

## HEAVY MAINTENANCE FOR SOFIA - CHALLENGES IN OVERHAULING AN OLDER AND HEAVILY MODIFIED AIRPLANE

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### Abstract

Having seen eight years of service, NASA's SOFIA – a heavily modified Boeing 747 SP – had to undergo scheduled maintenance and overhaul activities to meet continued airworthiness requirements. The last D-Check was performed while the airplane was extensively modified to become a flying observatory.

The Heavy Maintenance Visit (HMV - NASA terminology) was performed during the second half of 2014 in the overhaul facilities of Lufthansa Technik in Hamburg. This company was chosen for its extensive and proven experience with providing maintenance and overhaul services for Boeing 747 SP airplanes.

The set of task cards was geared towards the "standard aircraft" only. Modifications to the fuselage and in the cabin/aft compartment were mostly excluded from the work package. Most non-standard modifications to the airplane were removed and eventually reinstalled by NASA personnel. In a parallel effort also the telescope proper was maintained while staying attached to the A/C. This work was performed by DSI-personnel (DSI - Deutsches SOFIA Institut) with support from Lufthansa Technik.

During the layover more than 3000 findings were reported. These findings included everything from small out-of-tolerance dents in the fuselage to cracks in two engines, which resulted in an exchange of those engines.

For Lufthansa Technik the main challenges resulted from the ageing aircraft aspect of the SOFIA-airplane. The plane was originally built in 1977 and is now nearly 40 years old. NASA is the third owner and the documentation was not always as complete as desired. Finding spare parts for this type of airplane is another problem-area as they are increasingly hard to find. In a lot of instances existing parts had to be overhauled or refurbished and broken parts newly manufactured in Lufthansa Technik workshops.

The major technical highlights were:

- replacing a cracked frame in the cockpit
- replacing a big fitting in the wing (wing gear support end fitting) which was installed in the wrong orientation and shifted
- rectifying older repair-efforts on the engine pylons

Although NASA is the owner and operator of SOFIA, the maintenance contract with Lufthansa Technik was concluded by DLR Raumfahrtmanagement. The technical content of the contract was defined by NASA, the legal and administrative part was managed by DLR.

### 1. SOFIA – STRATOSPHERIC OBSERVATORY FOR INFRARED ASTRONOMY

SOFIA is a joint project of NASA and the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, DLR). It is an 80/20 partnership consisting of an extensively modified NASA Boeing 747SP aircraft carrying a DLR reflecting telescope with an effective diameter of 2.5 meters (100 inches). The telescope is optimized to collect infrared radiation, and is able to detect energy at a wider range of wavelengths than any other ground-based or space telescope. SOFIA operates at altitudes between 12 and 14 km above most of the atmospheric water vapour which otherwise would absorb the infrared radiation.

#### 1.1. Aircraft System (A/S)

The SOFIA-plane is a modified Boeing 747SP with the airframe number 21441.



BILD 1. SOFIA with open door.

It was delivered to Pan Am in May 1977 and went into service as Clipper Lindbergh. In 1986 the plane was sold to United Airlines and in 1997 bought by NASA.

From 1999 to 2007 the plane was located at the L-3 facility in Waco, TX for extensive structural modifications. A large hole was cut into the fuselage on the left side behind the wing to allow observations of the night sky. A new massive pressure bulkhead was also installed to reinforce the fuselage and to accommodate the telescope. Large sliding doors close the cutout through ascent, descent and on the ground to protect the telescope. In addition, the cabin layout had to be changed for installation of the mission systems, telescope systems and routing of additional wiring.

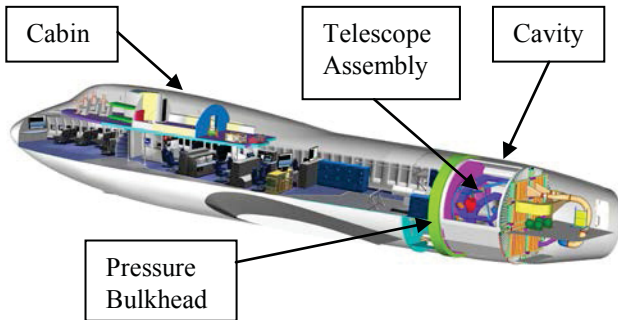


BILD 2. Cabin/Cavity Layout of SOFIA.

