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► **To cite this version:**

Sven Weikert. Space Applications Subject to Optimal Control and Sensitivity Analysis. SADCO Kick off, Mar 2011, Paris, France. inria-00585877

HAL Id: inria-00585877

<https://inria.hal.science/inria-00585877>

Submitted on 14 Apr 2011

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Space Applications Subject to Optimal Control and Sensitivity Analysis

Sven Weikert

SADCO Kick-Off Meeting

Paris, March 3-4, 2011



Outline

1. Company facts & figures
2. ASTOS software
3. Optimal control and sensitivity analysis for space applications

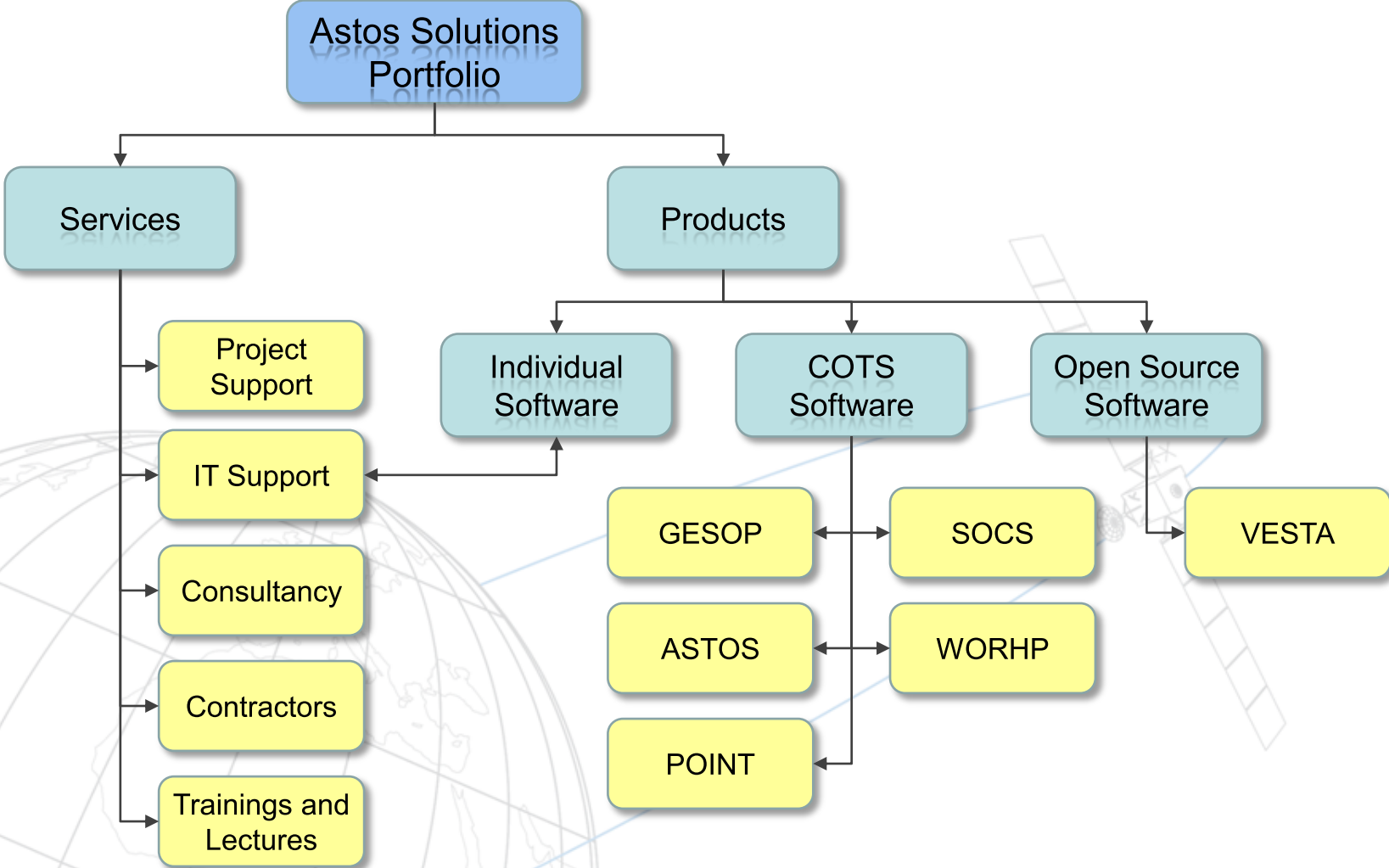


Astos Solutions

FACTS AND FIGURES



Summary of Products & Services



Scenarios

Interplanetary

Aero-Assisted
Maneuvers

Formations

RvD

Ascent

Constellations

Reentry

Station Keeping

Sounding
Rockets

Orbit Transfer

Techniques

- Optimisation
- Simulation
- Non-linear identification
- Monte Carlo simulations
- Sensitivity analysis
- Mission analysis
- Safety analysis
- GNC analysis

Astos Solutions History

- 1989 Start of GESOP/ASTOS (former ALTOS) development at MBB (now Astrium ST) and DLR Oberpfaffenhofen.
- 1991 Continuation at new Institute of Flight Mechanics and Flight Control (IFR) at University of Stuttgart as prime under the lead of Prof. Klaus Well.
- 1999 Beginning of commercialization (1st customer Fiat Avio => VEGA launcher)
- 2006 Foundation of Astos Solutions GmbH
Registered as SME
- 2009 Located in STEP (STuttgarter Engineering Park), Germany
- 2010 Enlargement of office to double size including laboratory



Company Development

Current Situation

Turnover:

