PARAMETRIC STUDIES FOR THE STRUCTURAL PRE-DESIGN OF HYPERSONIC AEROSPACE VEHICLES

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ABSTRACT

The Space Launcher Systems Analysis Group (SART) of the German Aerospace Center DLR is involved in various internal and multilateral hypersonic vehicle studies. Hypersonic transportation vehicles require structural analysis already in an early design phase to enable accurate structural mass estimations. A program for preliminary structural analysis of hypersonic transportation vehicles will be presented here. The program HySAP serves for rapid, parametric trade studies. The requirements will be derived and the program structure described in detail. Furthermore, first application cases for the program version will be discussed.

1. INTRODUCTION

The system analysis for aerospace vehicles comprises a large number of different disciplines, including structural design and mass estimation. In preliminary vehicle studies often empirical/statistical methods are being used for estimation of structural mass. These methods may be very reliable and accurate if a corresponding database is available and a new configuration resembles the vehicles in the database. For instance, the structural mass of a conventionel subsonic passanger aircraft can very easy and with a high level of accuracy be predicted with stucrtural mass data of existing and previous aircrafts. Also structural masses of conventional rocket launchers can be derived from existing launchers without making too large errors. For hypersonic vehicle concepts however, the benefit of such methods is limited. Firstly, virtually no statistical database for high speed transportation vehicles exists, since except of the Space Shuttle and Buran no hypersonic transportation vehicle has ever been developped or built. In addition, the configuration of a hypersonic vehicle often is very complex and unique, and can hardly be investigated with data from other vehicles, that differ significantly in configuration and structural layout. If, for example, the structural mass of a hypersonic vehicle is being investigated by different empirical/statistical tools or different design teams, deviations of 50% or more are not uncommon. However, precise mass estimation is important not only for performance predictions. For hypersonic vehicles the structural mass may also decide if the mission the vehicle is being designed for is even possible. Thus, it becomes clear that structural analyses are required already at a very early design level for a hypersonic transportation vehicle.

2. REQUIREMENTS FOR A STRUCTURAL ANALYSIS PROGRAM IN HYPERSONIC VEHICLE PRELIMINARY DESIGN

As usual in preliminary system analysis, tools are required that are suited for parametric studies with rapidly changing configurations while providing reasonable accurate results with low modelling and calculation times. For analysis of rocket launcher structures the tool LSAP (Launcher Structural Analysis Program) has being developped by SART in the past. The tool models a launcher as bending beam with rotational symmetry and uses analytical methods for structural analysis. It is very suited for investigation of rocket launchers with offering fast and flexible modelling capabilities and very fast computation times. Integral and non-integral tanks/structures as well as different structural design concepts are available.

For hypersonic vehicles however such simple analytic tools are less suited. Fig. 1 shows different vehicle concepts under investigation in DLR-SART or within EU projects with SART involvement. Representatives for different classes of high speed transportation vehicles are displayed. This includes configurations with conventional wing/body layout, more complex waverider-shaped designs or airbreathing vehicles with a high level of integration of propulsion system and structure. Typical challenges for structural analysis include propellant tank design and integration in complex vehicle shapes, propulsion or thermal protection system (TPS) integration, and in general efficient and light-weight structural design for vehicles shapes with poor structural-mechanical properties (e.g. low construction height, large surface-to-volume ratios).

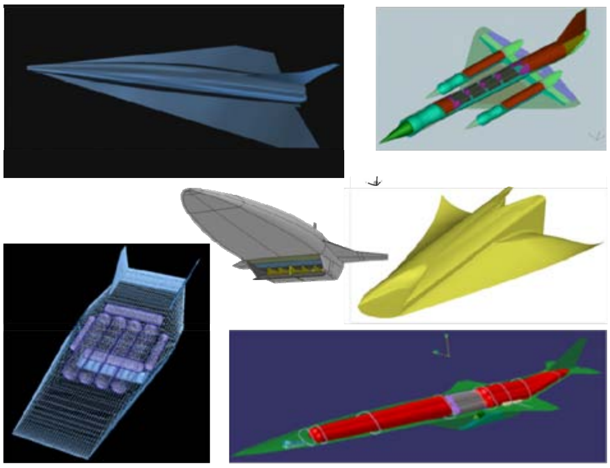

Figure 1. Different high speed transportation vehicle designs with DLR-SART involvement

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To cover these different concepts with their high geometric complexity levels it is appropriate to apply numerical methods rather than analytical ones. By doing this it is possible to take advantage of the rapid decrease in compuer calculation times in the recent years together with improved parametric modelling capabilities of modern finite elment analysis (FEA) software. Especially the ANSYS Parametric Design Language (APDL) provides an excellent environment for fast parametric modelling of even complex structures.