An interesting part of the modifications is the rerouting of the control wires from the cockpit to the aft flight controls. Usually the control cables run along the centerline of the plane. With the telescope in the back, the cabling was deflected to the starboard side of the plane, run along the fuselage through the bulkhead and telescope-cavity to the aft compartment and then back to its original position in the centerline of the plane. In a similar fashion all other standard aircraft system-cabling and -installations which are in the back of the plane, like the APU fuel-line, had to be rerouted.

The aft compartment is again separated from the cavity by a bulkhead. Here the electronics and installations for the cavity environmental control system are located.

### 1.2. Telescope Assembly (TA)

DLR concluded a contract in 1997 to design, pre-install and test the Telescope Assembly (TA) in Germany. In 2002 the TA was shipped to the L-3 facility in Waco, TX for integration into the aircraft.

The TA is made up of the optical part in the cavity and the mechanical/electronics part in the cabin of the plane. The optical part consists of three each mirrors and guiding cameras; the mechanical part consists of the spherical hydrostatic bearing, a pneumatic vibration isolation system, a mechanical coarse and an electro-magnetic fine drive system, and several control systems to help keeping the astronomical target in focus.

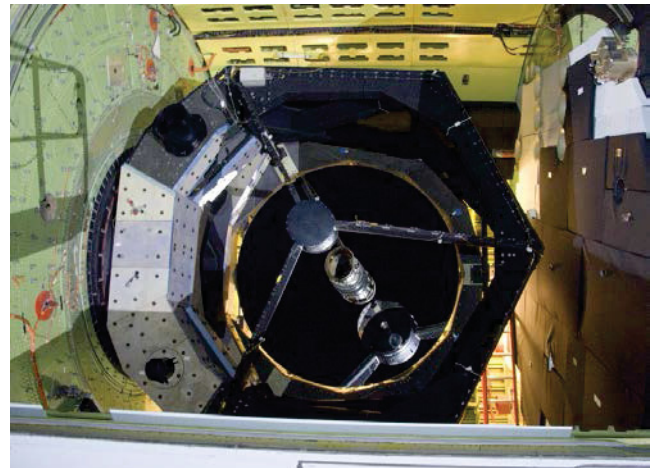


BILD 3. Optical part of TA.

The hydrostatic bearing of the TA is located in the center of the large bulkhead separating the cabin area from the cavity. For ease of operation it is important to keep both parts of the telescope in balance by means of an automated balancing system. The telescope, together with the science instrument, serves as pressure boundary between both areas.

Installations for the TA are located throughout the plane. Electronic units are installed in the nose section and in a rack close to the telescope. Pressure bottles for the vibration isolation system are located in the upper deck and the oil supply and cooling systems for the hydrostatic bearing in the forward cargo bay.

During the same time the aircraft was overhauled, scheduled maintenance and improvements of the TA-systems were also performed. However, these tasks were performed under a separate DLR-contract by personnel of the Deutsches SOFIA Institut (DSI) of the University of Stuttgart with support from Lufthansa Technik.

### 1.3. Mission Systems

SOFIA's mission systems consist primarily of the Mission Communications and Control System (MCCS), the Door System and the Cavity Environmental Control System (CECS).

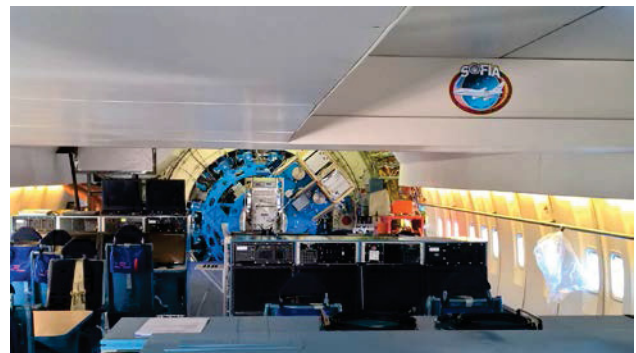


Bild 4. Cabin layout of SOFIA with operator consoles (foreground) and mechanical part of TA (background).