ESA projects: 55-85%

Software sales: 5-10%

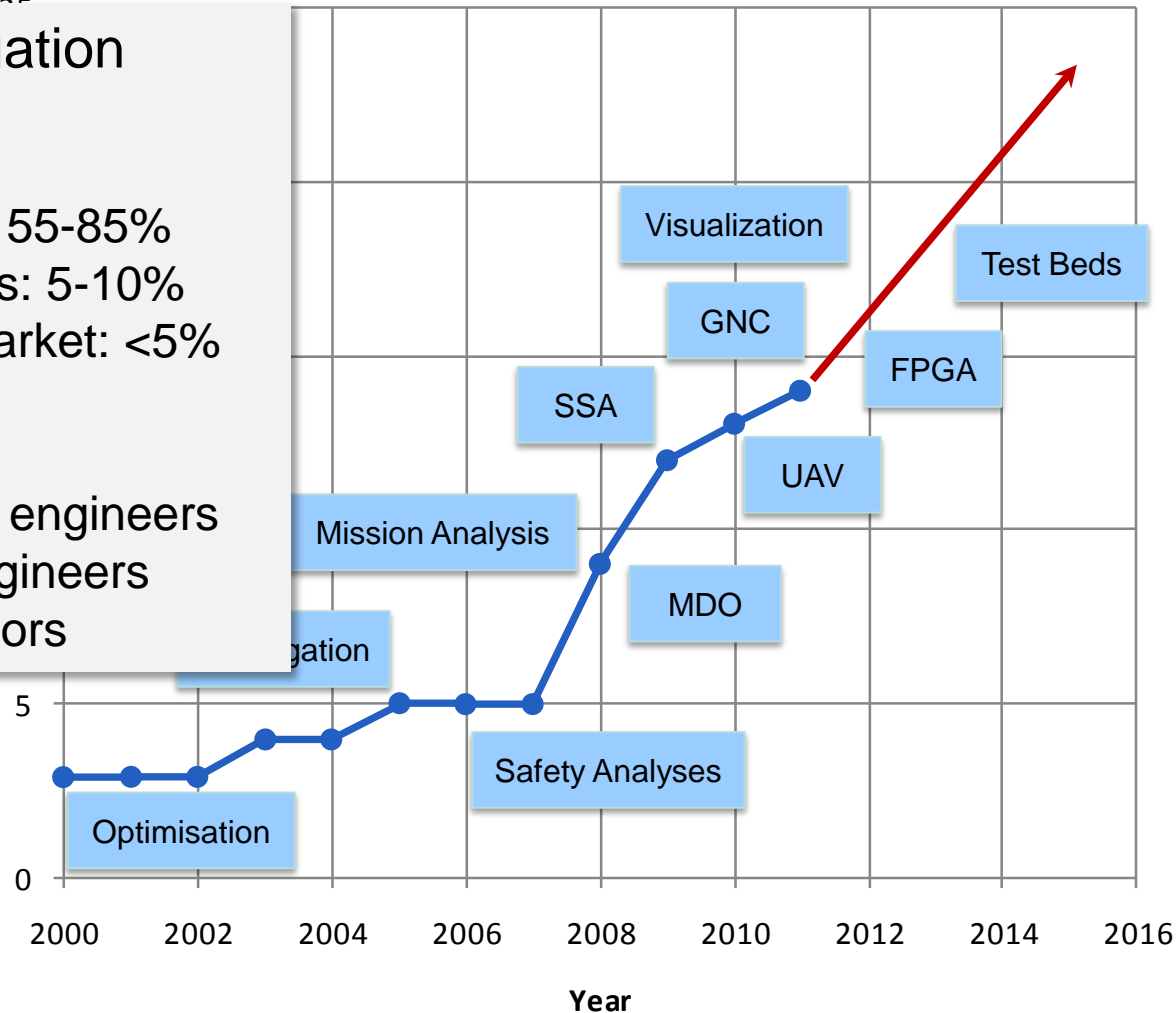
Non-space market: <5%

Personnel:

10 aerospace engineers

3 software engineers

3 senior advisors

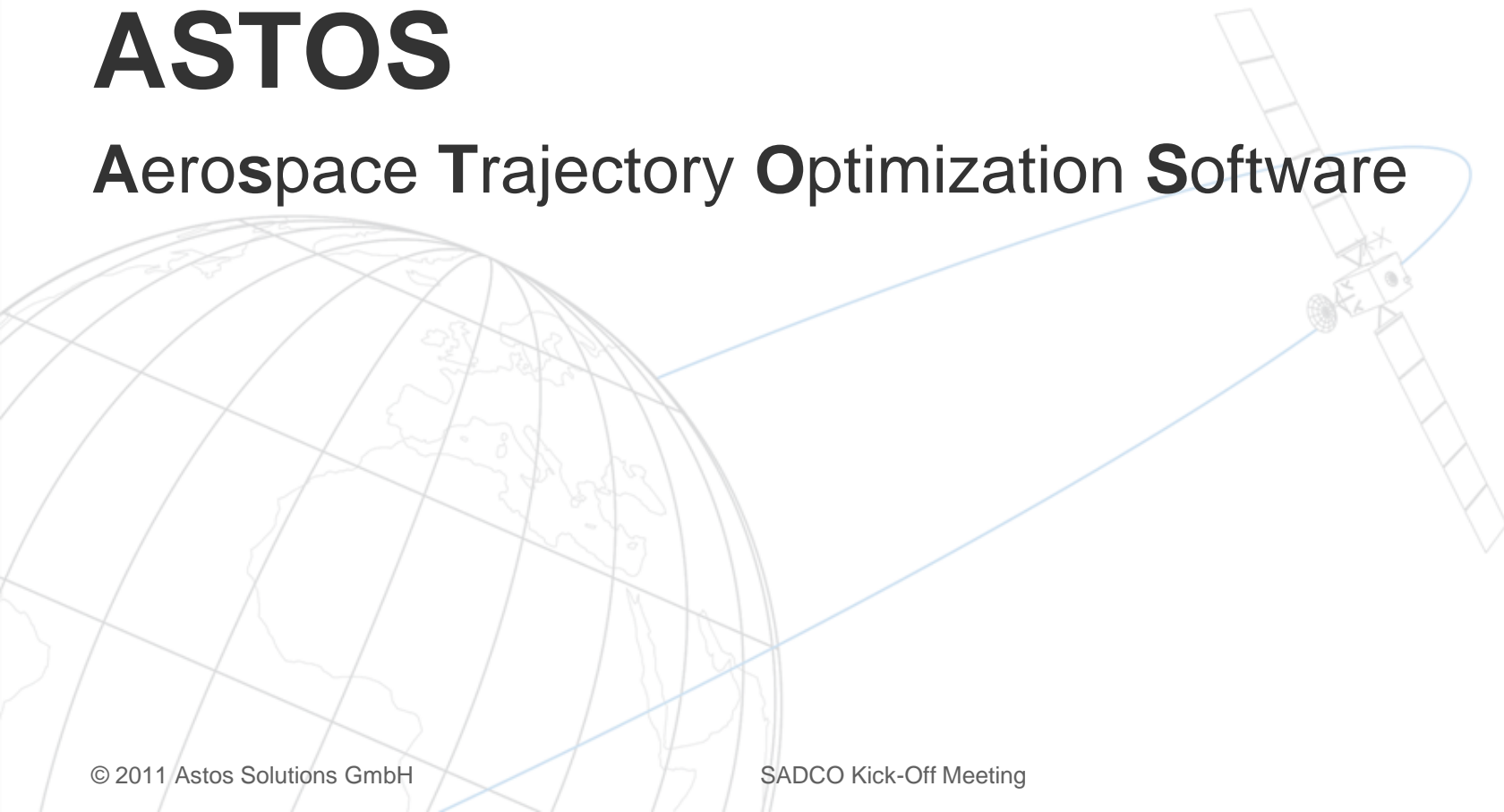


- University of Stuttgart, Faculty of Aerospace and Geodesy
 - Training courses in trajectory optimization with ASTOS in parallel to the lectures at iFR
 - Supervision of students in their master thesis work
- Worldwide cooperation
 - Lectures and student workshops organized at several universities, especially in USA
 - Software used by app. 30 universities worldwide for master and PhD theses



ASTOS

Aerospace Trajectory Optimization Software



ASTOS® Key Attributes

AeroSpace Trajectory Optimization Software

- Transcription methods: direct multiple shooting, direct collocation (also hybrid) with linear, constant or B-Spline control discretization
- Several NLP solvers: SNOPT, WORHP, SPRNLP (SOCS), SLLSQP and global methods (Particle Swarm, genetic algorithms)
- Jacobian approximated by finite differences, Hessian by BFGS updates or also by finite differences
- Various propagation methods (RKF45, RKF78, RKN11, RKR15, ODEX2, SGP4)
- Built-in batch processing tool, e.g. for Monte Carlo simulations
- More than 100 predefined constraints and cost functions
- Wide range of vehicle and environment models (no coding required)



