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# Space Applications Subject to Optimal Control and Sensitivity Analysis

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# **Space Applications Subject to Optimal Control and Sensitivity Analysis**

Sven Weikert

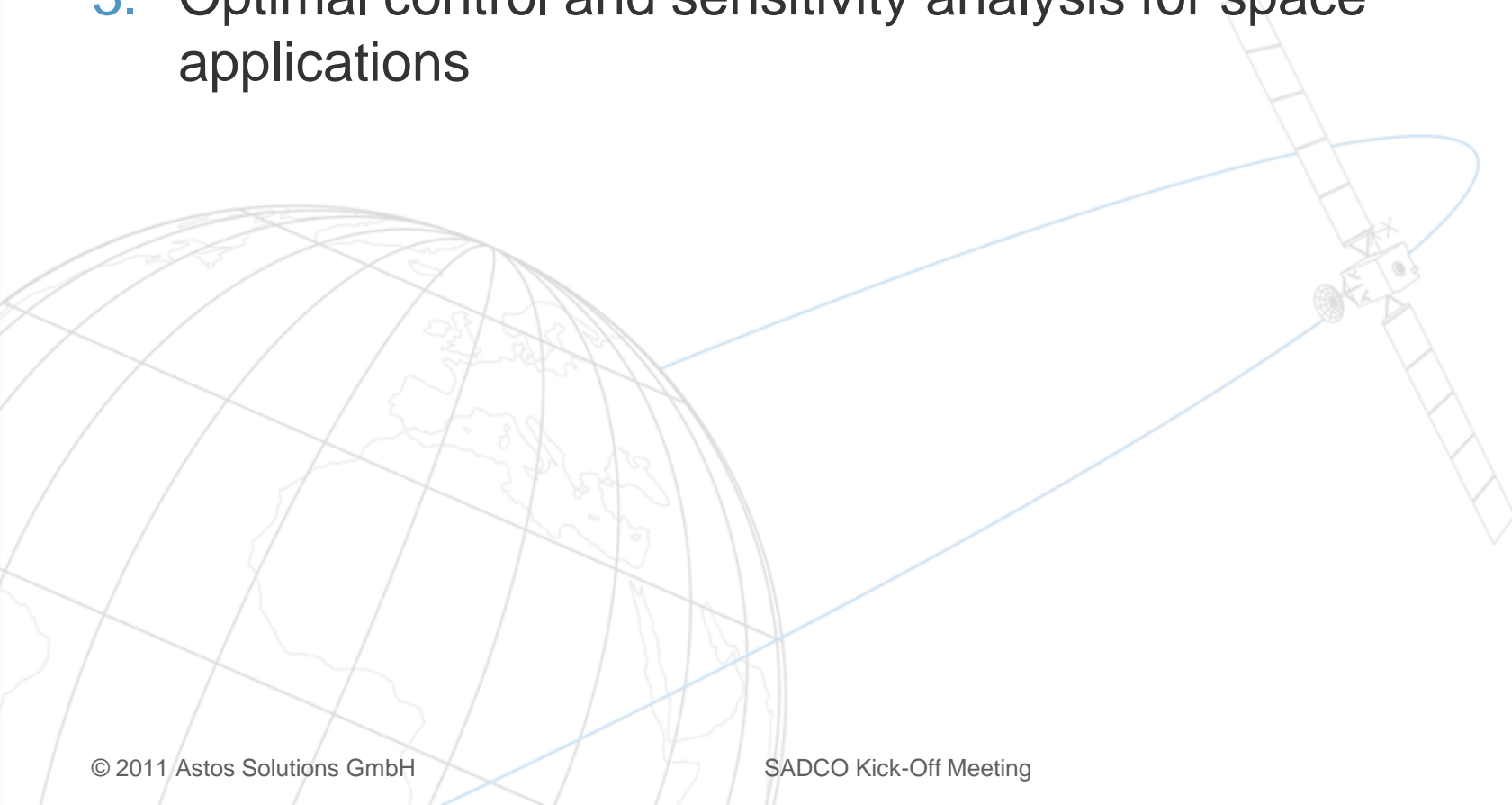