The MCCS provides the network for voice and data communications, science data handling and archiving, interfaces between telescope, science instrument, aircraft systems and observatory controls. It is the primary system to operate the observatory. The MCCS hardware components are located in the nose area of the plane as well as throughout the cabin.

The Door System consists of the two doors of SOFIA, as well as the door drive system. The upper door of SOFIA can be moved and sealed with this system; the lower door will be synchronized with the TA for the larger movements in the line of sight direction (around the length axis of the plane). Cabling and conduits for the door system run from the upper deck to the operator station and on through the bulkhead to the door systems.

With the CECS the cavity is thermally conditioned after a flight. Warm and dry air is blown into the cavity to ensure there is no condensation during descent or on the ground while the primary mirror and the cavity are still cold having been exposed for many hours to the chilling conditions in the stratosphere. Most hardware components of this system are located in the aft compartment behind the TA-cavity. However, controls and the dryer-drum for the air-conditioning unit are located in the cabin and upper deck.

## 2. BACKGROUND – WHY LHT?

In 2010, NASA indicated for the first time their desire to perform a heavy maintenance visit at a renowned Maintenance, Repair and Overhaul (MRO) facility.

A D-Check had been performed during the years of structural modification at the L-3 facility in Waco, TX. However, this D-Check was done on a system-availability basis over a longer period of time. Thus, the older calendar-driven maintenance events began cropping up at a time when SOFIA started to get into a regular observation schedule.

In addition, documentation deficiencies became obvious once SOFIA was operated and flown on a - more or less - daily basis. Maintenance tasks had to be performed at ever increasing levels of complexity and missing or outdated documentation became a problem.

NASA therefore started a market research and came up with several MRO facilities in the US which were still able to perform heavy maintenance on B747 "classic"-type of aircraft. However, none of these facilities had a regular B747SP-customer base. Solid experience with this type of aircraft and also required special tooling was often missing.

At this stage Lufthansa Technik AG (LHT) in Hamburg/Germany came into consideration. LHT provides worldwide MRO-services for a large customer base. Customers are mostly airlines, but also operators of VIP jets and public-sector clients. The LHT-facility in Hamburg is well known for its capabilities in performing aircraft conversions and cabin modifications for both government and private customers.

The proven history of maintaining B747SP aircraft was the decisive reason which eventually led to issuing the

maintenance-contract to LHT. For a period of about 30 years LHT held and still holds service contracts with several operators of this type of aircraft. During the layover in Hamburg there were indeed two instances when another B747SP was placed next to our dock.

The advantages of using the LHT-facility in Germany led to a somewhat unusual contract situation. As NASA is the owner and operator of the SOFIA aircraft, the technical content - the set of task cards - of the Heavy Maintenance Visit was defined by NASA. However, DLR placed and administered the contract with LHT. With this legal arrangement DLR was able to provide a substantial part of its 20%-share of the operational cost without transferring money to NASA. The legal means for this procedural method are baselined in the Memorandum of Understanding between the partners.

## 3. HEAVY MAINTENANCE VISIT (HMV)

In preparation for the HMV, NASA and DLR visited the LHT-facility in Hamburg and LHT-personnel performed first inspections of the aircraft at the SOFIA home base in Palmdale.

For more than a year NASA and LHT defined the documentation for the HMV. A Sharepoint web-site was set up in order to work in parallel on large numbers of documents. Coordination telecons were held at regular intervals as well as meetings in the US and Germany as needed.

A joint team of NASA and LHT identified missing task cards and amended/completed the necessary documentation for the HMV. In total more than 2100 task cards were changed or rewritten to conform to both LHT's and NASA's quality requirements.

In parallel to the technical activities DLR and LHT negotiated the HMV-contract. As the contract had to be laid out to suit legal requirements of both the German government as well as NASA, it took longer than anticipated to finish this task. In addition, budgetary issues with the NASA SOFIA funding in the USA forced the program to delay the start of the HMV for a month. SOFIA eventually arrived in Hamburg June 28, 2014.



Bild 5. SOFIA arrival at LHT.

### 3.1 Arrival and docking

Immediately after arrival a multitude of activities commenced to prepare the plane for docking. An engine run needed to be performed first to check and adjust all parameters of fuel and air flow.



Bild 6. Docking preparation.