GESOP/ASTOS Customers



Aero-Space



Universities Europe

- | | |
|------------|------------|
| Berlin | Naples |
| Stuttgart | Cranfield |
| München | Glasgow |
| Bremen | Madrid |
| Athens | ETH Zürich |
| Greifswald | Dresden |
| FH Aachen | Zaragoza |
| | Pisa |

North America

- California
- Stanford
- Seattle
- MIT
- Illinois
- Austin, Texas
- Carleton, Qu
- Edmonton, Al
- Toronto
- Minneapolis
- Maryland
- Iowa State
- UCLA Los Angeles
- Purdue
- Cincinnati
- Pennsylvania State
- Ryerson

South America

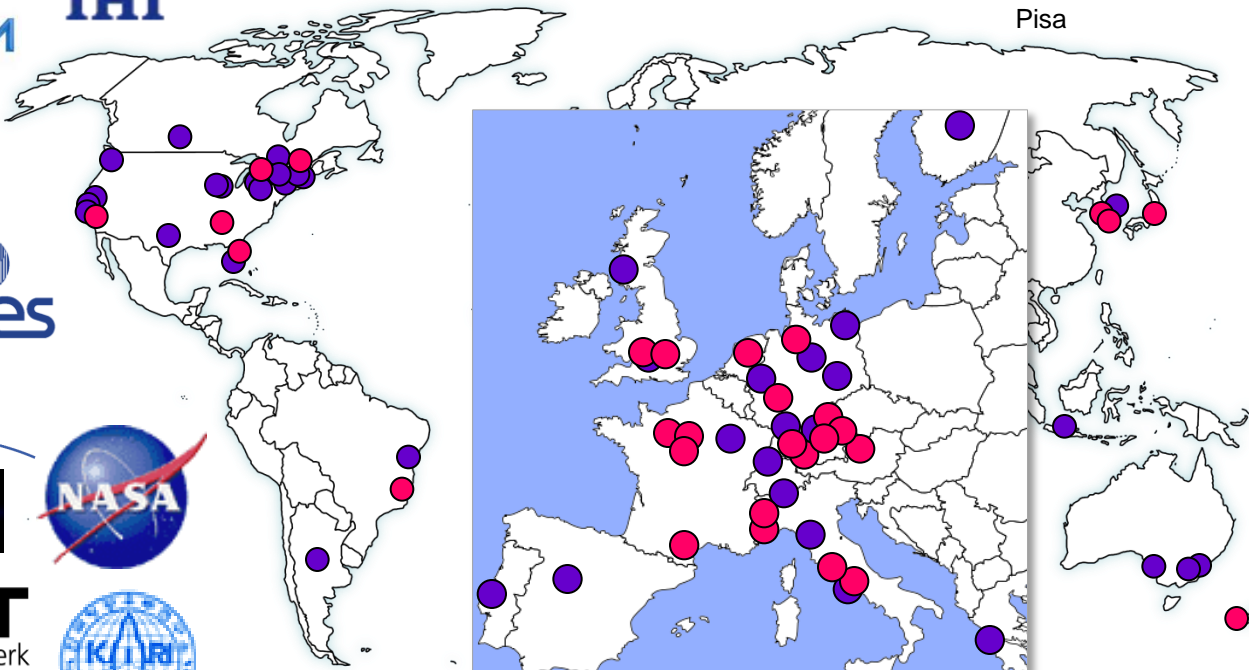
- Cordoba, Ar
- Minas Gerais, Br

Asia

- Yonsei, Seoul, Kr
- Nanjing
- Yogyakarta

Australia

- Sydney
- Canberra
- Adelaide



Automotive



ESA projects with ASTOS Launch Vehicles

Ariane 5

MLV

VEGA

VEGA 1st flight

Electrical VEGA

CTV

CTV 2

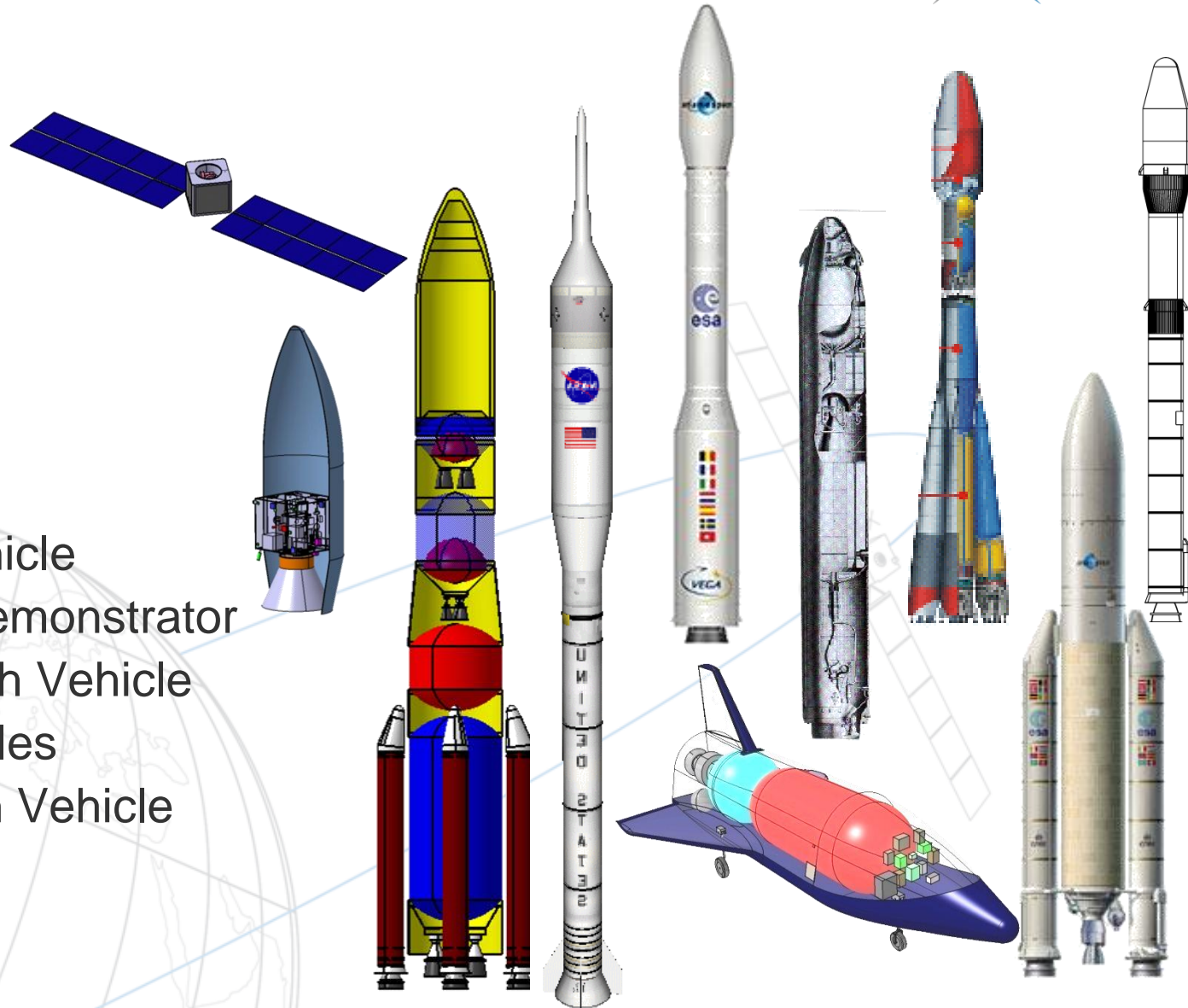
Mars Ascent Vehicle

Socrates RLV Demonstrator

Heavy Lift Launch Vehicle

IXV launch vehicles

Crew Exploration Vehicle



ESA projects with ASTOS

Re-entry, Exploration, Science

X38/CRV

Sphinx

ACRV

ARD

JEP

Beagle-2 & BeagleNet

ExoMars09

Mars Demo Lander

Mars Sample Return

Mars Excursion Vehicle

CX-OLEV, SMART-OLEV

Aerocapture Demonstrator

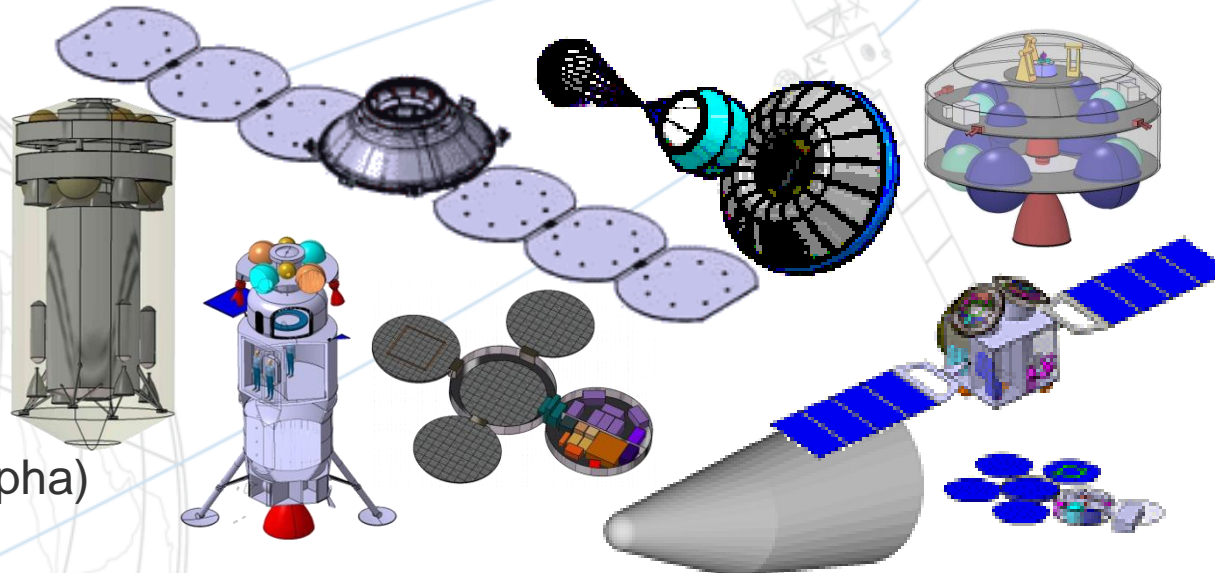
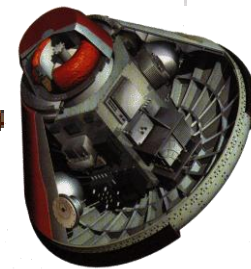
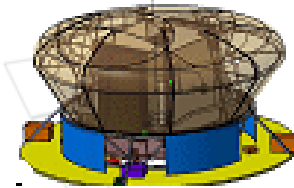
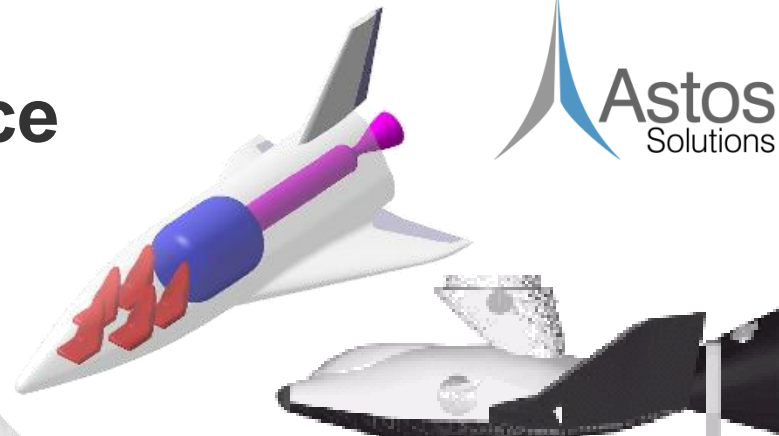
Lunar Exploration Study