The system analysis on a preliminary level not only demands fast modeling and computation times. It is also required that tools may be applied by users that are not experts in the particular discipline. Therefore, the input has to be simple and easy to understand and the tool needs corresponding "fail safe" capabilities in order to prevent users from defining unreasonable models and inputs.

Finally, the limited amount of time that can be spent on developments of individual tools in the system analysis also requires tool development and testing in a comparatively short amount of time, which prevents from incorporating too high levels of detail.

3. HYSAP – HYPERSONIC VEHICLE STRUCTURAL ANALYSIS PROGRAM

According to the requirements as derived in the previous section, the Hypersonic vehicle Structural Analysis Program (HySAP) has been developed. HySAP combines Fortran pre-processor and Fortran sizing routines with the ANSYS Mechanical program system. Currently, the development of HySAP is not finished, but a preliminary version is in the validation phase.

3.1. Program Structure

The Fortran based pre-processor HySAP creates an APDL input file for ANSYS. This file, named 'ansysinput', contains all commands for geometry generation, loads application, meshing, solution and post-processing as well as iteration step and load case information. Once launched, ANSYS is able to perform all operations as provided in the input file fully automatic. The structural sizing however will be done outside ANSYS with the help of a separate Fortran sizer. This tool is being called by ANSYS after finishing a solution. The sizer validates the structure against several strength and stability failure modes and adapts wall thicknesses if necessary. ANSYS then restarts the modelling and computation process with the adapted wall thicknesses. This procedure is repeated several times and for several load cases until convergence has been reached. No user intervention is required. Fig. 2 shows the general program organization.

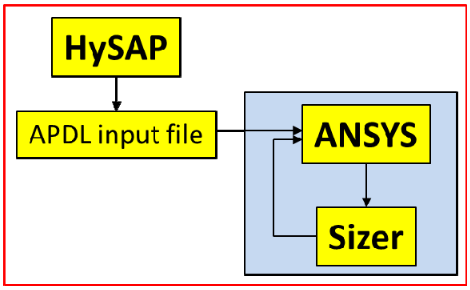

Figure 2. HySAP – general program organization

Four different operation modes are available. In the first one only geometry modelling is performed. This gives the user the opportunity to visually inspect the vehicle and to rearrange the geometry, if necessary. In further modes geometry meshing, single calculations, and finally the complete iteration cycle is added.

3.2. Input Processing

HySAP is connected to other system analysis tools available in DLR-SART in order to receive input data from the particular disciplines. Aerodynamic pressure distributions as well as the surface mesh are provided by the DLR-code Hotsose. Hotsose generates hypersonic aerodynamic data sets by using inclination based methods. A panel code derived from the NASA program PanAir [1] is planned to be connected to HySAP as well in order to provide low speed pressure distributions. Propellant tank geometry, propellant mass and pressure data will be generated by the SART-tool PMP (Propellant Management Program), while subsystem masses and c.o.g.'s will be provided by STSM (Space Transportation System Mass). Furthermore, the 1D thermal analysis code TOP2 will be connected to HySAP in the future to estimate TPS thickness.

User defined load cases will be read from a separate file. For each load case, accelerations or the utilization of inertia relief capability have to be specified as well as the use of the present aerodynamic pressure distribution. Additional discrete forces or moments may be defined by the user by just indicating the geometry key point numbers, where the loads are to be introduced in the structure and the forces and force/moment magnitudes. If fixed accelerations are imposed rather than inertia relief, the mounting conditions have to be specified. This is simply done by providing the subsystem(s) identification number(s), where the vehicle is to be mounted on (e.g. the main gears for a landing load case or the main engine for a vertical lift off case). For typical vehicles and trajectories, sets of standard load cases are available.