Thereafter the plane was towed to the hangar and placed in its docking berth. It was weighed and Center of Gravity calculations were performed before the plane could be lifted for about 3.5 meters. This was necessary to allow for complete coverage of the plane with docking platforms.

SOFIA has a telescope with a mass of 18 tons installed in the back of the airplane. Owing to this weight a special lift configuration had to be used to safely jack the plane to its desired height. Using five jacks instead of the usual three the crew slowly hoisted the plane up to 3.5 meter "altitude". As this is not the standard way of operations, the engineering department performed the necessary calculations and special authorization was asked for and granted.



Bild 7. Jacking of SOFIA.

As a last step the crew moved the work platforms of the dock into position around SOFIA. Now all parts of the plane were accessible for inspections and overhaul tasks.

### 3.2 Inspection

As a first step, NASA-personnel removed all interior installations like observatory electronics and consoles to allow inspections at these locations. In addition, the LHT-trades removed all floor covers, sidewall- and ceiling-panels in the cabin. On the outside, all four engines and the respective engine pylons were removed, as well as the landing gear and all panels which provide access to aircraft structures in the wings, the fuselage and the tail. All cabling and conduits had to be loosened or removed in order to perform the necessary inspections of the aircraft structure. Eventually the cabin was virtually empty with the exception of the telescope and its control electronics in the back of the cabin. At one point during this time it was possible for a person being in the cargo area to look out of the escape hatch of the cockpit and see the cranes moving below the hangar-roof.

Very soon after docking SOFIA started to become sprinkled with a lot of decals. These decals in different colors denoted findings which became apparent during inspections. They included dents in the fuselage, cracks in structures, missing bolts, leaks of any kind ... etc.



Bild 8. FINE decals on the fuselage.

All findings went into a database – the Finding Notification Environment, FINE - and were dispositioned on technical level first and on management level between DLR/NASA and LHT later. All FINE-items with a value below 1000 € or less than 10 man-hours to handle were listed but worked on immediately. All other FINE-items had to be approved by DLR/NASA before they could be rectified. In daily meetings DLR/NASA approved or rejected the LHT-proposals to handle each FINE-item. For example when LHT proposed to repair a certain part and NASA owned an airworthy spare part, the proposal to repair was rejected and the spare part was shipped to Hamburg. In other cases the merits of buying used parts on the world-market were weighed against a proposal to refurbish parts in the LHT-shops.

In total, more than 3000 Fine-Items eventually accumulated in the FINE-database. Of these, the following groups needed significant efforts to rectify:

- two frames in the cockpit: 360RH (repaired) and 380RH (replaced) (RH/LH = right hand/left hand)

- all four engine mounts; with #3 requiring special repair procedures from Boeing
- RH wing gear support end fitting
- all air-conditioning and system-air distribution ducts
- most seat tracks
- all doors
- trimming and adjustment of all control surfaces
- check and partial rerouting of the electrical wiring interconnection system (EWIS)
- exchange or repair of most bearings/bushings/sleeves in wing- and tail-control surfaces
- extensive rework of cabin installations like flooring, insulation mats, sidewall panels.



Bild 9. SOFIA in Dock, engines removed (left).

### 3.3 Modifications of aircraft

From a technical point of view the

- repair of the #3 engine pylon,
- the replacement of frame RH380, and
- replacement of RH/LH wing gear support end fittings proved to be the most challenging overhaul tasks.

In the engine pylon for the #3 engine the LHT-team detected an interesting accumulation of findings. Older cracks were covered by doublers or even a tripler; bolt-holes were found to be either out of size or out of drawing tolerances; repairs showed damages and needed to be repaired again.

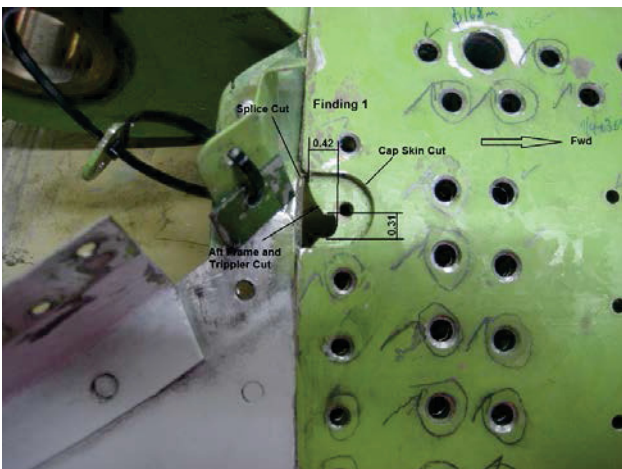


Bild 10. Example of findings on #3 engine mount. Finding is marked, measured and damages are described. Bolt-holes within tolerances are checked.

The LHT-engineering team proposed several approaches for repair to Boeing. None of these were approved and different repair procedures were sent by Boeing. The Boeing-procedures were technically not feasible and LHT sent new proposals to Boeing. It took six weeks to reach an agreement how to perform the repairs and prepare the necessary documentation for airworthiness certification.



Bild 11. New Frame RH380 (green) installed.

Removal of frame RH380 and repair of frame RH360 proved to be straightforward compared to the work on the engine mounts. Both frames were removed and either repaired at the LHT-facility (RH360) or replaced with a new frame sent by Boeing (RH380). However, in order to be able to access the frames, the flight engineer station in the cockpit as well as all the wiring had to be removed.

With a three-shift operation for three weeks LHT managed to de-install and repair/replace the frames.

The RH wing gear support end fitting was a very interesting example of a finding. During structural inspections of the wing to fuselage area, LHT-mechanics noticed the peculiar position of this fitting. They checked drawings and other technical documentation and eventually determined the fitting was installed in the wrong orientation; it needed to

be flipped 180°. In addition, a shifting of the bushing was noted. This kind of finding had never been reported on a B747SP. LHT therefore asked for a procedure to replace the fitting. Boeing sent the procedure which contained the sequence for removing connecting bolts and bearings. They also sent an instruction to pull the beam, which held the fitting at its end, sideways with a force of 1000 pounds; then the beam was supposed to come free. This indeed happened as prescribed. With a sling the necessary force was applied to the beam and the fitting came free.



Bild 12. RH wing gear support end fitting removed.

In order to reach the fitting the mechanics dismantled large portions of this wing-area. In addition, they removed hydraulic lines and control cables until the fitting was accessible. All of this took weeks to complete.

As we had concerns about the same fitting on the LH wing, it was removed and replaced with a new one too.

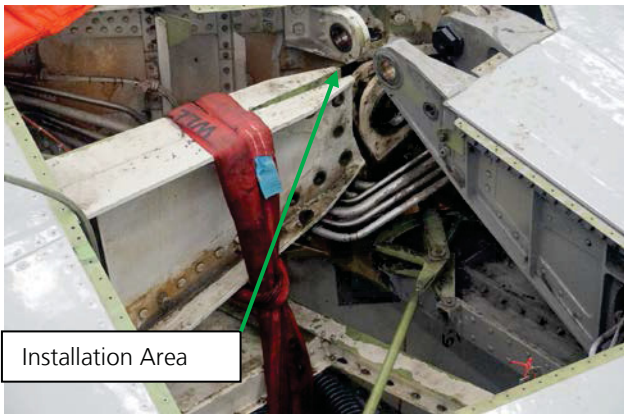


Bild 13. Installation area of RH wing gear support end fitting.

### 3.4 Telescope-Maintenance

The overhaul of the SOFIA-aircraft was restricted to the "standard-"aircraft; e.g. fuselage, wings, engines and standard avionics. Most of the observatory special

modifications were either removed or left untouched by the LHT-crew. However, the layover provided an excellent opportunity to perform scheduled and preventive maintenance, necessary repairs, and multiple improvement tasks on the telescope systems.

The main tasks were:

- Exchange of all air springs and damping elements of the vibration isolation system
- Replacement of three of the four pressure/temperature seal levels that isolate the cavity environment from the cabin
- Maintenance, repair, and improvement of all pressure, hydraulic, and electronic systems
- Exchange of shims for the holding structure of the Secondary Mirror.