Expert

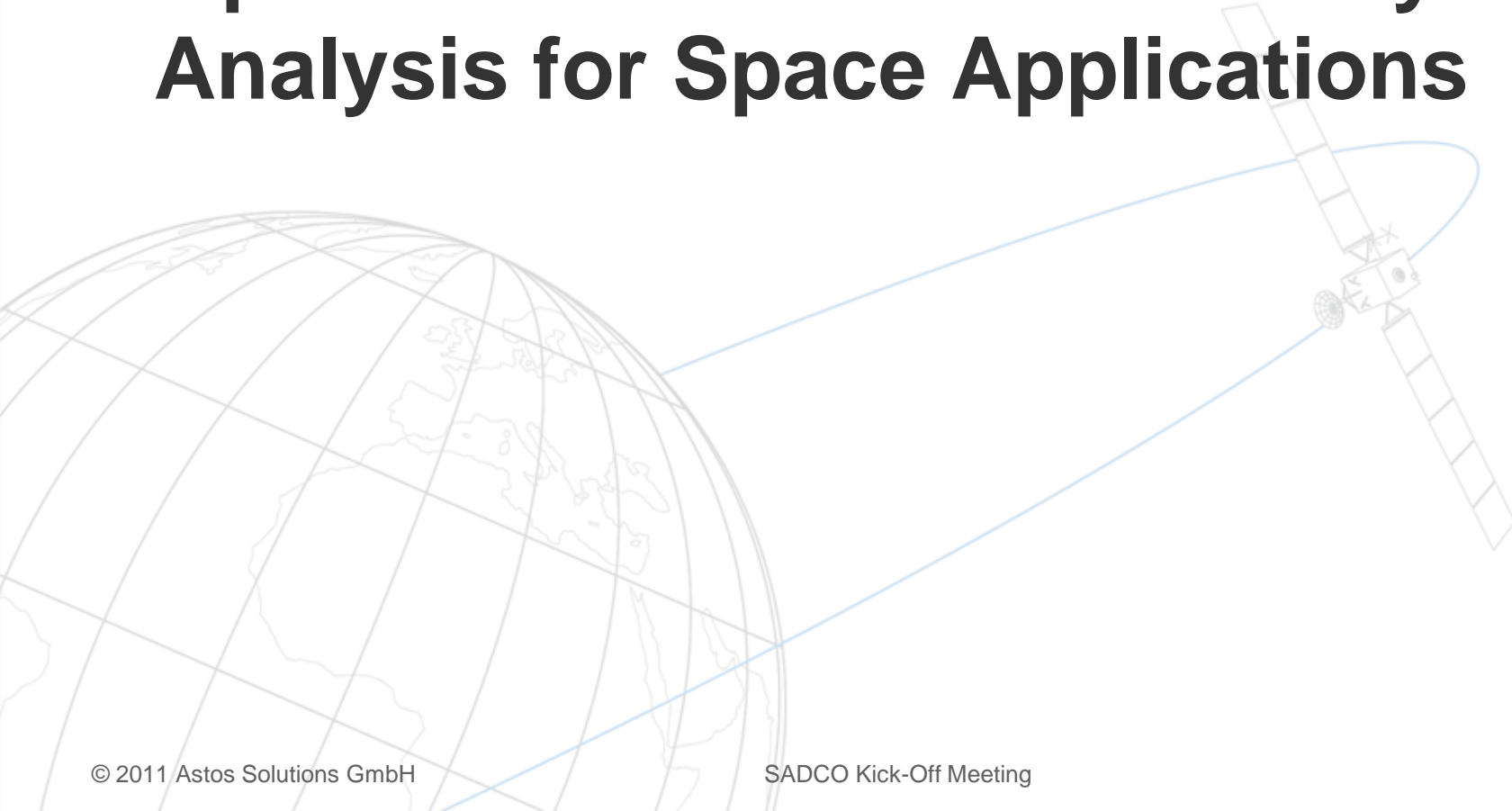
VRAE

Lunar Exploration Orbiter

FAST20XX (Spaceliner, Alpha)



Optimal Control and Sensitivity Analysis for Space Applications



An Aerospace Mission

Model Definition

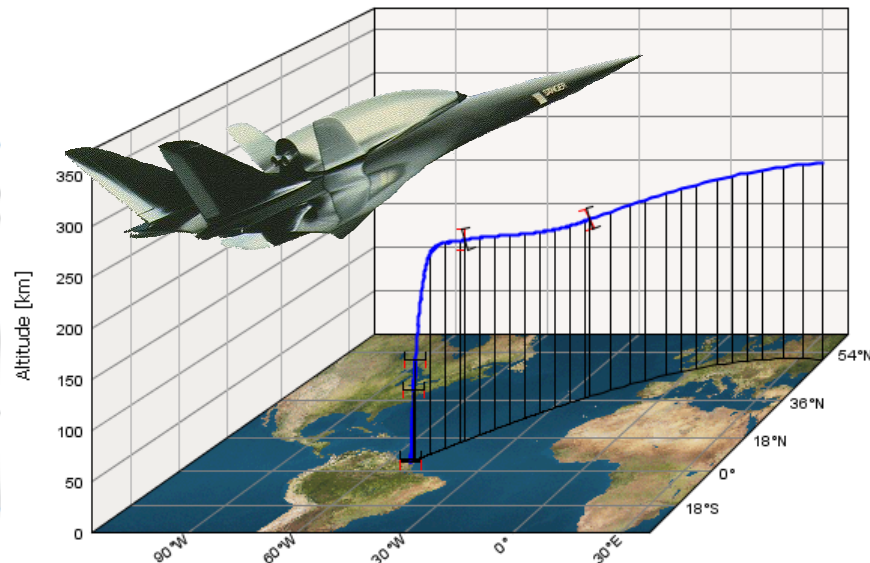
- Environment
 - Planet
 - Atmosphere
 - Wind
 - Solar System
- Vehicle Components
- Propulsion Systems
- Aerodynamic Configurations

Mission Definition

- Cost Function
 - Maximum Payload
- Constraints
 - Boundary Constraints
 - Path Constraints

Phase Configuration

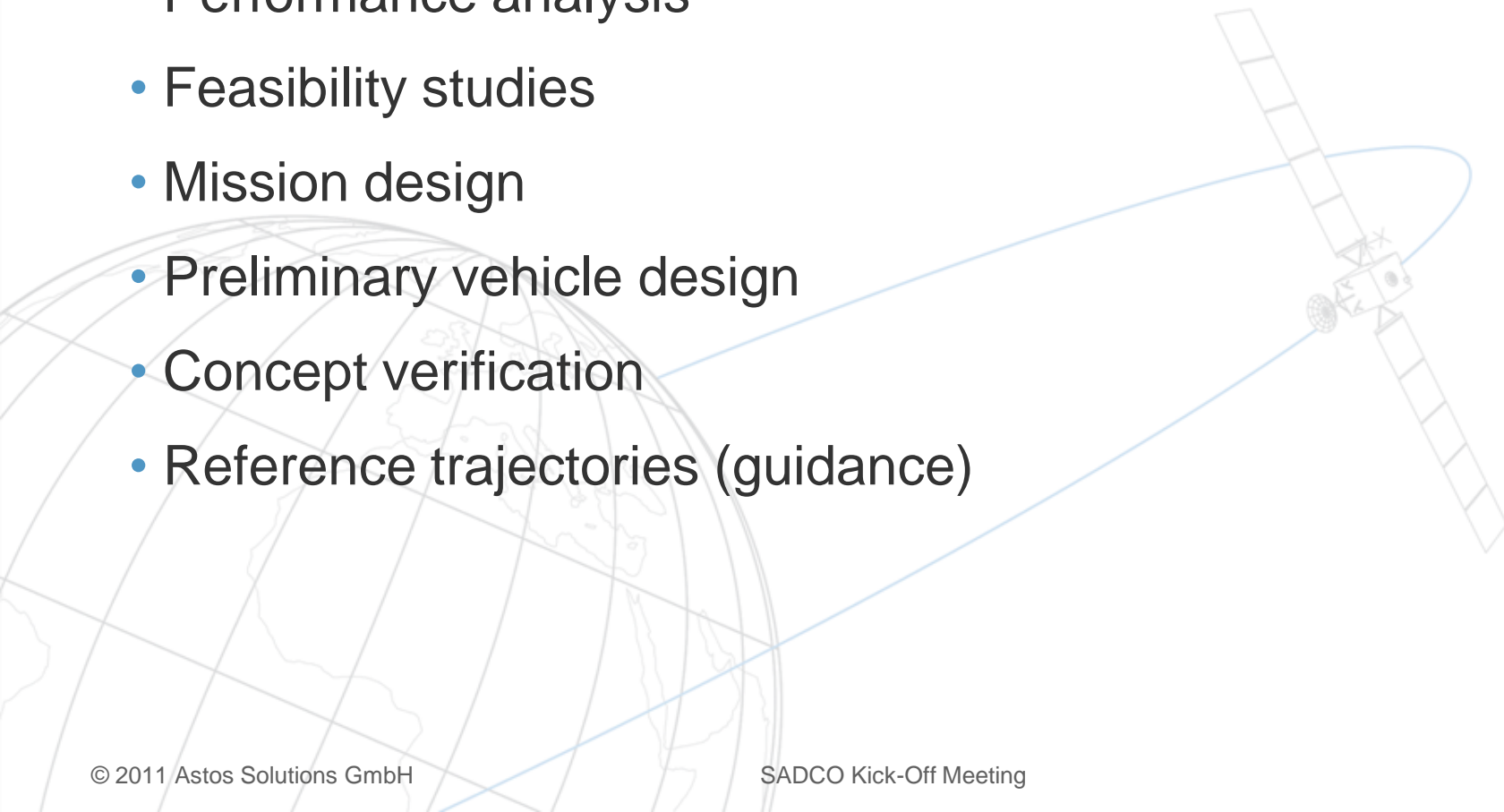
- Initial State and Epoch
- Multi-Phase Definition
 - Dynamic System
 - Aerodynamic Configuration
 - Active Propulsions
 - Jettisoned Components
 - Branching
 - Attitude Controls