Structural data and material selections have to be provided by the user as well. This includes data such as rib, spar of frame positions, skin or web stiffening concepts and initial wall thickness. Materials may be selected for structural groups such as wing ribs, wing spars, wing skin etc. separately.

FEM (Finite Element Methods) specific parameters generally do not have to be specified by the user. This allows also users with no FEM experience to apply the program. The only exception is the average element size, which can be adjusted in order to control the calculation times.

3.3. Geometry Modelling

The vehicle outer mold line as provided by the aerodynamic mesh is segmented in components (e.g. fuselage, wings, fin etc.). This segmenting will be taken over by HySAP. The aerodynamic mesh is transformed to an ANSYS geometry mesh with lower resolution, which may be seen in Fig. 3.

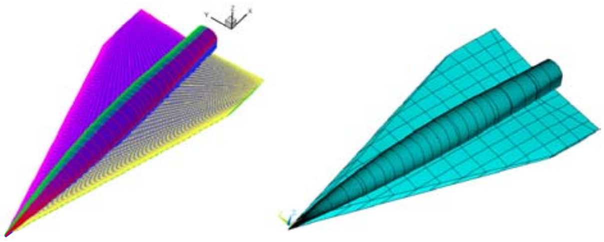

Figure 3. Aerodynamic (left) and ANSYS geometry mesh

The geometry contour will be defined by rib-spar or frame/bulkhead-skin junctions. Key points will be generated at these junctions. Additional contour definition key points will be generated automatically, if necessary, to better match the aerodynamic contour. With the help of the key points defined, areas will be generated such as rib, spar or skin areas. Fig. 4 exemplarily shows a geometry key point mesh of a double delta wing (top) and the corresponding areas with the skins removed (bottom).

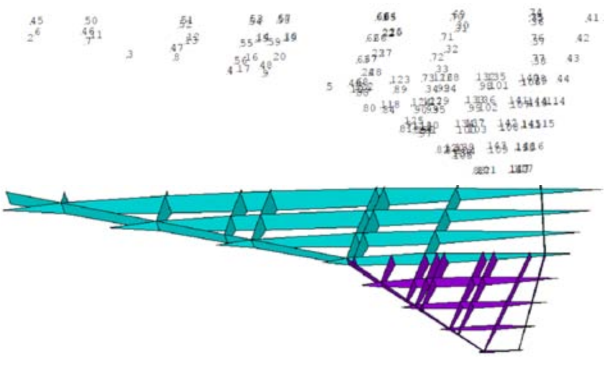

Figure 4. Key point mesh and areas (skin removed)

Initially, wing and fin components will be modelled. Ribs and spars will be generated as indicated in the input file. Additional spars will be generated automatically at the rib/leading edge junctions. Subsequently, the fuselage is being modelled and the wings and fins attached. Frame/bulkhead stations will be created at user defined positions and additionally at wing-fuselage or fin-fuselage spar attachment points. The bulkheads will transmit wing bending loads though the fuselage rather than wing-box carry-through constructions. The latter type of load transmission is not available in HySAP since hypersonic vehicles usually demand large, fuselage mounted and pressurized propellant tanks that cannot be intersected by a carry-through. After fuselage generation, the propellant tanks will be modelled. Cylindrical and conical tanks in single- and multi-lobe design can be modelled, as shown in Fig. 5. The geometry is completely being read from PMP output files.

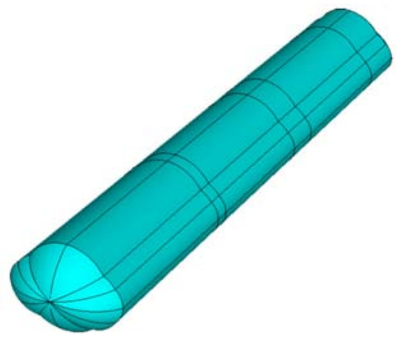

Figure 5. Multilobe tank as generated by HySAP from PMP geometry data

Bulkhead-tank intersections will be considered with Boolean operations and corresponding cut-outs in the bulkheads will be generated. An example may be found in Fig. 6. Currently, the bulkheads are completely connected to the tanks. Consequently, they support the fuselage in carrying longitudinal bending loads. Alternative mounting concepts are planned to be introduced in further modifications.