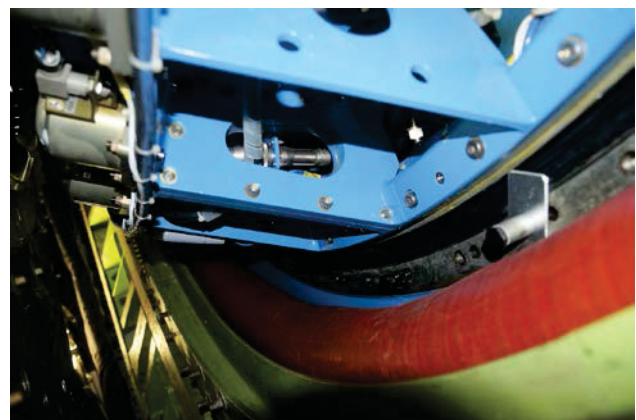


Bild 14. Main seal assembly (in orange) of the TA. This seal is bolted both to the aircraft-bulkhead and to the TA. It provides the first level of protection for the cabin.

All of these tasks were performed in parallel to the aircraft-maintenance by personnel of the Deutsches SOFIA Institut (DSI) with support from LHT.

### 3.5 Re-Installation

After about three months of inspections and modifications, new or repaired parts started to flow back into the aircraft. Every day more insulation matting appeared on the cabin walls, and new reinforced floor panels were installed. In the cockpit, mechanics installed the RH360 and RH380 frames and the avionics group started to reassemble the flight engineer station as well as the rest of the cockpit. Work sections on and in the wings could be closed again. The RH/LH wing gear support end fittings had been replaced and repairs in the tanks and on the fuel lines completed.

Most of the seat-tracks in the aircraft had to be replaced due to cracks and corrosion in their structure. This proved to be a challenge, since all trades - including NASA and DSI - were eager to complete their work in parallel.

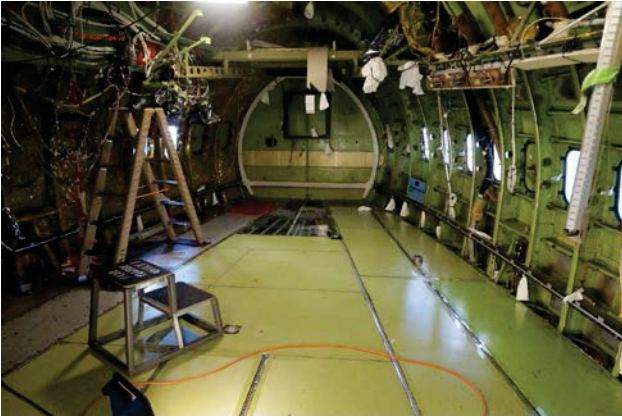


Bild 15. New floor and seat tracks in nose section.

The refitting of the ducting for the air-conditioning system proved to be another challenge. The main ducts had to be replaced with new ones since they showed heavy damages. In addition, the plane had arrived without insulation of these ducts and there were no spares. LHT therefore ordered new ducts and manufactured the required insulation as needed. In an effort to stabilize the temperature conditioning in the back of the cabin, LHT designed and manufactured completely new ducting for the aft section of the cabin. In a last minute effort they were installed shortly before functional checks of the aircraft-systems commenced.

However, in the wake of all of these activities new FINEs were opened every day. They included new findings or were related to the closure of older FINEs. For example, while testing and adjusting the control surfaces, the test crew detected a lot of defect bearings in the hydraulic system of these surfaces. Due to misleading maintenance procedures the bearings had been only partially serviced over a long time. As a result they all had to be removed and repaired or replaced. The replacement of the bearings in the tail section was especially challenging, since the tail had to be stress-free for this task. It needed to be bolstered with a special construction before work on the bearings could be completed.

NASA had shipped a newly overhauled landing gear to Hamburg. LHT inspected and prepared the different parts before installing the landing gear. In a similar way the engines went back to their place on the wings. This happened late due to the long time needed for the repairs on the engine pylons.

It also took a lot of effort to get the six passenger doors back to specification. All seals and most of the moveable parts had already been replaced in the shop. Several days of installation and adjustment were then required before the doors could be handled as described in the maintenance manual.

As one of the late tasks LHT-saddlers reinstalled the cabin panels and floor matting. Especially the side panels needed a lot of work to finish. The SOFIA program didn't have the complete set of the original side panels anymore. LHT therefore acquired surplus panels on the world market. They cleaned and modified them according to the SOFIA layout and eventually achieved a much better paneling than before.

It also serves as a means to reduce noise and improve cabin temperature control.