Typical Optimal Control Applications

These are the typical applications for optimal control in the space segment at Astos Solutions:

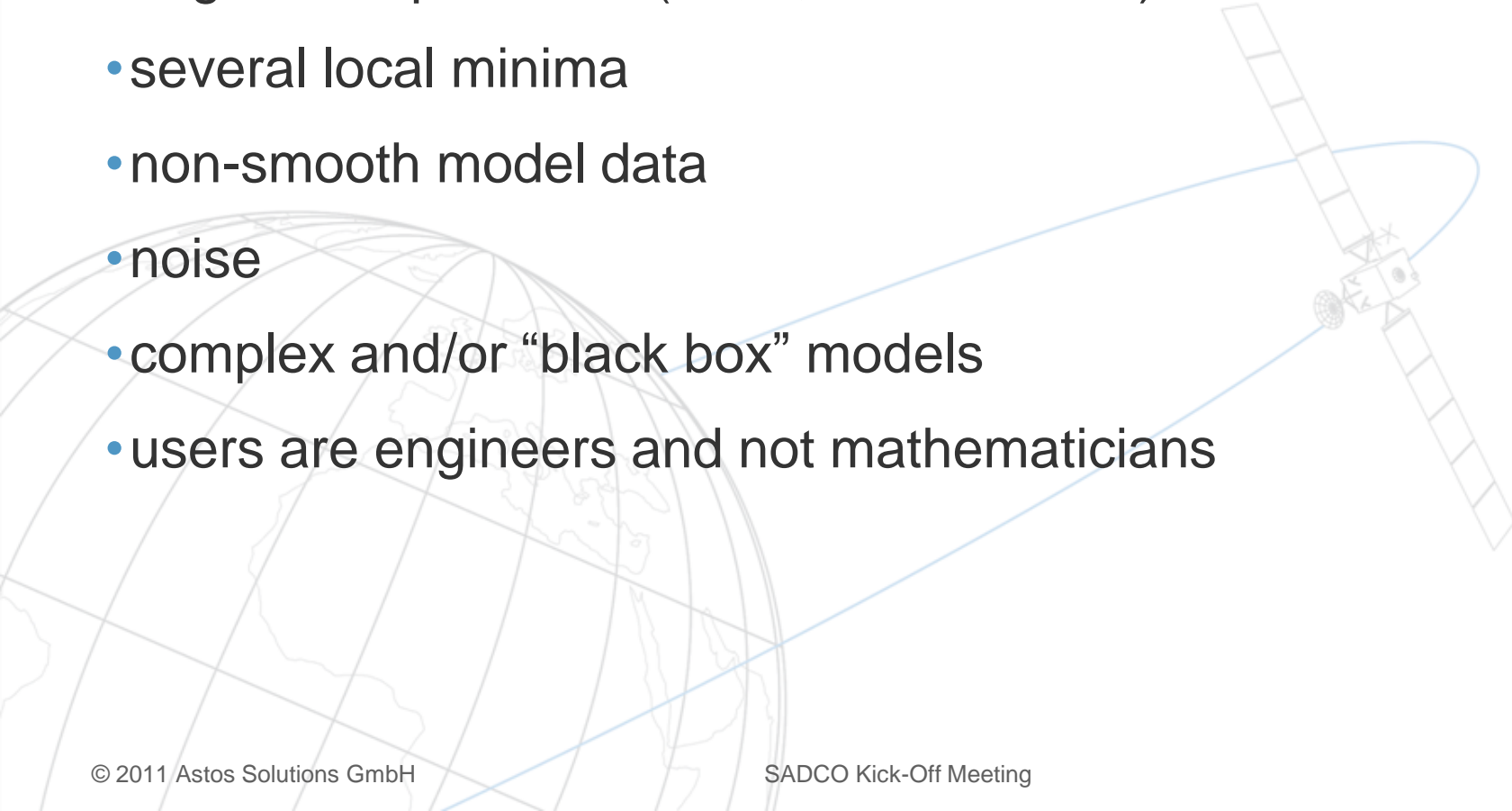
- Performance analysis
- Feasibility studies
- Mission design
- Preliminary vehicle design
- Concept verification
- Reference trajectories (guidance)



Challenges of Space Applications

Applying non-linear optimization to space applications is often accompanied by one or more of the following challenges:

- large scale problems ($>100,000$ variables)
- several local minima
- non-smooth model data
- noise
- complex and/or “black box” models
- users are engineers and not mathematicians



DLR “Blackbox Solver” Research Activity

- Project Goals:
 - Reduction of user interaction
 - Reduction of required user expertise
 - Increase of solver robustness
- Joint project together with Uni. Bremen (C. Büskens)
- Based on the WORHP solver (<http://www.worhp.de>)
- Automatic analysis of optimization problem
 - Check for non-smooth functions (f, g_i)
 - Model formulation errors
- Automatic scaling of variables and constraints
 - Variable scaling based on parametric sensitivity analysis
- Automatic mesh refinement and generation
- Improved finite differences by means of adaptive variable perturbation