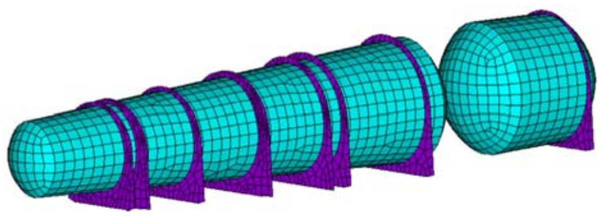

Figure 6. Tank/fuselage connection

All main structural members such as ribs, spars, bulkheads or skins are defined by areas. All of the areas will later be meshed with shell elements. Stiffening of the areas may be selected by the user. However, currently only stringer stiffening is available. Generally stiffening is modelled with a “smeared” approach, as often done in preliminary analysis. This is performed by assigning two different layers to each area. The first one represents the “real” skin, while the second one represents the smeared stringer layer. An approach derived from [2] and [3] has been applied to model the stringer layer. According to stringer spacing and thickness equivalent densities and Young’s Modulus will be computed.

3.4. Loads Modelling

Several groups of loads may be applied: aerodynamic pressures, tank static and hydrostatic pressures and accelerations, which yield inertia loads. The latter includes the loads from the structure itself, as well as from subsystem masses. Finally, also user-defined point loads or moments can be introduced.

Aerodynamic pressures will be read from a file and directly applied to the structure during the geometry generation process. A rather simple method has been implemented to interpolate the aero-mesh to the structure mesh. This may lead to minor deviations in the total force and moment balance. The total lift on the FE model usually differs only by 1-2% compared to the sum of the aerodynamic pressure distribution. The drag however may show larger deviations, especially for configurations with large nose or leading edge radii. This problem is addressed by just "scaling" the pressure distribution. The difference will be applied as additional nodal forces to the external surface to match the original loads. For enabling this procedure, an initial FE solution is performed by ANSYS for each load case involving aerodynamic loads. No other loads are considered in this initial solution. Thus, the resulting reaction forces resemble the total aerodynamic forces.

Propellant static pressures will be read from PMP files and applied to the internal surfaces of the tanks. Also pressurized passenger cabins may be modelled in this way. Additionally, hydrostatic pressures will be computed according to the present accelerations and the propellant mass. The corresponding fluid surface position and attitude will be computed correctly as shown in Fig. 7.

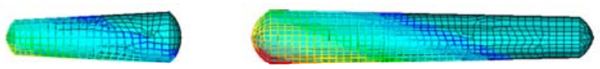

Figure 7. Hydrostatic tank pressures resulting from axial and normal accelerations

Subsystem masses and positions will be read from STSM output files. In HySAP, all subsystems will be modelled as mass points. The introduction of their inertia load is being realised with Multi-Point-Constraint (MPC) elements. Fuselage subsystems will be attached to the nearest forward and aft bulkhead with several MPC's. Wing systems such as gears instead will be connected to up to four rib/spar junctions. Fig. 8 shows subsystem mass points with their MPC attachments for a vehicle configuration. The vehicle is seen from the top and the structure has been removed in this figure. The most upper and lower mass points represent landing gears accommodated in the wings. Great care has to be taken concerning automated definition of number and attachment positions of the MPC's. During tool development the MPC's often led to problems in the FE solutions and their results, especially when combined with the ANSYS inertia relief mode. Most of these difficulties could be solved by assuring, that a fuselage node is not connected to more than one MPC.

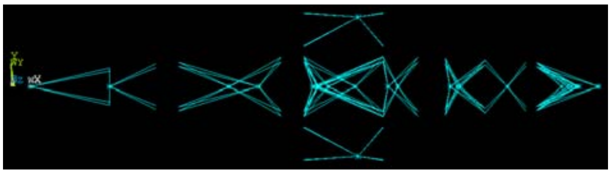

Figure 8. Subsystem mass points and MPC attachments

Furthermore, user-defined point forces or moments can be applied, if demanded. The user just has to specify the geometry key point, load type (e.g. Fx, Fy, Fz, Mx etc.) and magnitude. Mounting conditions can be applied in a similar way. For inertia relief computations, no mounting conditions need to be specified.