LHT also replaced the 30 year old seats which were used up to the HMV. They installed surplus business class seats in the nose section and upper deck. Last but not least all lavatory-equipment was replaced or refurbished. With these changes the cabin now looks more like an airliner than a research plane.



Bild 16. Improved cabin interior with new floor matting, side and ceiling panels and lighting.

### 3.5 Acceptance

Once all technical systems were re-installed, test- and verification activities started.

The cockpit-systems had been re-installed and all functions were tested. In a first step the avionics group checked connections and then functions. All electrical wiring was rechecked to verify correct power and signal transmission.

The control surfaces needed to be adjusted and tuned to the activation commands from the cockpit. For days the control surfaces were commanded into every conceivable position. Section by section, all systems were tested and verified. This task took quite a long time, since extensive changes and improvements had been implemented.

Verification of the new landing gear consisted of a so called "gear swing". The purpose of this test is to confirm correct and timely opening of the doors and swinging the landing gears into the correct position.

Once the landing gear tests were finished the aircraft was again towed into the engine hangar for verification of engine performance, control functions and fuel distribution.



Bild 17: Gear swing of nose gear

These activities led to a new rush-in of FINE-items. Every discrepancy to the manuals or test-procedures was noted and eventually corrected.

This phase of the layover was especially challenging for all parties, since some loose ends just didn't come together. There were fuel and oil-leaks, a burnt-up motor in one of the landing gears, ill-fitting flight controls, a spare unit which didn't work, and last but not least bad weather which prevented final acceptance of the plane.

Eventually all systems reported "Go" and the required check flight could be conducted. During an eight hour flight across northern Europe all flight-systems were tested and verified.



Bild 18. Flight crew preparing for check flight

In parallel to these activities, QA-personnel of NASA and LHT went through the documentation and checked whether all FINE-items had been dispositioned and closed off. In the same manner management of all parties checked for open issues in order to complete the contractual paperwork.

Again, several new findings needed attention after the check flight. The LHT-crew worked overnight to resolve all issues and finally cleared the plane for the return flight to the USA on December 14, 2014.



Bild 19. SOFIA taking off for the return flight to USA

#### 4. CONCLUSION

SOFIA stayed nearly six months at the LHT-facility in Hamburg. The combination of the unexpected findings described above and wear and tear in an ageing aircraft led to this long layover. Although the long duration provided for negative repercussions on the science side, the program as a whole gained from this HMV.

From a maintenance point of view the plane is (nearly) new. Corrosion was not a real issue and most of the movable parts or parts in high-usage areas are now either new or refurbished. In addition, the documentation is now in a much better state than it was before. More than 2000 task cards and entries in the maintenance manual were corrected, updated, or added.

As happens so often with SOFIA, all parties learned something new about their own procedures:

- LHT had to deal with a major first-ever technical finding (RH Wing gear support end fitting) and a customer (NASA) with different ways of discussing and approving technical issues.
- NASA learned a lot about inspections ("frustrating" thoroughness) and organizing maintenance tasks acc. to location instead of maintenance manual numbering system.
- DLR after all learned how to adapt the standard research and development contract applied to space research to the contractual framework which is usual in the international MRO-business.

The SOFIA program can now concentrate again on performing successful science flights.



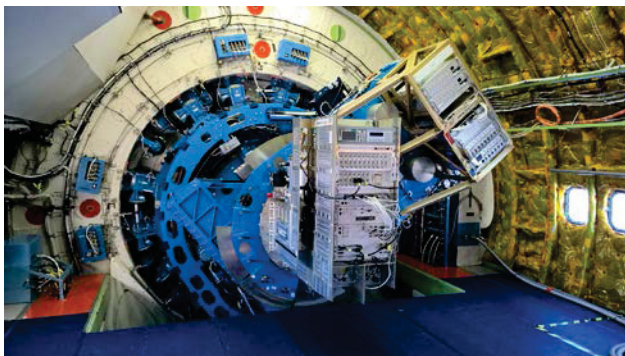


Bild 20. German science instrument GREAT on SOFIA

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## 6. PICTURE REFERENCES

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- [3] Bild 10: LHT
- [4] Bild 4 - 8; 11 - 18; 20: H.T. Hammes, DLR
- [5] Bild 19: DLR