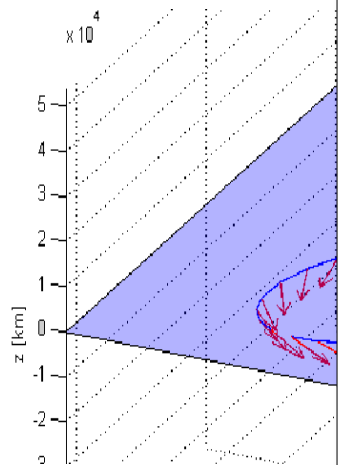
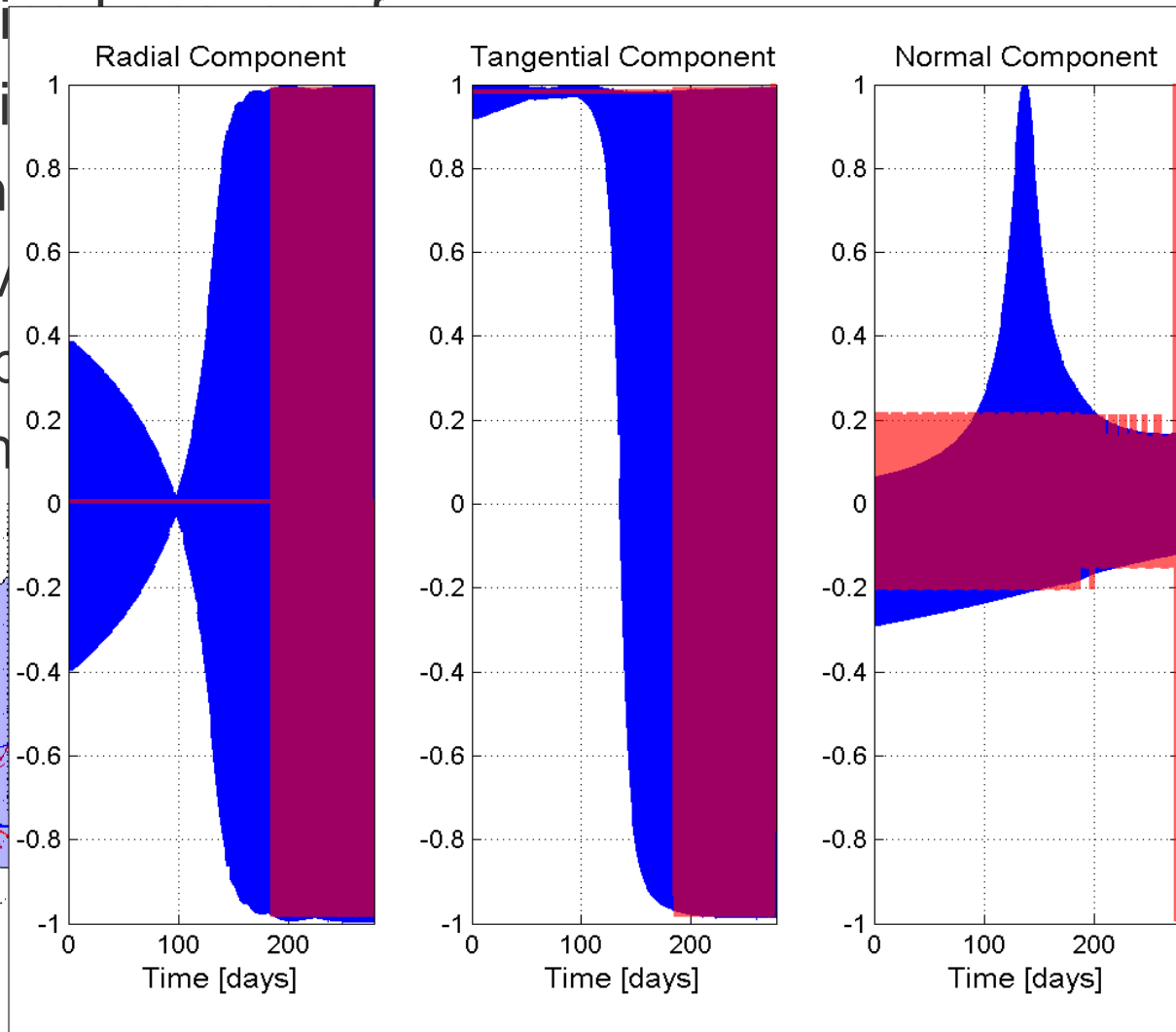
Challenging Space Applications



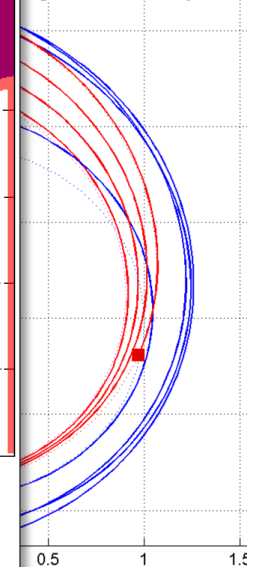
Low-Thrust Orbit Transfer and Low-Thrust Interplanetary Mission

Challenges

- Long mission duration
- Local maximum thrust
- Thrust vector control
- Throttling
- Other mission constraints



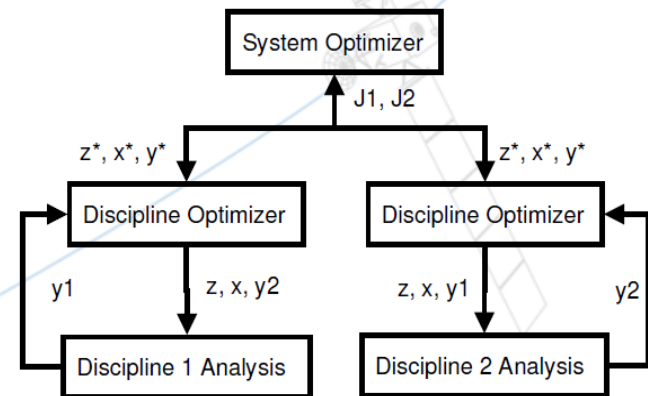
budget
(aspects)



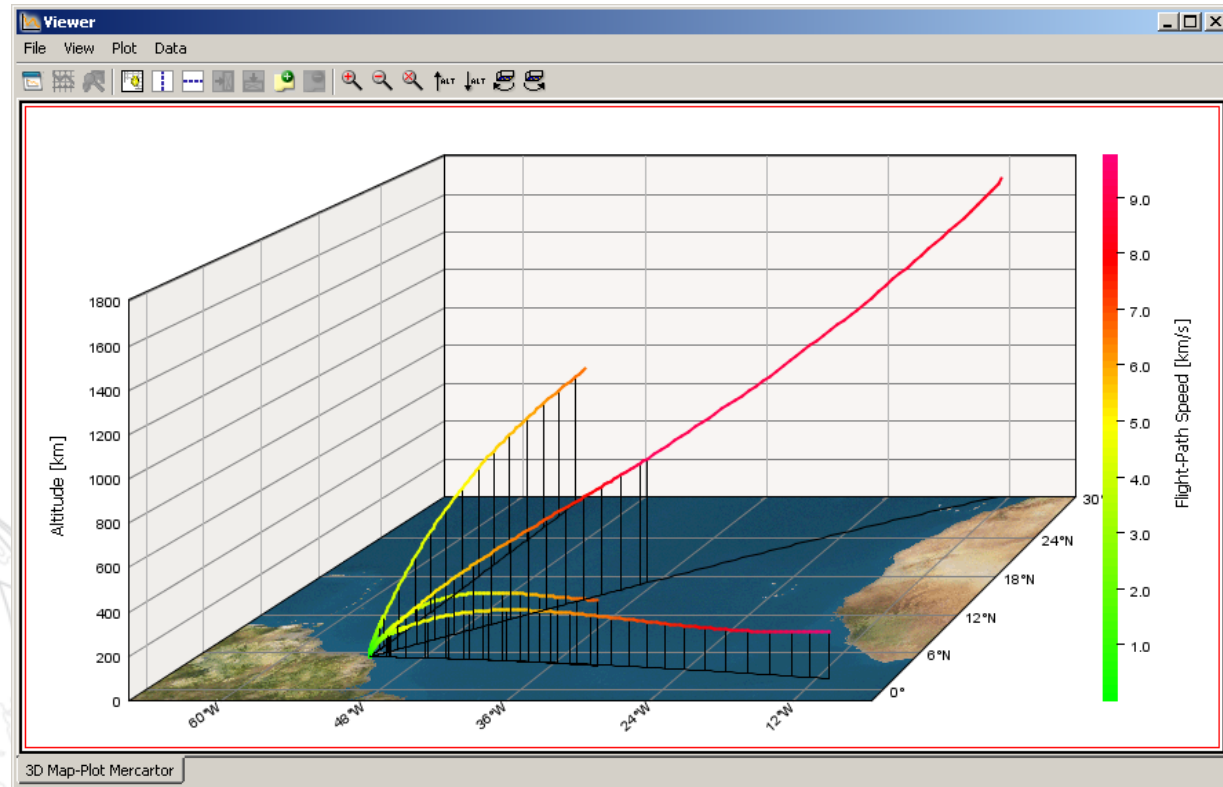
Multidisciplinary Design Optimization (MDO)