3.5. Meshing

Two-layered shell elements will be used for the complete model. The only exceptions are the MPC and point elements for subsystem mass definition. The meshing scheme is not predefined due to the complex geometry. Instead, the "free meshing" capability of ANSYS is exploited. The average element size can be specified by the user, thus allowing for computation time and accuracy control. ANSYS is instructed to use quadrilateral shell elements for meshing, whenever possible. A small number of trilaterals is unavoidable. However, when the thickness to area ratio becomes too small (because the sizer reduces the wall thickness), ANSYS dramatically increases the number of trilaterals, which often leads to program aborts due to meshing problems. This problem could at least partly be solved by using the "mesh by ascending order" and "mesh expansion" features of ANSYS.

3.6. Structural Analysis and Sizing Strategy

Structural sizing is done by a separate Fortran-based sizing tool. After every iteration step the sizer will be called by ANSYS and performs the structural sizing. In the next iteration step, ANSYS will apply the adapted wall thickness to the structure. The data exchange between ANSYS and Fortran has been realized on a file basis.

The structure is segmented in 'optimization components'. Each of these components will be sized individually and assigned a uniform wall thickness. For wings, each geometry area forms an optimisation component, which means that each skin, rib or spar panel will be sized individually. For fuselages and tanks instead, the whole section between two bulkhead stations is defined as optimisation component and assigned a uniform thickness. This approach leads to conservative structural mass estimations and may be adapted in further program modifications.

Currently, Von Mises stress and several buckling failure modes for stiffened and unstiffened plates are available. Design curves can be found in [4] and other sources in order to evaluate the buckling coefficients. Only quadrilateral areas will be sized. However, each model usually includes a small number of triangular areas (< 1% of all areas). Since no appropriate design curves are available for them, the wall thicknesses of the neighbouring quadrilateral area with the highest wall thickness will be taken for a trilateral.

No optimization procedure is implemented so far and only skin and stringer thicknesses will be varied during the iteration process. The procedure of sizing each optimization component individually will not ensure the finding of any optimum. However, proper selection of minimum and maximum allowable wall thicknesses and defining relationships between components yields reasonable results. Nevertheless, the later implementation of an optimisation procedure is required.

4. INITIAL APPLICATIONS: THE SPACELINER AND ATLLAS-II

Two completely different hypersonic vehicles will be the first application cases for HySAP. The first one is the SpaceLiner, which will be discussed in the next section. The second vehicle is the reference configuration of the EC co-funded ATLLAS-II study. The latter one is a Mach 5-6 airliner with air-breathing, fuselage- and wing-integrated turbo-ramjet engines. It will not be discussed here since its configuration is still under definition.

4.1. The SpaceLiner

The SpaceLiner is a concept for ultrafast antipodal passenger transport [5]. The concept is being investigated by DLR-SART since 2005 and also is one of the reference configurations in the current FAST20XX and CHATT EC-FP7 projects as well as in the DLR internal THERMAS study.

The SpaceLiner is a vertical lift-off, rocket propelled, suborbital passenger transportation system with the launch being assisted by a liquid propellant booster. The main stage, also denominated "Orbiter", performs the range flight in a gliding mode. The rocket propulsion system and the booster only serve to build up the initial velocity of about 6.5 km/s. The reference mission carries 50 passengers from Europe to Australia and vice versa. The total flight time from launch to landing is about 90 minutes. Also other missions with lower flight times are under investigation. Fig. 9 shows the SpaceLiner2 at booster separation and the latest version of the SpaceLiner7, which is currently under detailed investigation.

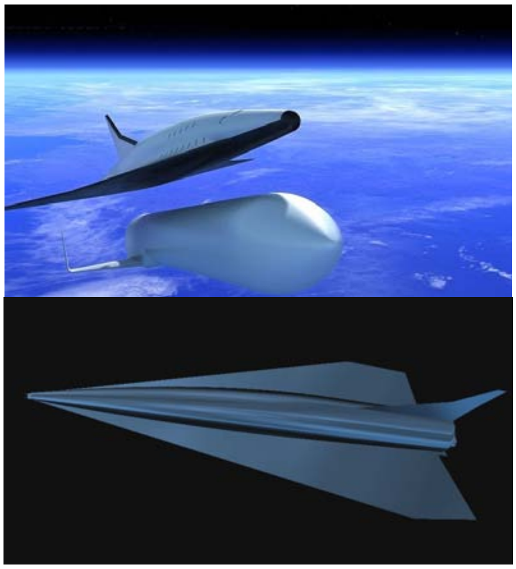

Figure 9. SpaceLiner2 at booster separation (top), potential design for SpaceLiner7 "Orbiter" (bottom)

The SpaceLiner Orbiter is equipped with a separate passenger stage, which is encapsulated in the vehicle main structure. A preliminary design is shown in Fig. 10. The stage serves as a rescue vehicle in the case of a catastrophic accident and can be ejected with the help of small solid rocket boosters. This concept shall account for the comparatively low reliability of rocket launchers in contrast to conventional passenger aircraft equipped with air-breathing turbo engines.