SADCO Kick-Off Meeting

Paris, March 3-4, 2011



# Outline

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

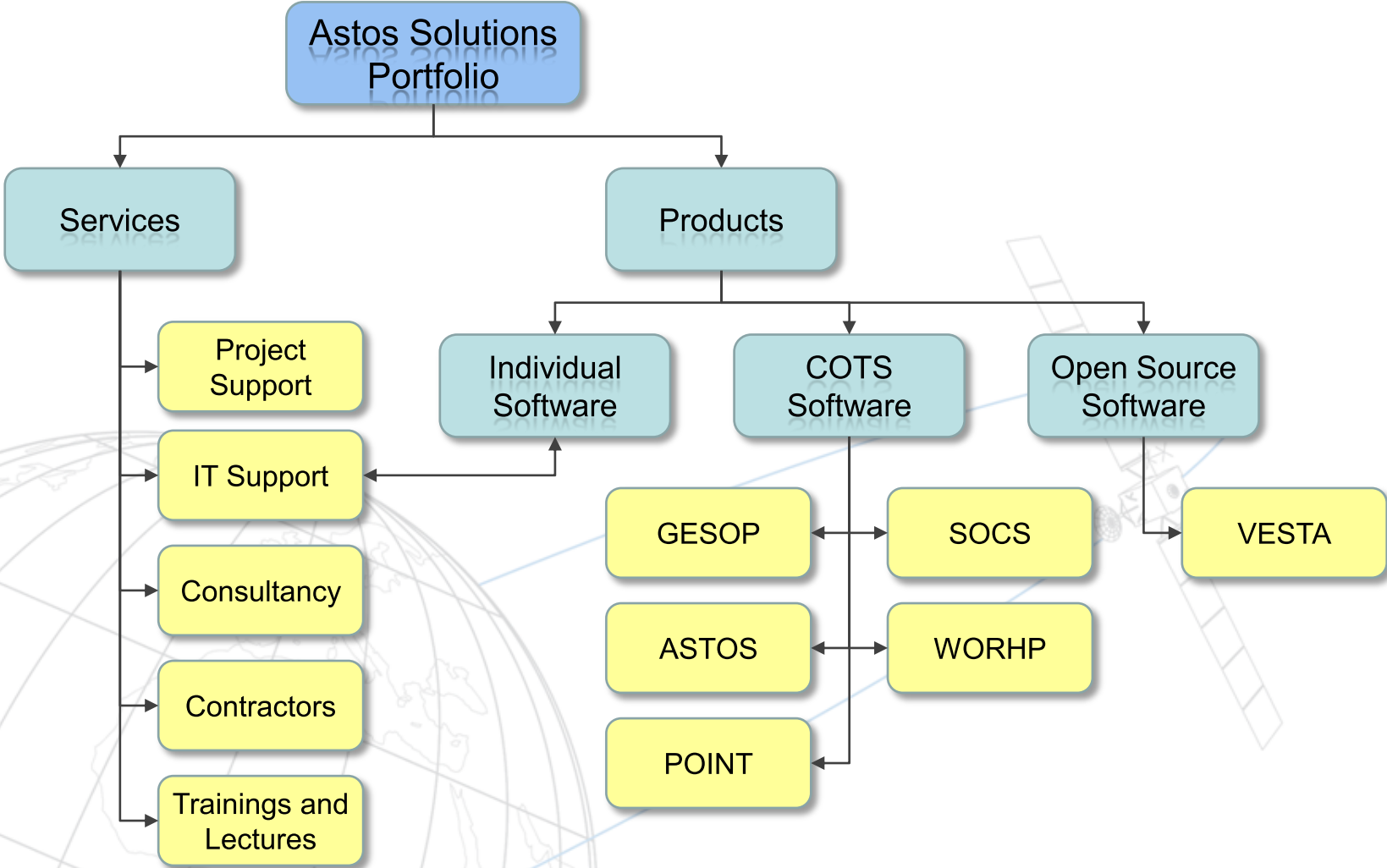


Astos Solutions

# 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%

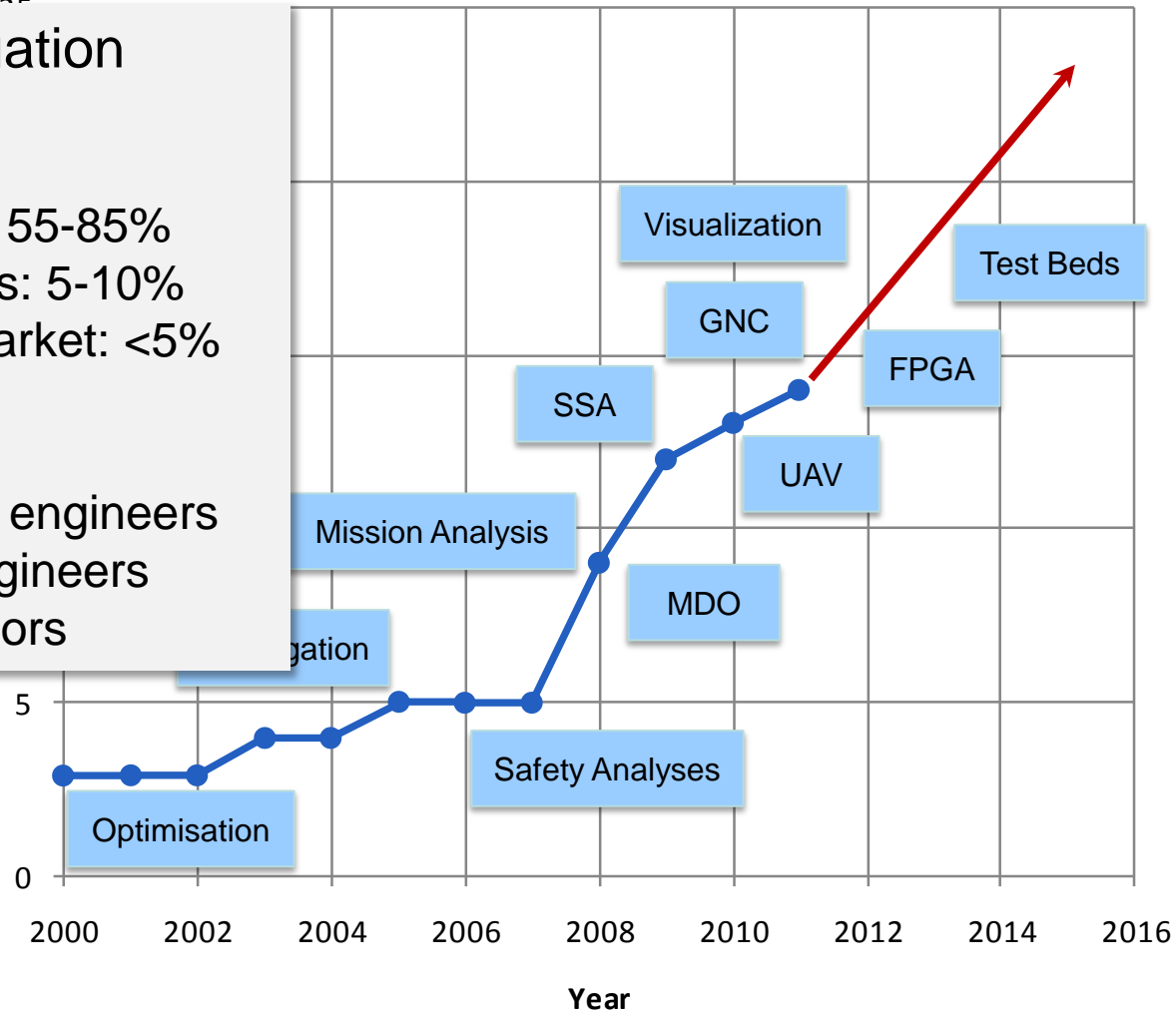
Non-space market: <5%

Personnel:

10 aerospace engineers

3 software engineers

3 senior advisors



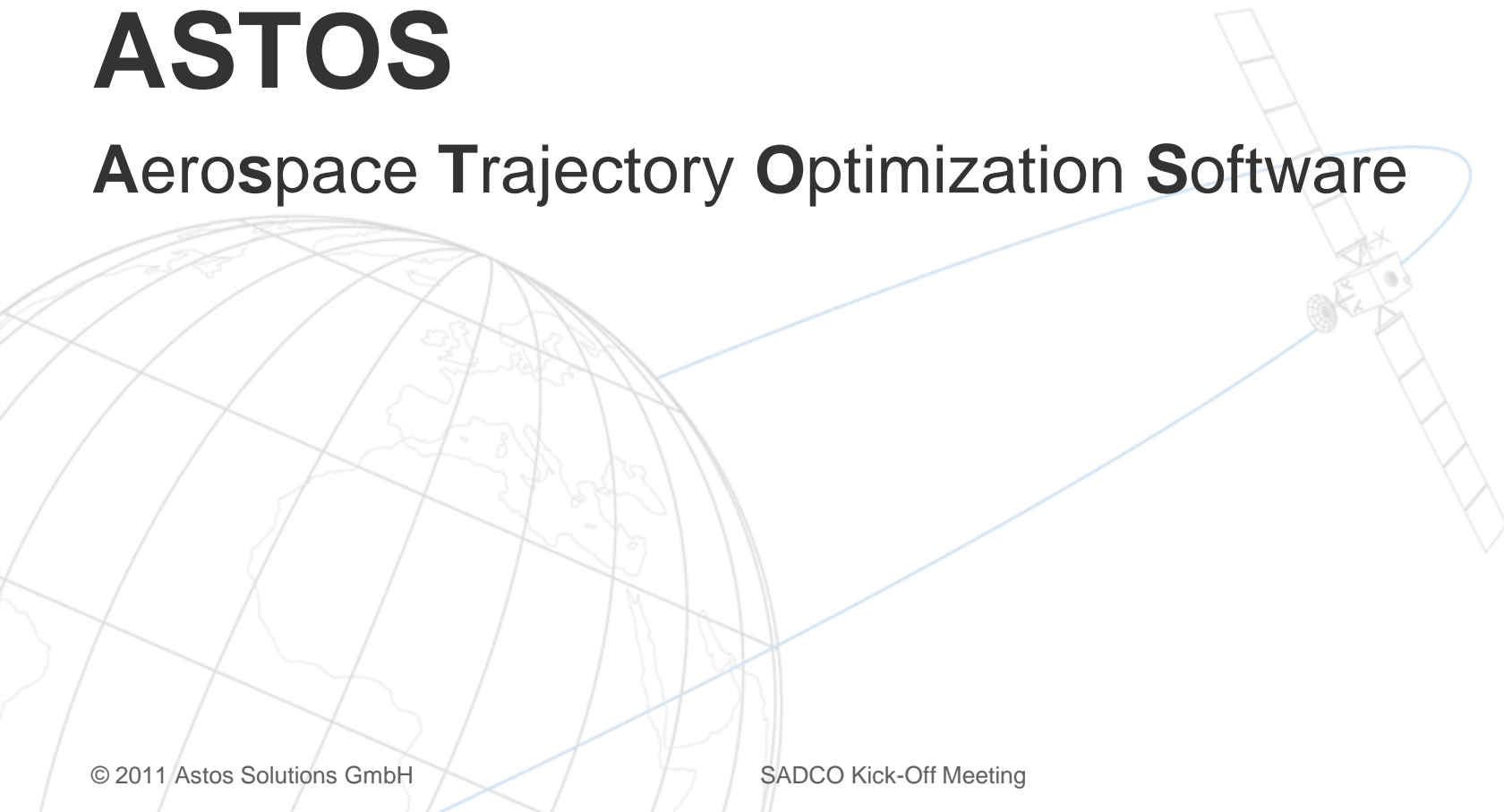


- University of Stuttgart, Faculty of Aerospace and Geodesy
  - Training courses in trajectory optimization with ASTOS in parallel to the lectures at iFR
  - Supervision of students in their master thesis work
- Worldwide cooperation
  - Lectures and student workshops organized at several universities,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



