Thoughts on Producing “Ancillary Data” to Support a Planetary Flight Project

Rev. 2

January 2015

Topics

- What are “ancillary data?”
- Approach and skills needed to produce ancillary data files
- Information about the “SPICE” methodology for producing and using ancillary data

Caution Regarding Terminology

- Caution: this presentation uses terminology and lingo familiar to the NAIF team. It could be that "our" interpretation and "your" interpretation of a term are different.

Motivation - 1

- Planetary* flight projects need a set of “ancillary data” to support:
  - mission design (pre-Phase A through Phase C/D)
  - ground segment design, development and testing (Phase B/C/D)
    - » including instrument team science observation planning and science data analysis tools
  - flight engineering operations (Phase E)
  - science observation planning (Phases C/D and E)
  - initial science data analysis (Phase E)
  - science data archive preparation (Phase E)
- “Ancillary data” refers, at a minimum, to spacecraft trajectory and spacecraft orientation (attitude)

* Some of this is applicable to the other space science disciplines as well

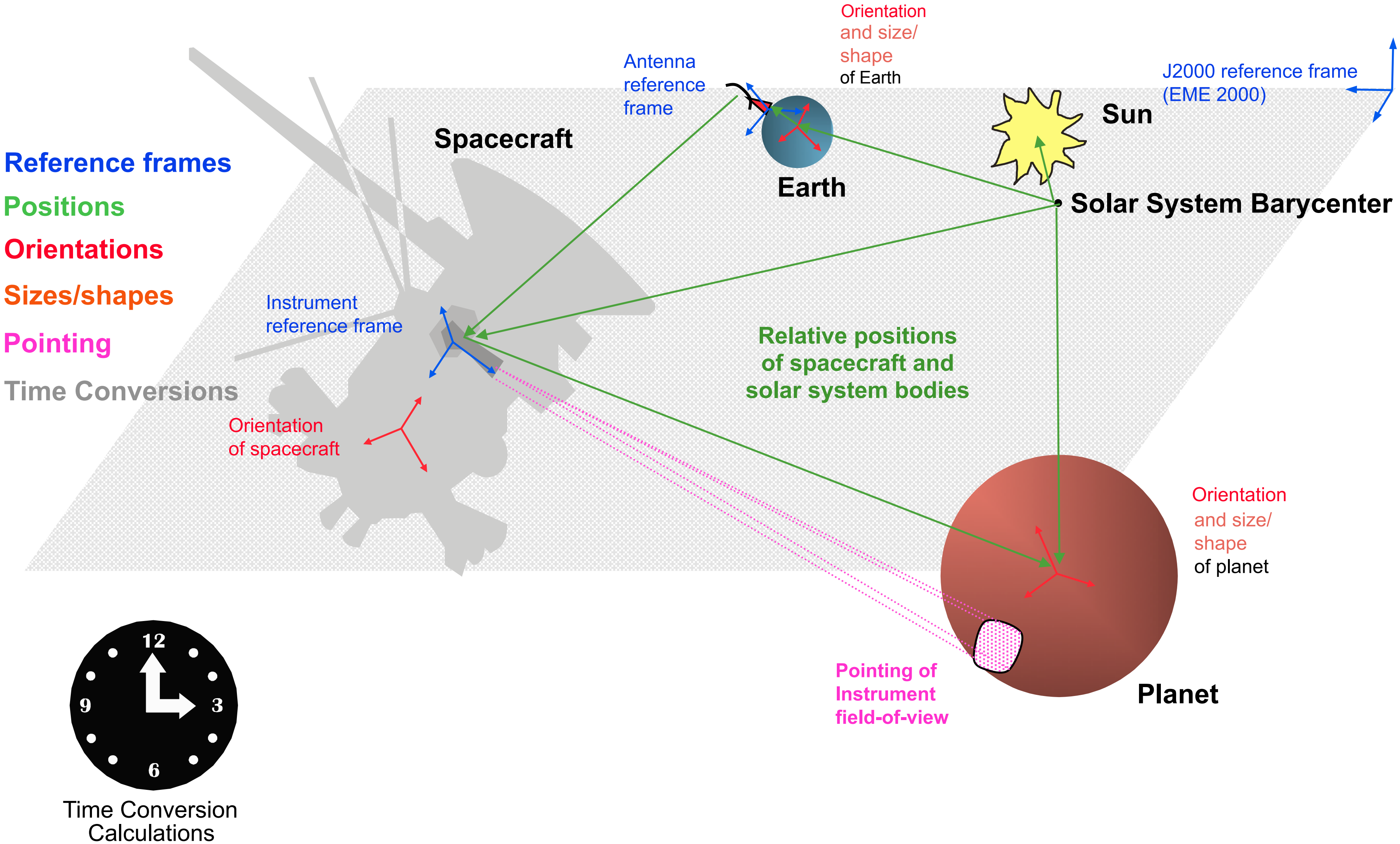
Motivation - 2

- Ancillary data often also include some or all of:
  - reference frame* specifications
  - instrument mounting alignment and instrument field-of-view specifications
  - target body physical and cartographic constants
  - data needed for time system conversions

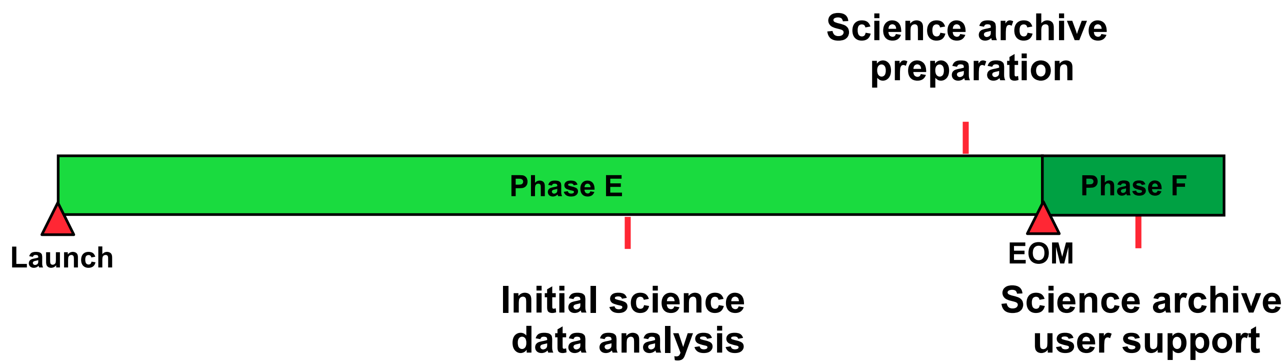
- The next chart provides a pictorial representation of one vision of ancillary data
  - