MANUFACTURING AND TESTING OF THE ELECTRICAL PART OF SOLAR ARRAY FOR THE CHINA-BRAZIL EARTH RESOURCES SATELLITE – CBERS 2B

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Abstract. *This paper addresses the manufacturing and testing of the Electrical Part Solar Array (EPSA) for the China-Brazil Earth Resources Satellite (CBERS-2B). The EPSA is composed of Silicon type photovoltaic solar cell circuits, and associated cabling, assembled over three carbon-fiber facesheet with aluminum honeycomb core panel structures, each panel structure having 1758 mm x 2581 mm lateral dimensions. The EPSA basic manufacturing processes are described starting with the primary component responsible for energy generation, the well known Solar Cell Assembly (SCA), followed by its serial conection to form the "solar modules" and, finaly, the laydown and cabling over the solar panel structures. The in-process and also acceptance tests results are shown. The electrical performance test results show that EPSA is capable of generating more than 1500 Watt (AM0, 25^{o}C, 1353W/m2), exceeding the minimum power generation requirement. The manufactured EPSA successfully passed the acceptance tests and was delivered for the Brazilian Space Research Institute (INPE) for integration with the CBERS-2B. The EPSA for CBERS-2B was manufactured using equipment and processes developed and qualified with the finantial support of the "Technological Innovation in Small Business Program - PIPE" of "The State of Sao Paulo Research Foundation - FAPESP".*

Keywords: *Solar array, photovoltaic, solar cells, satellite, manufacturing.*

1. INTRODUCTION

The China-Brazil Earth Resources Satellite CBERS is a partnership program that placed Brazil between the nations that developed the strategic space remote sensing technology for Earth environmental monitoring, applications as maps of forest fires and deforestation of the Amazon region and studies in the urban development in big capitals of the country. As one of the results of the CBERS's Program, Brazil is today one of the biggest distributor of satellite images around the world.

The CBERS-2B is the third satellite developed in cooperation with China. Its objective is to replace CBERS-2 and continue the images supply initiated in 1999 with CBERS-1. The CBERS-2B has almost the same equipment configuration of CBERS-2, which is operational in orbit and generating images since October, 2003.

The power generation equipment within the framework of a power subsystem of a satellite or other space application system that requires electrical power is the photovoltaic solar cell array or, namely, solar array.

The CBERS' 2B Solar Array is a deployable single wing type configuration with the following characteristics: three solar panels (inner, center and outer) assembled over a flat composite substrate with aluminum honeycomb core and carbon fibber face sheet structure having 1758 mm x 2581 mm lateral dimensions; one positioning structure (yoke) to support and positioning the solar panels away from the satellite main structure; and a set of holddown and deployment mechanisms.

The Electrical Part of Solar Array - EPSA for the CBERS-2B was manufactured by Orbital Engenharia using equipment and processes developed and qualified with the financial support of the "Technological Innovation in Small Business Program - PIPE" of "The State of Sao Paulo Research Foundation - FAPESP" through the project "Solar Array for Aerospace Applications" (FAPESP Process 01/03041-2). This represents a hallmark in the Brazilian Space Program, since it is the first time that a complete electrical part of solar array was manufactured in Brazil using technology completely developed in house by a private company.

2. MANUFACTURING

The CBERS-2B EPSA was manufactured using monocrystalline silicon solar cells, with 20 mm x 40 mm lateral dimensions, covered with anti-reflecting coating coverglasses. The EPSA was designed to have two main circuits; one to recharge the batteries, named SG1, and another to meet the equipment loads, named SG2. The SG1 was designed to supply 596 W end-of-life (EOL) at 58.1 V, divided into two circuits. The SG2 was designed to supply 510 W EOL at 31.4 V, divided into six equal circuits. The division of the power circuits into sub-circuits is a functional requirement of the digital shunt type used in the power control unit of CBERS spacecraft [Vaz, 2006].

One of the critical equipment for EPSA manufacturing is the *Welding Equipment* used to perform the solar cell electrical contacts (cell interconnect) welding. The welding equipment is composed of the following main parts: a *Welding Pulse Generator and Welding Monitor,* both are commercial of-the-shelf equipment; a *Mechanical Welding Head* composed of a "x-y" table and an electrode head, with linear motions powered by step motors; a Welding Control Unit composed of a Personal Computer, Control Software and other accessory equipment necessary to provide control and real time monitoring and of the welding process parameters.

Another critical equipment for EPSA manufacturing is the *Coverglass Bonding Machine*, used to bond a borosilicate type glass cover slide to protect the solar cells against the particle radiation (protons and electrons) found in the space environment.

Both, the *Welding Equipment* and the *Coverglass Bonding Machine*, as well as other accessory tooling and equipment for EPSA manufacturing were designed, developed and qualified by *Orbital Engenharia*, under financial support of PIPE/FAPESP.

The EPSA main manufacturing processes are:

2.1 Cell Interconnector Welding

The electrical contact between two adjacent serial solar cells is performed using a 12 µm thick silver foil electrical conductor component named Cell Interconnector. The interconnector is welded to the solar cell front side bus bar, and afterwards to the solar cell rear side using the parallel electrodes dc resistance welding process. Figure 1A shows the solar cell with interconnector schematic drawing, while Figure 1B shows a picture of an actual cell interconnector welded to a solar cell front side bus bar.

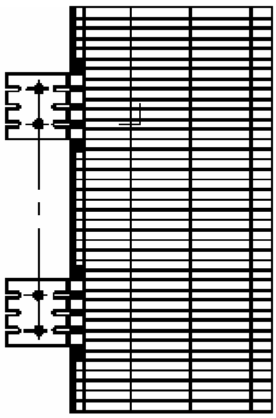

Figure 1a: Solar cell with interconnector.

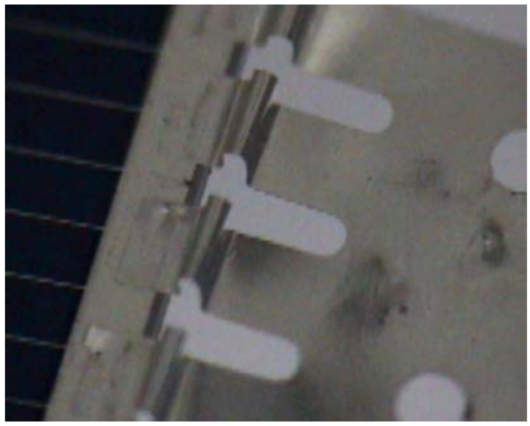

Figure 1b: Cell interconnector welded to the front side bus bar of a solar cell (50x magnification)

The welding process shall meet severe product assurance requirements to avoid solar cell electrical degradation, cell break and interconnector mechanical imperfections. For CBERS-2B 16000 solar cells were welded. More than ¼ of million of welding points were executed. The total manufacturing loss due to the welding process was 0.49%. Every single welding point had its parameters stored in the computer for traceability purposes. Every cell was inspected and electrically tested after interconnector welding.

2.2 Coverglass Bonding

The Coverglass Bonding Process consists of the application of a layer of approximately 20 µm thick space grade encapsulant two component silicon type adhesive over the solar cell surface with the welded interconnector, the coverglass positioning over the cell surface and the means to provide acceleration of the adhesive curing cycle.

As the welding process, the coverglass bonding process shall meet severe quality assurance criteria in order to avoid defects in the adhesive bonding layer, like bubbles for example, coverglass cracks, coverglass mispositioning, inverted coverglasses external side, lateral protruding adhesive, adhesive opacity and other related mechanical defects. The total coverglass bonding manufacturing loss was 0.28%. It is important also to remark that the coverglass bonding adhesive is relatively expensive. One kit with 500g costs approximately US$ 5000,00 FOB. The 16000 solar cells (20 x 40 mm) were covered using 750g of space encapsulant.

2.3 Solar Cell Assembly Electrical Grading

Each solar cell after having the interconnector welded and the coverglass bonded is named Solar Cell Assembly (SCA). All SCAs are electrically tested using a continuous solar simulator, to determine its electrical characteristiscs and current capacity at the specified test voltage, in accordance to a current grade range, named current class. Table 1 shows the current classes used to classify the CBERS-2B SCAs. Figure 2 shows the total amount of SCAs in each current class.

Current Class	Current Range (mA)	Current Class	Current Range (mA)
00	< 245	11	295,1 – 300,0
01	245,1 – 250,0	12	300,1 – 305,0
02	250,1 – 255,0	13	305,1 – 310,0
03	255,1 – 260,0	14	310,1 – 315,0
04	260,1 – 265,0	15	315,1 – 320,0
05	265,1 – 270,0	16	320,1 – 325,0
06	270,1 – 275,0	17	325,1 – 330,0
07	275,1 – 280,0	18	330,1 – 335,0
08	280,1 – 285,0	19	335,1 – 340,0
09	285,1 – 290,0	20	340,1 – 345,0
10	290,1 – 295,0		

Table 1: Solar Cell Assembly (SCA) Current Class. (V_{test} = 480 mV, AM0, 135,3 mW/cm^2, 25^o C)

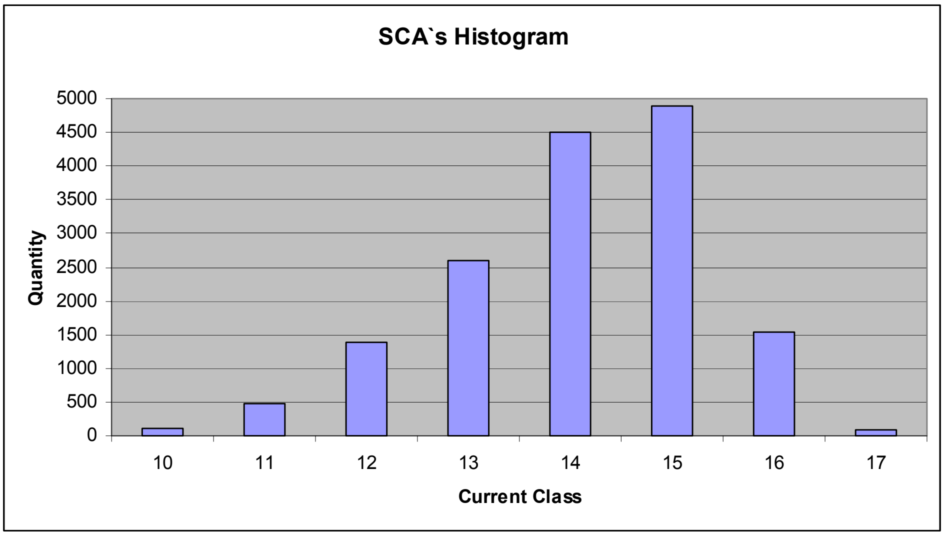

Figure 2: SCAs distribution in the current classes.

2.4 Solar Modules Composition

Solar Modules are a number of solar cell assemblies (SCAs) electrically connected in series. For CBERS-2B it was manufactured the solar modules types indicated in Table 2. The SCAs used to manufacture each solar module shall belong to the same current class in order to avoid solar cell current mismatch and, as a consequence, to increase the electrical losses in the photovoltaic power circuits (SG1 and SG2) [Vaz, 2006].

Module Designation	Module Quantity	Number of Serial SCAs
M7	13	7
M12	14	12
M15	66	15
M47	33	47
M52	8	52
M61	4	61
M81	146	81

Table 2: Solar Module types and number SCAs electrically connected in series.

After manufacturing, all solar modules were submitted to visual inspection and electrical performance test. The solar modules electrical performance test was performed at the Integration and Tests Laboratory (LIT) of the Brazilian Space Research Institute – INPE. Figure 3 shows the typical electrical performance test result (current versus voltage characteristic) of the M81 solar modules. Figure 4 shows a set of M81 modules being prepared for electrical performance test at LIT/INPE.

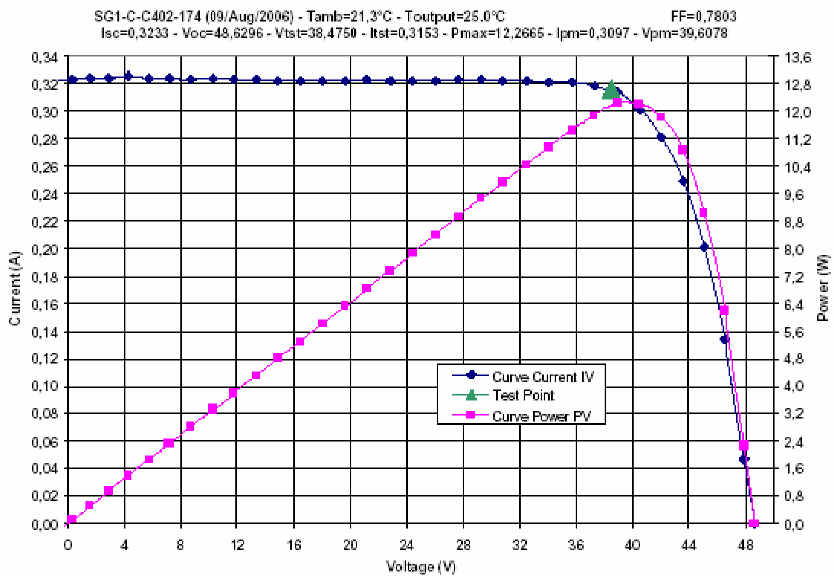

Figure 3: Typical electrical performance test result of the M81 solar modules type.

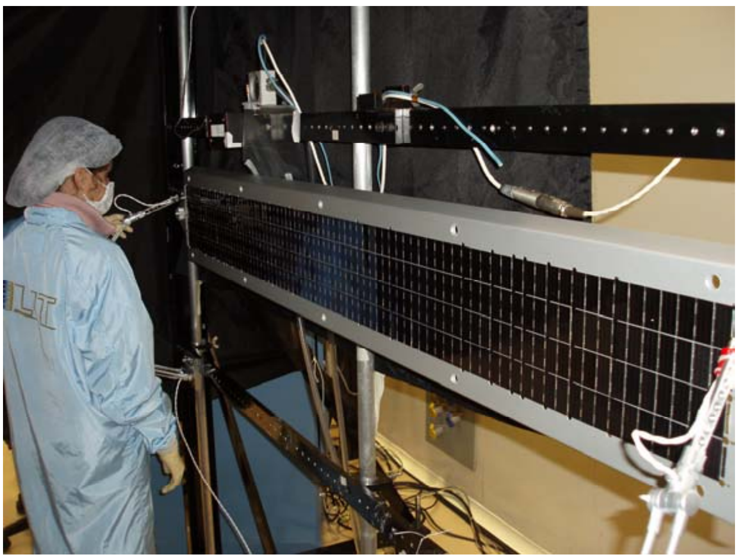
Figure 4: Solar modules M81 being positioned for electrical performance test.

2.5 Solar Modules Laydown

The solar modules laydown process consists of the solar modules bonding over the electrically insulated solar panel structure. The execution of this process must guarantee the exact position of the solar modules over the panel structure, as well as, to avoid permanent mechanical and electrical defects in the solar panels, that may be caused during the laydown process. Some examples of this types of perment solar panel defects are misaligned solar modules, solar cell edge short circuits, mechanical deformation of cell interconnectors and electrical contacts, coverglass break. Broken cells are not allowed. After CBERS-2B solar modules laydown, only 2 coverglasses in 15286 were found with small corner cracks. No cell break was found in the solar panels after manufacturing. Figure 5 shows one of the CBERS-2B solar panels after solar module laydown [Vaz, 2006].

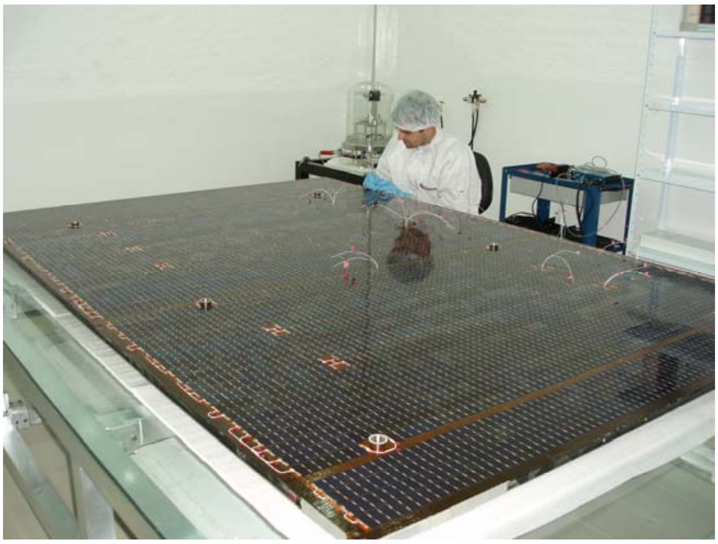

Figure 5: CBERS-2B Solar panel after solar modules laydown.

2.6 Cabling Manufacturing

The solar panel cabling and wing cabling were manufactured using opposite electrodes dc resitance welding process for cabling electrical joints, diode and resistor boards and soldered MTC type connectors. After manufacturing all cabling was submitted to electrical continuity and electrical insulation tests. Visual inspection was performed on all cabling assembly.

3. CBERS-2B EPSA ACCEPTANCE TESTS

The CBERS-2B EPSA flight model was submitted to the acceptance inspection and tests sequence indicated in Table 3. The results of all inspection and test show that the delivered equipment meets or exceed the specified requirements.

Inspection/Test Sequence	Solar Panels	Wing Power and Signal Cabling
Mass Verification	X	X
Visual Inspection	X	X
Electrical Insulation	X	X
Electrical Grounding	X	
Electrical Continuity	X	X
Electrical Performance	X	
Thermal-Vacuum	X	
Visual Inspection	X	X
Electrical Insulation	X	X
Electrical Grounding	X	
Electrical Continuity	X	X
Electrical Performance	X	

Table 3: CBERS-2B EPSA acceptance inspection and tests.

3.1 Mass Verification

The EPSA mass verification was verified subtracting the panel structure mass from the total panel mass after EPSA manufacturing. The mass of the power and wing cabling were verified during the EPSA wing assembling. The EPSA mass requirement was met. The CBERS-2B solar array wing total mass requirement is total mass lower than 56 kg.

3.2 Visual Inspection

Visual inspection was performed to verify the conformance of assembled parts and components to the design and manufacturing requirements and to identify eventual assembling discrepancies or defects caused by workmanship or equipment mishandling. No major non-conformance was opened as a result of the final acceptance visual inspection. Figure 6 shows the CBERS-2B EPSA panel final acceptance visual inspection performed at LIT/INPE.

Figure 6: CBERS-2B EPSA panel final acceptance visual inspection performed at LIT/INPE.

3.3 Electrical Insulation Test

Electrical insulation test was performed in the photovoltaic circuits to verify its conformance to the electrical insulation requirements. The electrical insulation requirement is insulation resistance higher than 10 MΩ at 250 Vdc. The electrical insulation test results shows that all measured values are typically higher than 1 GΩ, thus meeting the minimum required value.

3.4 Electrical Grounding Test

Electrical grounding test was performed in the grounded parts and circuits to verify its conformance to the electrical grounding requirements. The electrical grounding requirement is that all metallic parts or components with 1 square cm or higher shall be grounded. The ground resistance shall be lower than or equal to 100 Ω. The electrical grounding test results shows that all measured values are typically lower than 22 Ω, thus meeting the minimum required value.

3.5 Electrical Continuity Test

Electrical continuity test was performed to verify that electrical connections were performed in accordance to the designed electrical circuits diagrams. The electrical continuity test results show that all electrical connections were done in accordance to the designed circuits.

3.6 Electrical Performance Test

Electrical performance test was executed to verify if the electrical power circuits (SG1 and SG2) meet their minimum specified power requirements. The minimum required total EPSA BOL power is 1500 W. Figure 7 shows a typical electrical performance test result for 2 circuits of SG1 power circuit.

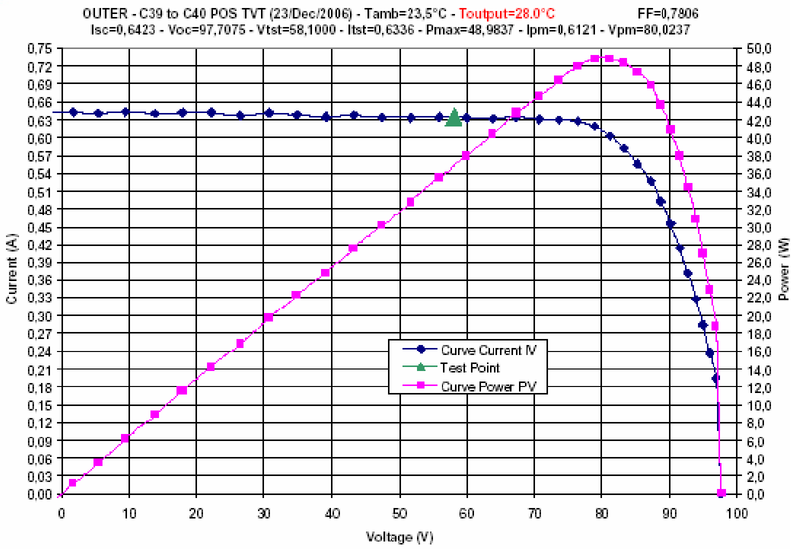

Figure 7: Typical electrical performance test results of 2 parallel circuits of SG1.

The total measured power of SG1 circuit was 833.77 W and for the SG2 circuit 747.65 W, both measurements performed after the thermal-vacuum test, thus meeting the specified requirement (power at operating voltage Pop > 1500 W). The total measured CBERS-2B EPSA power was 1581.42 W, which not only meets but exceeds 5.4% the specified minimum power requirement.

3.7 Thermal Vacuum Test

The Thermal Vacuum Test for the Solar Panels (Inner, Center and Outer) was performed at the LIT/INPE. The main objective of the test was to submit the panels to thermal-vacuum environment that they will experiment in orbit.

The specimens were installed inside the 3x3 Thermal Vacuum Chamber (TVC). The test profile was imposed on specimen by thermal vacuum chamber. The test was conducted according the following specification:

- Chamber pressure: $\leq 10^{-5}$ Torr
- Number of Cicles: 1
- Hot soak temperature: + 70°C
- Cold soak temperature: - 70°C
- Duration in each soak: 12 hours

Besides the specimen, the test set-up was comprised mainly by the TVC and Data Acquisition System.

The results indicate that the test was carried out within the conditions specified. From the visual point of view it can be said that the test specimens showed no signs of deterioration as a consequence of the Thermal Vacuum Test.

All electrical tests were repeated after thermal vacuum test. The CBERS-2B EPSA successfully passed on all test verifications, meeting all specified requirements. Figure 8 shows the CBERS-2B EPSA being installed in the thermal vacuum chamber for test.

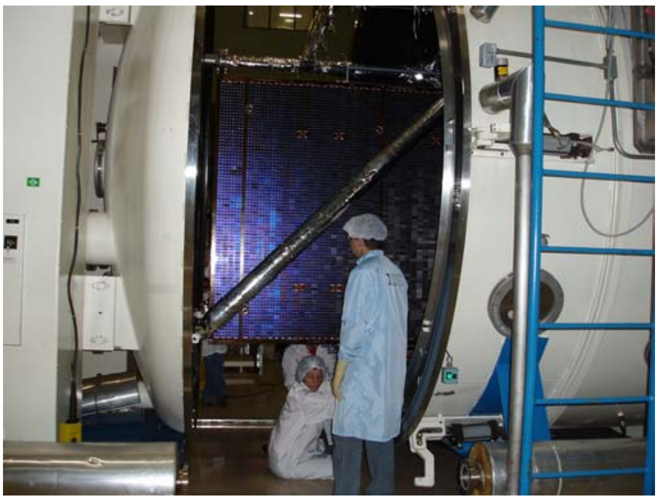

Figure 8: CBERS-2B EPSA being installed in the thermal vacuum chamber for testing.

4. CONCLUSIONS

The electrical performance test results show that EPSA is capable of generating more than 1500 Watt (AM0, 25^{o}C, 1353W/m^{2}), exceeding the minimum power generation requirement. The manufactured EPSA successfully passed the acceptance tests and was delivered for the Brazilian Space Research Institute (INPE) for integration to the CBERS-2B' Satellite. The CBERS-2B EPSA inequivocally demonstrates and confirms that capacity of Orbital Engenharia to develop and qualify technology for application in flight hardware intended one of the most important programs in the space sector in Brazil.

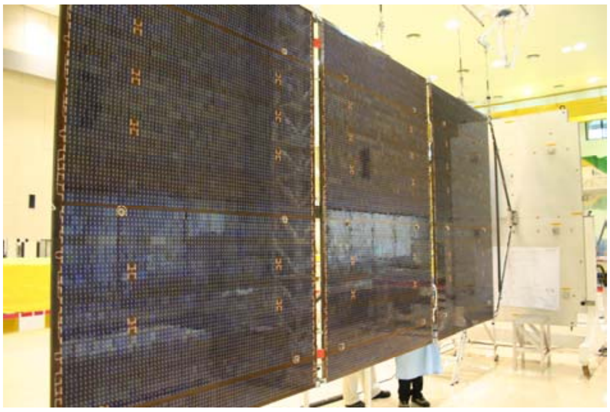

Figure 9a: Assembled CBERS-2B solar array wing – front side view.

Figure 9b: Assembled CBERS-2B solar array wing – rear side view.

5. ACKNOWLEDGEMENTS

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