# ASTOS

## Aerospace Trajectory Optimization Software



# ASTOS<sup>®</sup> 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

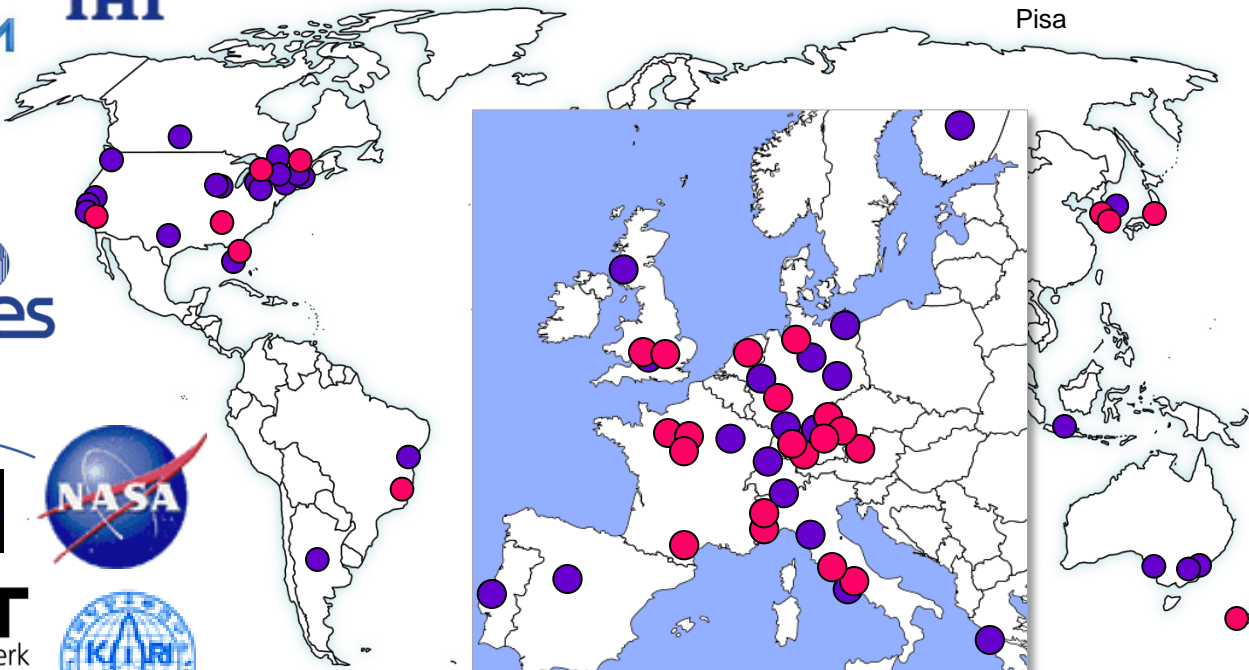
- Cordoba, Ar
- Minas Gerais, Br

## Asia

- Yonsei, Seoul, Kr
- Nanjing
- Yogyakarta

## Australia

- Sydney
- Canberra
- Adelaide



## Automotive







# ESA projects with ASTOS

## 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

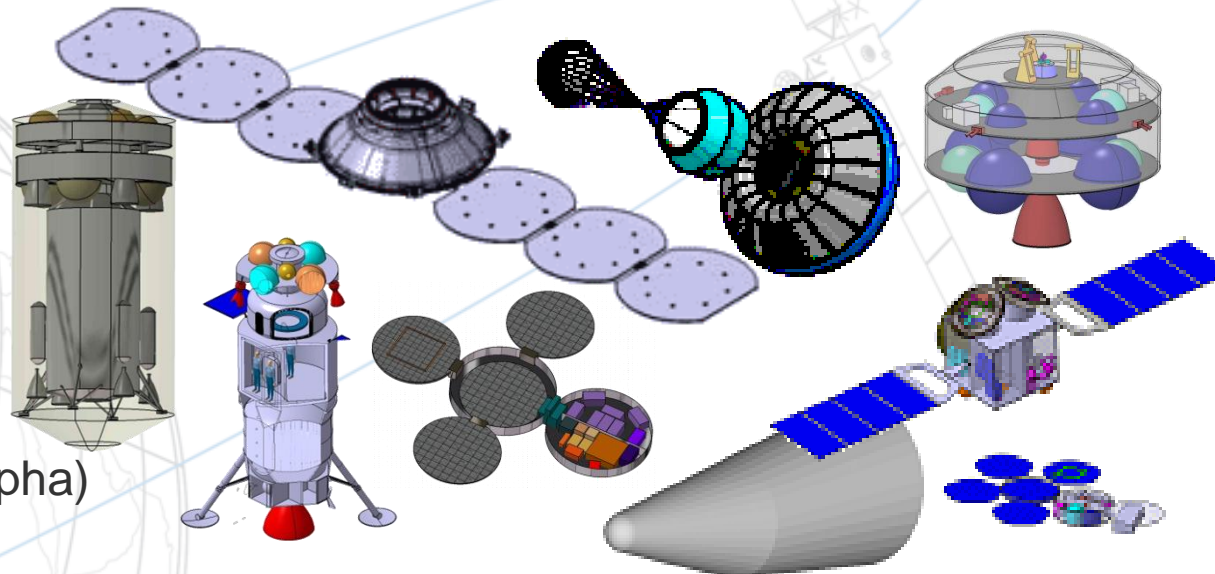
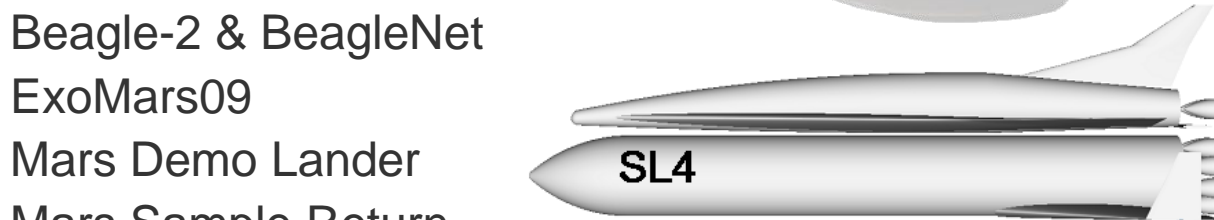
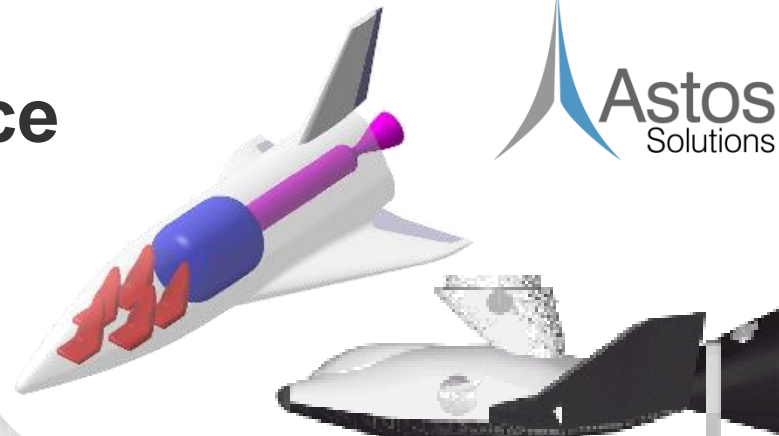
Lunar Exploration Study

Expert

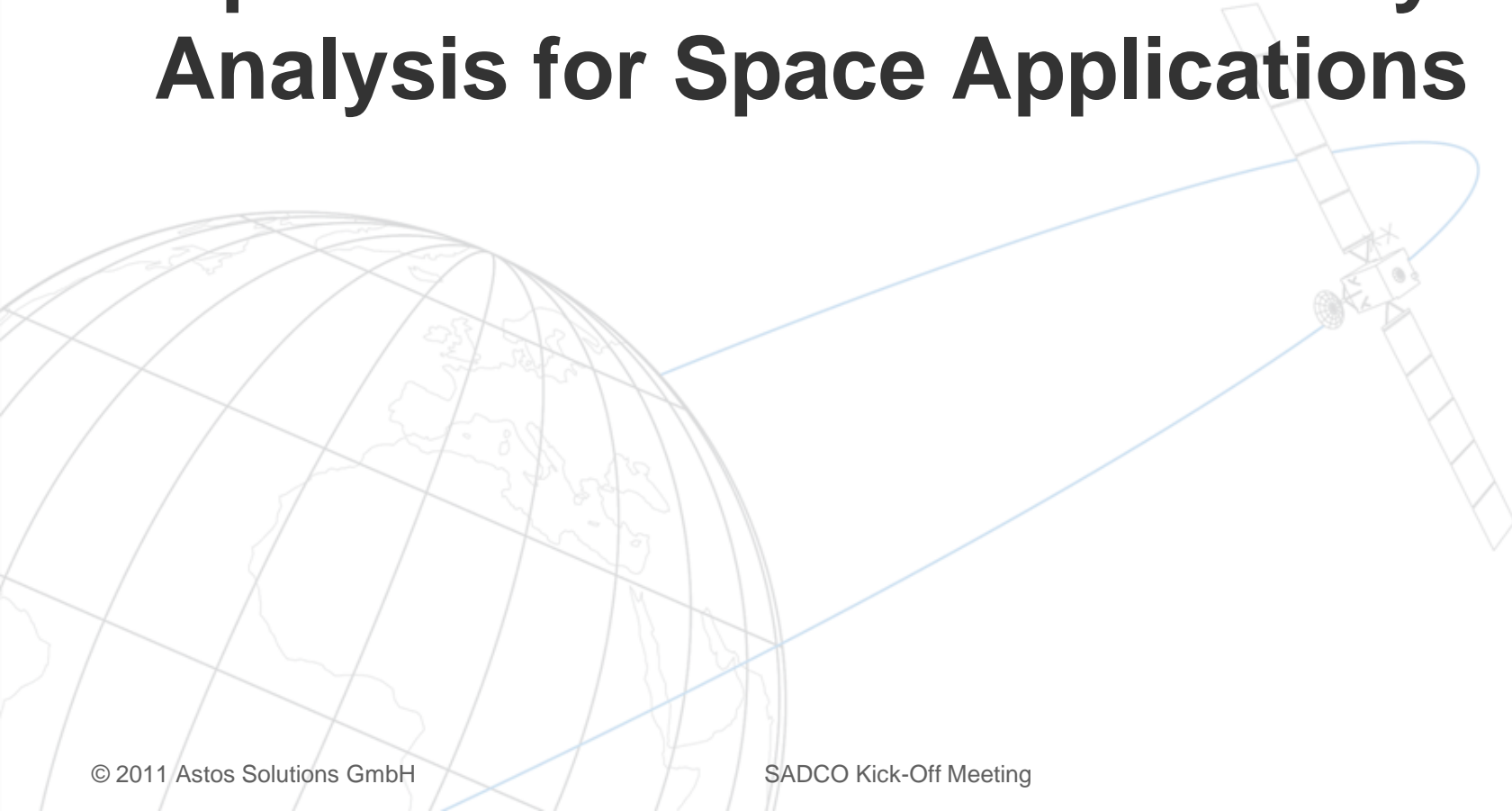
VRAE

Lunar Exploration Orbiter

FAST20XX (Spaceliner, Alpha)



# Optimal Control and Sensitivity Analysis for Space Applications





# An Aerospace Mission

## Model Definition

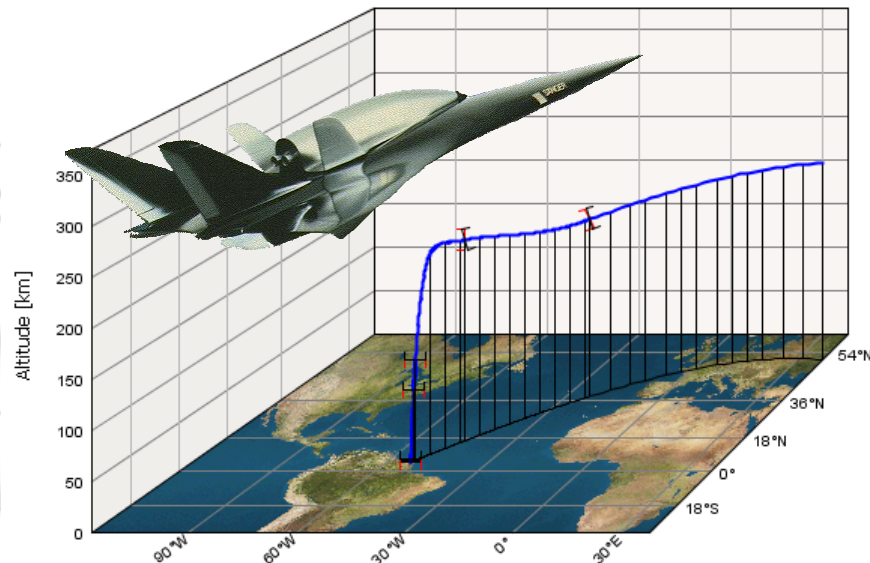
- Environment
  - Planet
  - Atmosphere
  - Wind
  - Solar System
- Vehicle Components
- Propulsion Systems
- Aerodynamic Configurations

## Mission Definition

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

## Phase Configuration

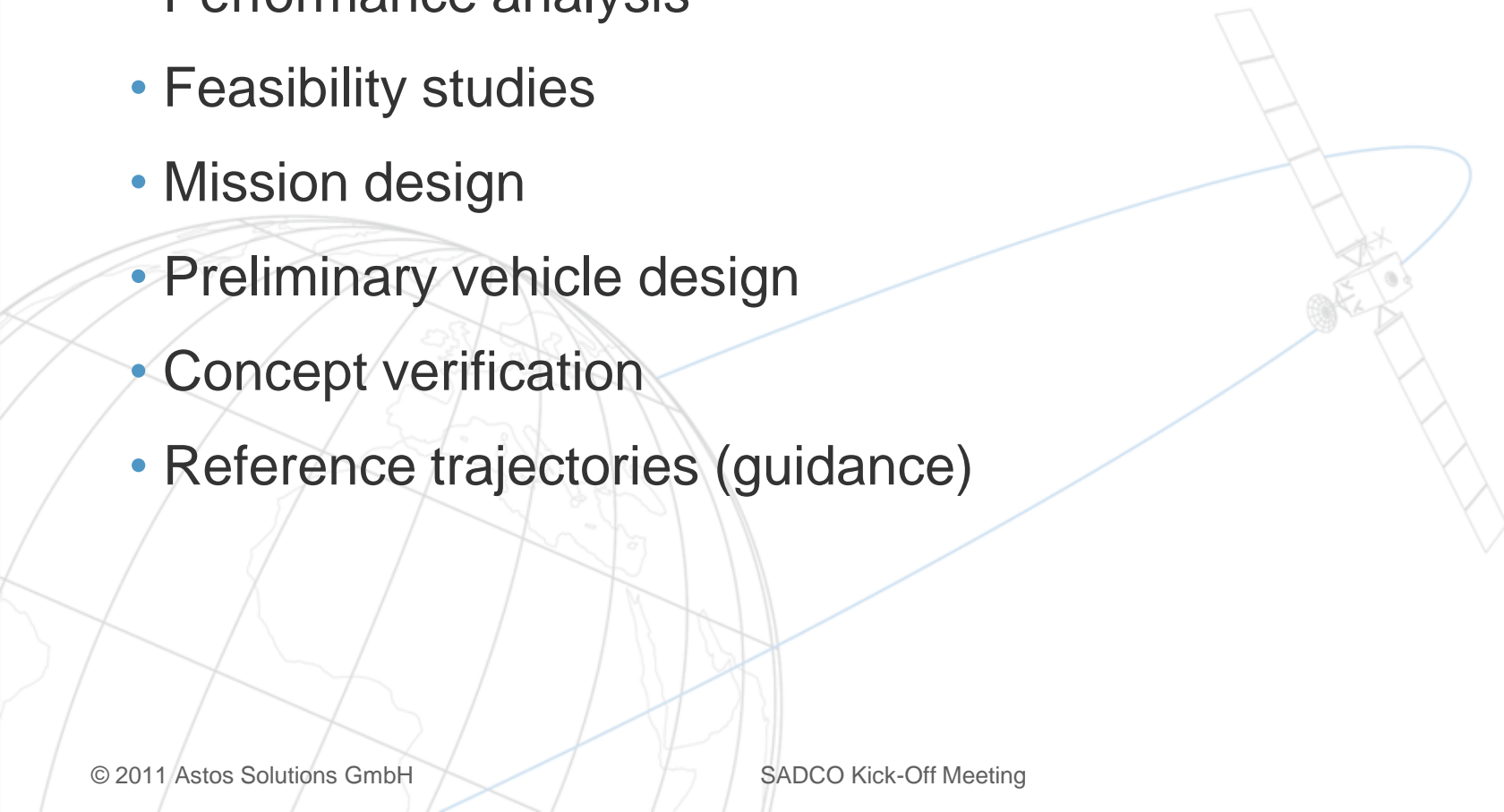
- Initial State and Epoch
- Multi-Phase Definition
  - Dynamic System
  - Aerodynamic Configuration
  - Active Propulsions
  - Jettisoned Components
  - Branching
  - Attitude Controls



# Typical Optimal Control Applications

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

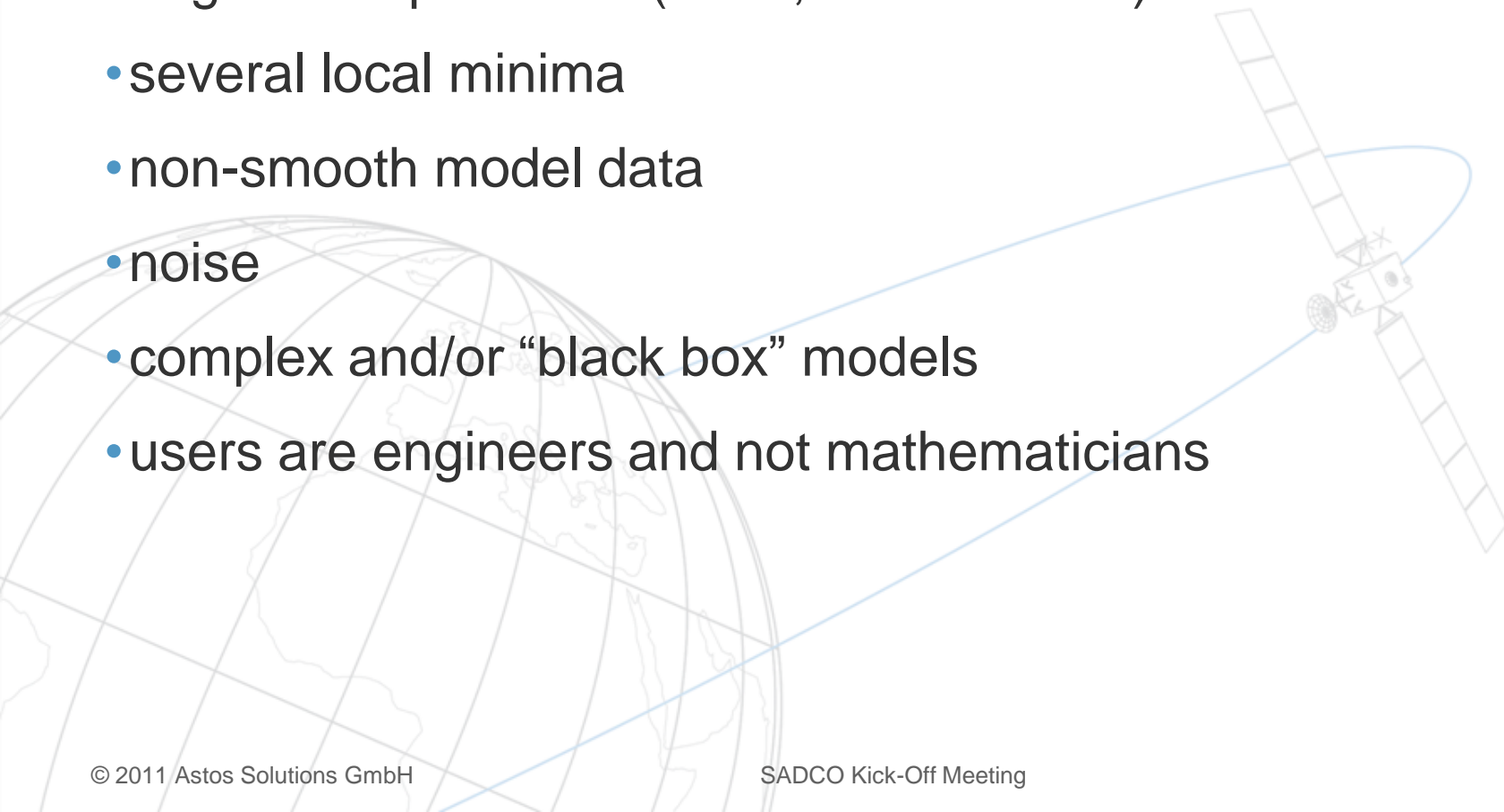
- Performance analysis
- Feasibility studies
- Mission design
- Preliminary vehicle design
- Concept verification
- Reference trajectories (guidance)



# 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

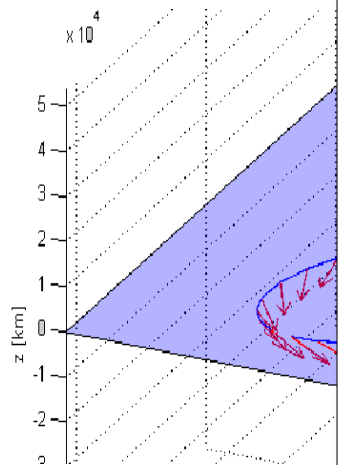
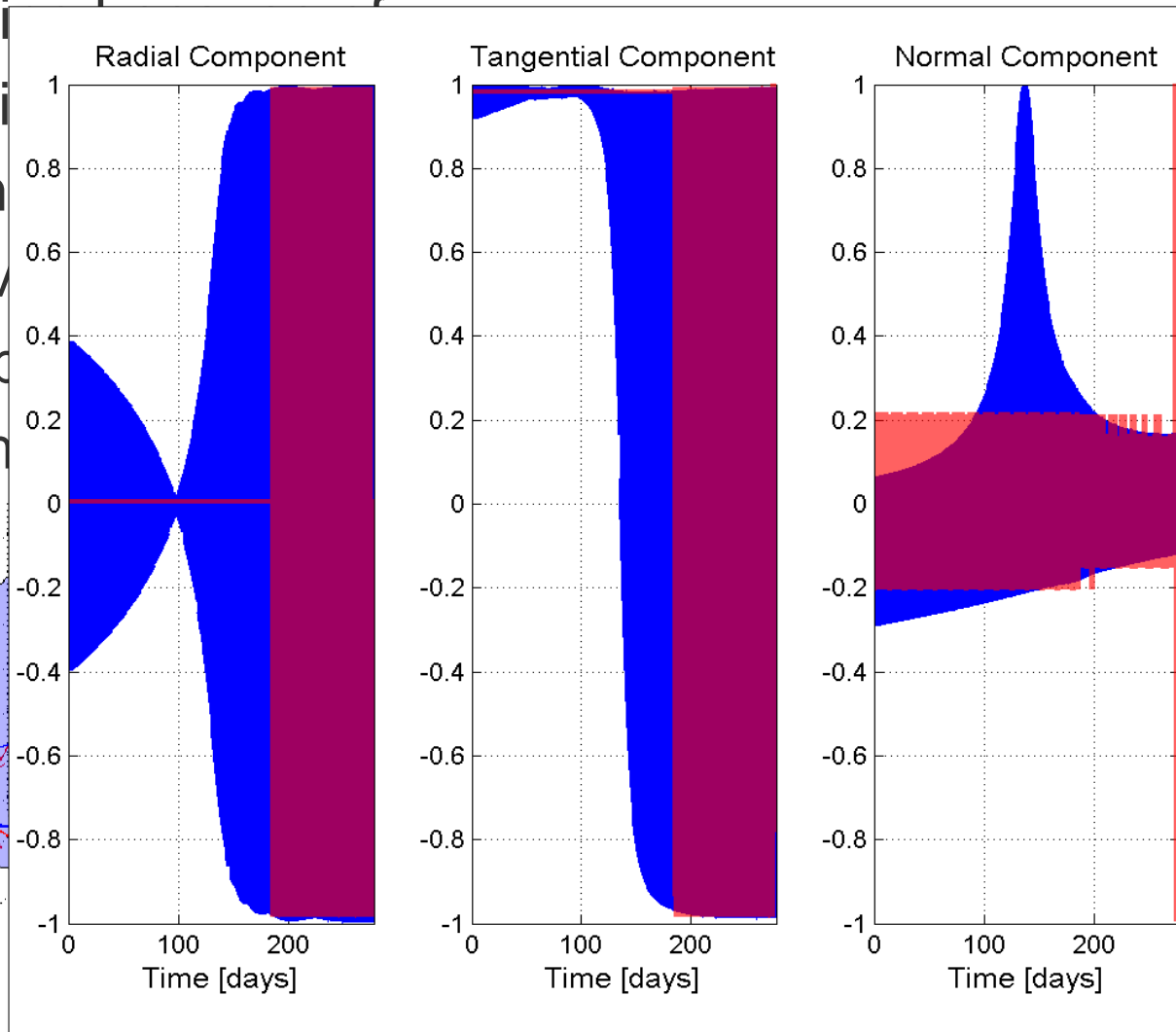
# Challenging Space Applications



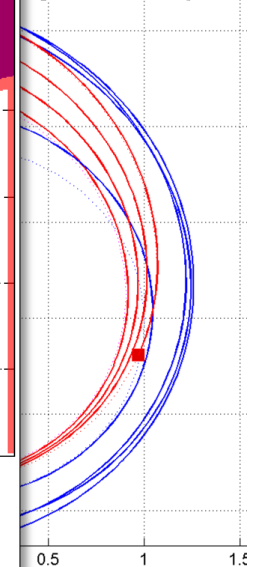
# Low-Thrust Orbit Transfer and Low-Thrust Interplanetary Mission

## Challenges

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



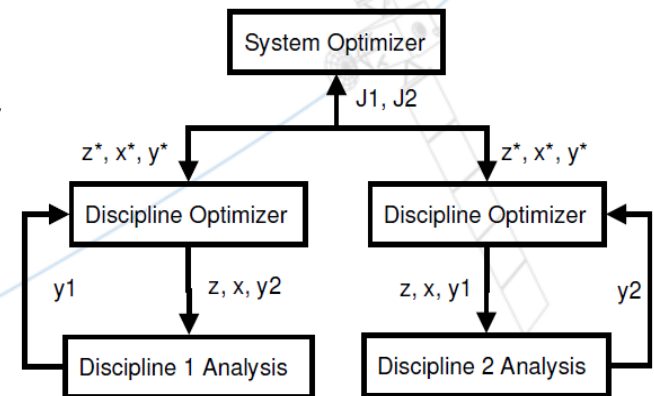
budget  
(aspects)



# 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

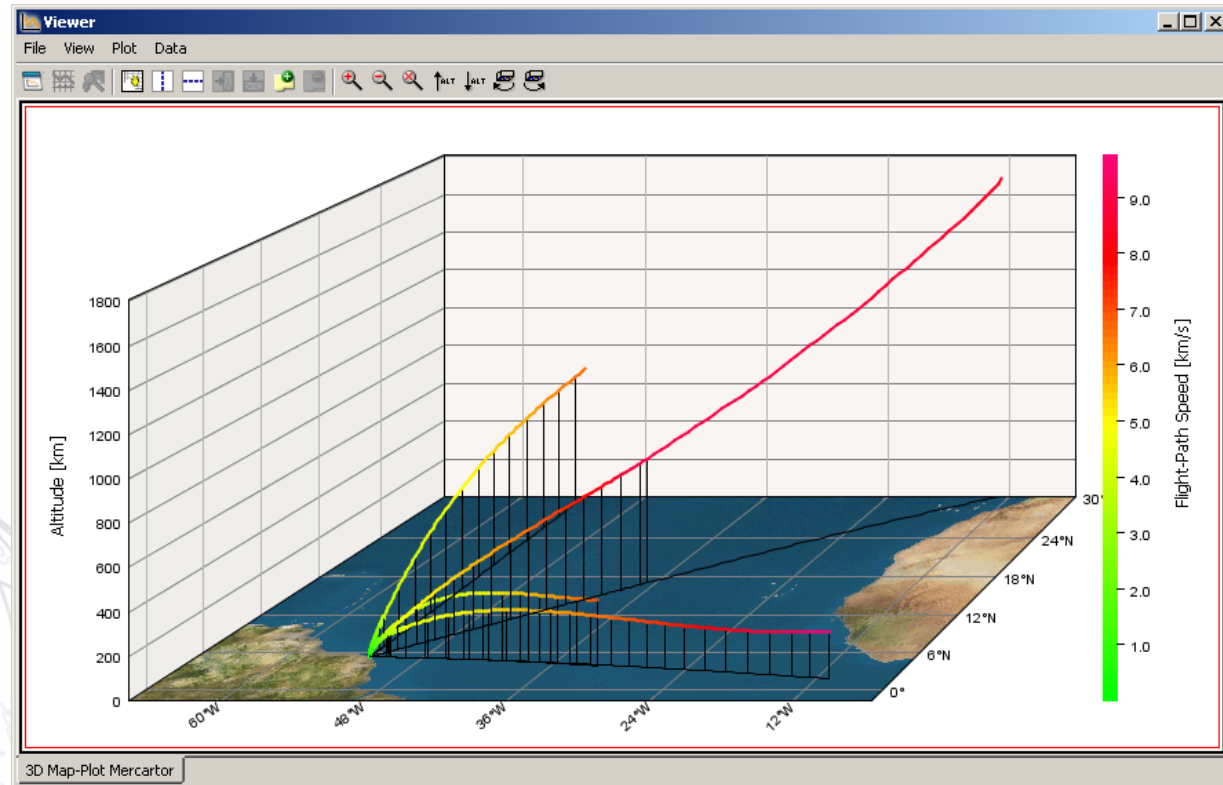
SQP is applied  
main task is to find best MDO strategy





# Multi-Mission Optimization and Design

- 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



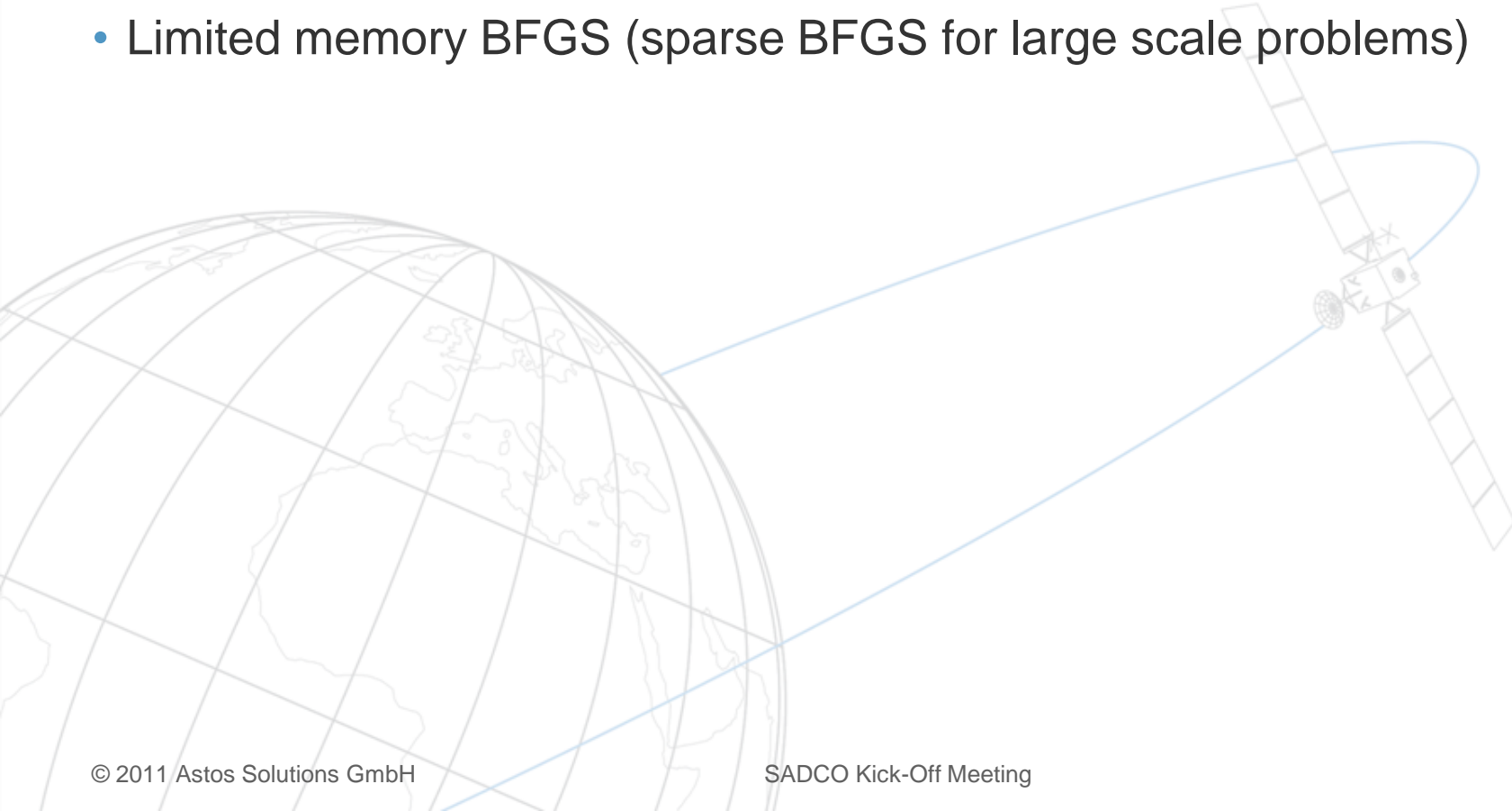
# Sensitivity Analysis After Design Optimization

- 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?

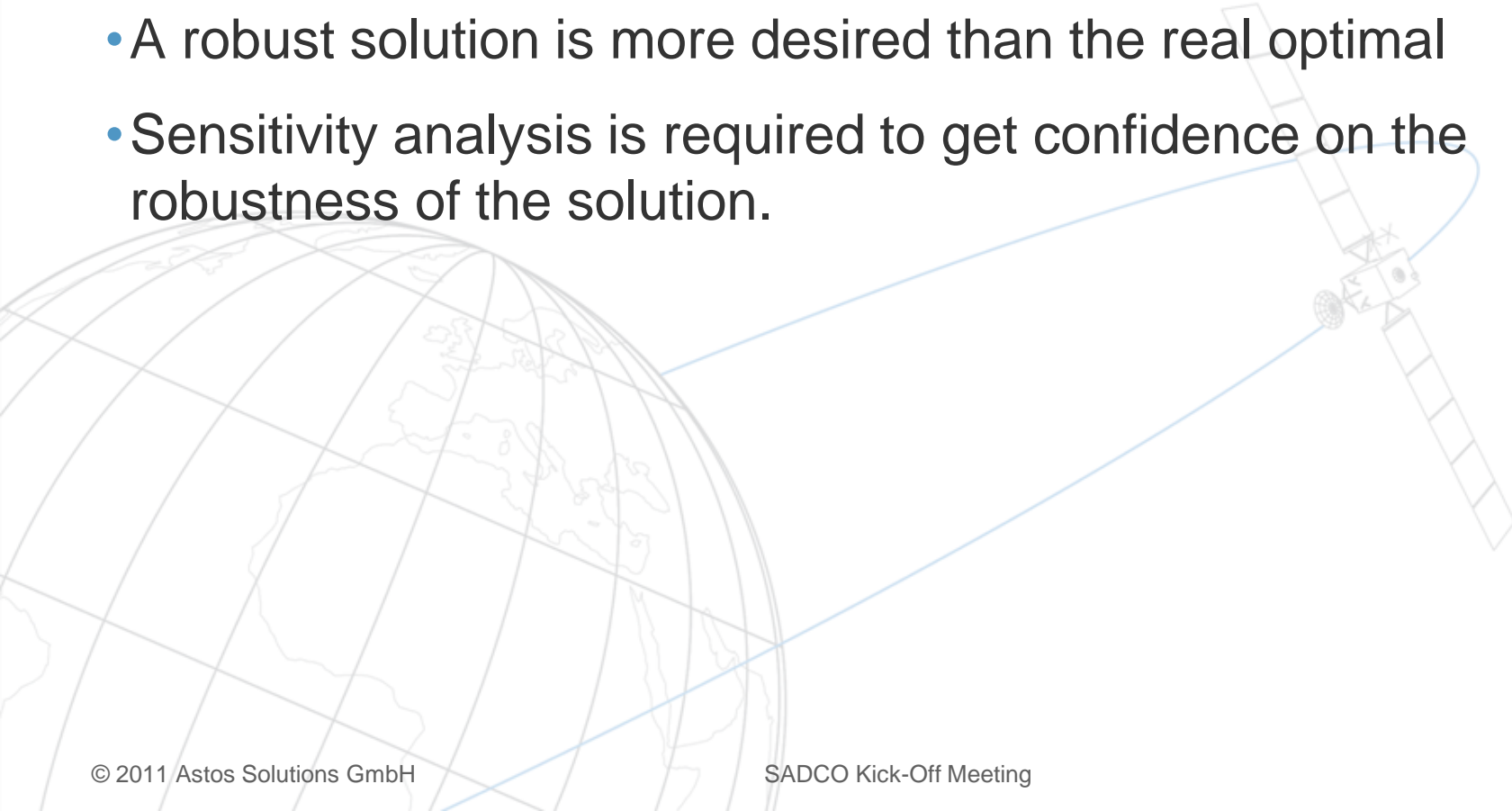
Foreseen activities in cooperation with Uni. Bremen and SADC0 fellow Sonja Rauski:

- 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!**

