emitted intensity measured over a number of sessions is 571MW/strd with an average standard deviation of 9 MW/strd, which is very stable and in line with predictions.

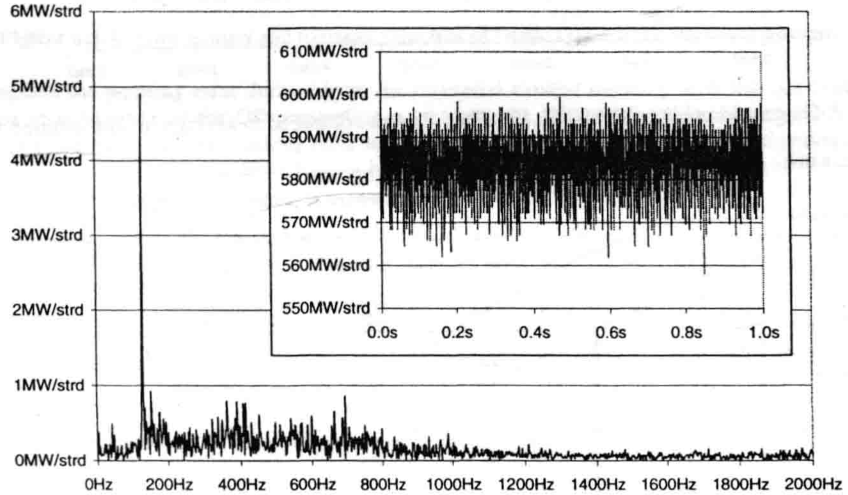

Figure 6.5.1: Time history (8KkHz sampling frequency) and frequency content of PASTEL emitted intensity

Figure 6.5.2 and 6.5.3 compares the emitted intensity with minimum and maximum predictions of the Far Field Pattern. The average bias pointing error based on average expected Far Field Pattern can be estimated to 0.85μrad for PASTEL and 1.5μrad for OPALE , which is below that expected.

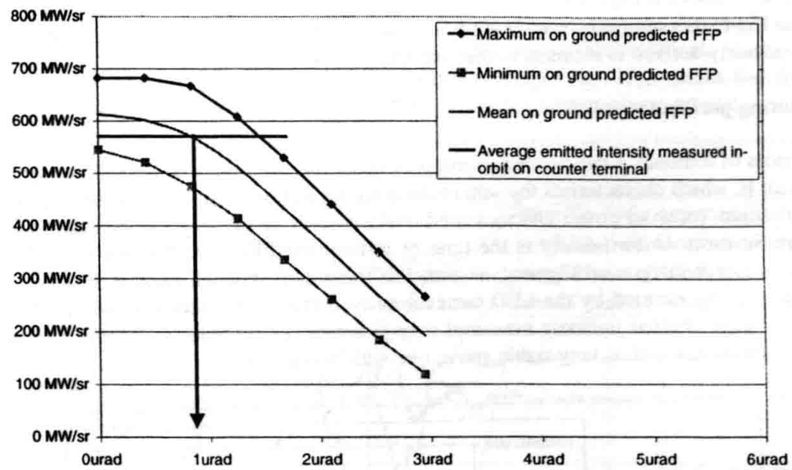

Figure 6.5.2: On ground predicted PASTEL Far Field Pattern compared to average in orbit emitted intensity

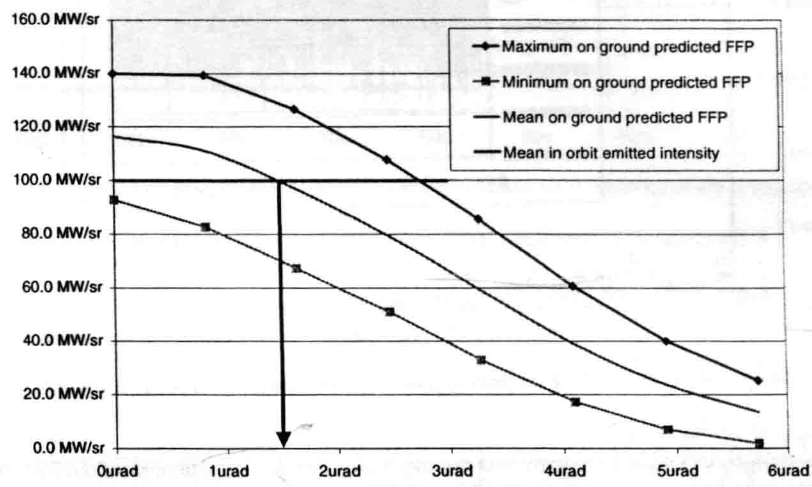

Figure 6.5.3: On ground predicted OPALE Far Field Pattern compared to average in orbit emitted intensity

Figure 6.5.4 shows OPALE's tracking error derived from the QD centroiding output. The a major part of the tracking error derived from the QD centroiding is quantification noise, which is actually filtered out above approximately 350Hz by the relative low frequency response of the Fine Pointing Assembly.

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