- Complex systems and subsystems
- Several disciplines (propulsion, aerodynamics, TPS, structure, dynamics)
- Various MDO techniques: AAO, IDF, BLISS, CO
- Difficulties: computational time, convergence

SQP is applied
main task is to find best MDO strategy



- Trajectory and stage optimization of a launcher family with different
 - target orbits
 - payloads
 - number of boosters
 - filling ratios (propellant)
- considering
 - mission constraints
 - launch site constraints
 - environmental constr.
- Including
 - engine design
 - stage sizing
 - splash down
 - station visibility
 - load limits



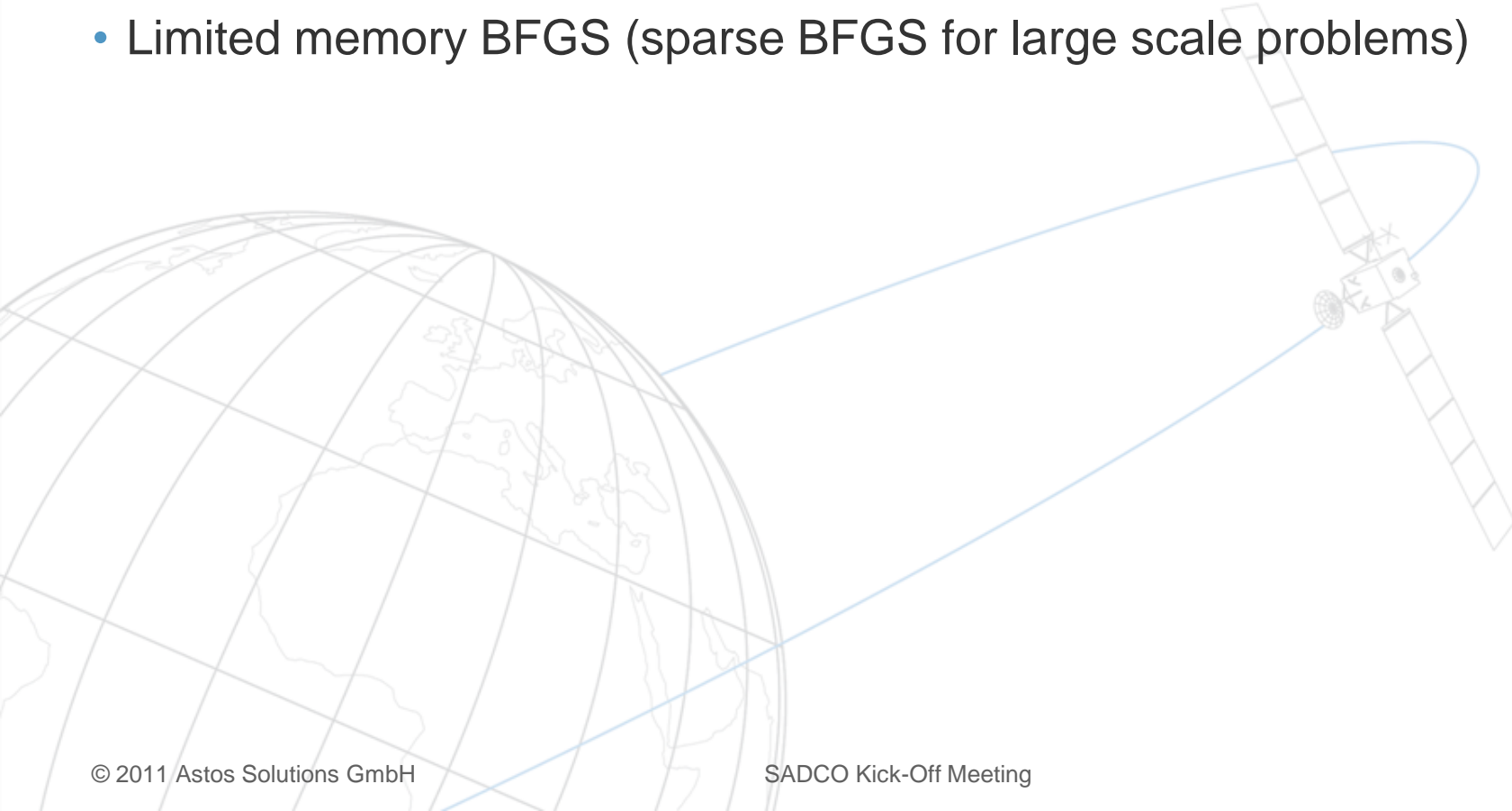
Sensitivity Analysis After Design Optimization

- Model uncertainties -> in reality model parameters might be different from the ones assumed in the optimization
- Not an optimal but a robust solution is required!
- Local sensitivity analysis based on KKT-matrix and/or
- Trust region analysis in the regime of 1 sigma -> Monte Carlo
- Sensitivity analysis with respect to optimizable variables and fixed parameters (e.g. assumed Isp of the engines) is required

Link to SADC0?

Foreseen activities in cooperation with Uni. Bremen and SADC0 fellow Sonja Rauski:

- Parametric sensitivity analysis based on KKT-matrix
- Limited memory BFGS (sparse BFGS for large scale problems)



Wrap-Up

- A small set of mathematical approaches (transcription method, NLP solver) is applied to a wide range of optimization problems and applications
- A robust solution is more desired than the real optimal
- Sensitivity analysis is required to get confidence on the robustness of the solution.

Industrial Workshop

Industrial SADCO Workshop at Astos Solutions

- Tentative date: 2-3 February 2012
- Industrial applications
- “Learn about the engineer’s perspective”
- Hands-on software trainings
- In direct neighbourhood of the University of Stuttgart
- Global players with optimization demands are located in Stuttgart, e.g.
 - Daimler
 - Bosch
 - Behr
 - Thales ATM

➤ **Chance for further networking**



Leadership requires solutions



Thank you!