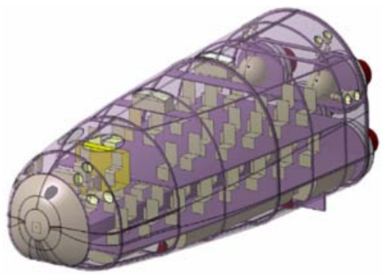

Figure 10. Potential early design of SpaceLiner rescue capsule

The SpaceLiner concept poses several challenges for the structural design. First of all, the enormous heat loads require thick thermal protection systems (TPS). Preliminary 1D TPS sizing studies revealed that in fact the TPS integration significantly reduces the remaining construction height for the structure, thus leading to a heavier structural mass [6]. Detailed TPS/structure integration studies and hot/cold structure trade-offs need to be performed in order to find satisfying solutions. A second major concern is the integration of the rescue stage, with three different concepts having been proposed. Finally, also the availability of sufficient fuselage volume is an issue, since in addition to the passenger stage a large amount of liquid hydrogen and oxygen have to be stored in pressurized tanks.

Initial structural investigations had been performed before HySAP development and published recently [7]. This includes a preliminary wing design and simplified structural dynamic analysis, as shown in Fig. 11. Detailed parametric investigations and trade offs will be the next step.

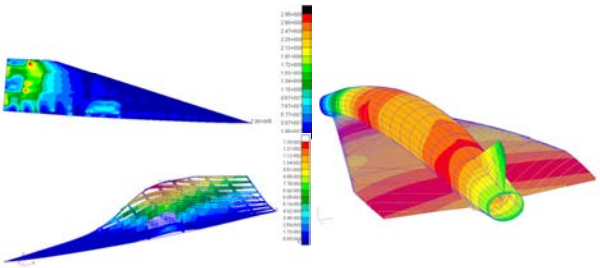

Figure 11. Preliminary wing structure analysis and structure-dynamic investigations as published in [7]

4.2. Initial HySAP Investigations

The development of the initial HySAP version could not be finished early enough to present detailed results of SpaceLiner structural analysis here. Fig. 12 shows Von Mises stress distribution after several iteration steps from the first validation runs of HySAP.

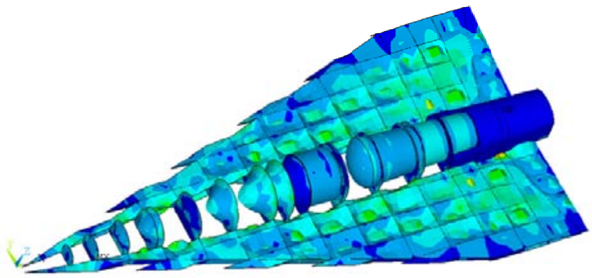

Figure 12. Von Mises stress distribution in the SpaceLiner7 structure

5. CONCLUSION AND OUTLOOK

A parametric structural analysis tool named HySAP has been developed. The requirements have been derived. The program structure and the used methods have been described. The SpaceLiner, which will be one of the first study vehicles for HySAP, and its challenges for structural analysis have been discussed. Since the development of HySAP could not be finished until publication of this paper, no results can be presented here.

The next steps will be to finish and validate the initial HySAP version. HySAP will then be applied for the SpaceLiner and ATLLAS-II reference vehicle. In future tool modifications an optimization procedure will be implemented in HySAP and the modeling and structural analysis capabilities will be improved in order to increase the flexibility of the tool.

6. ACKNOWLEDGMENTS

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Further information on FAST20XX can be found on http://www.esa.int/fast20xx.
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Further information on ATLLAS II can be found on http://www.esa.int/techresources/atllas_II.

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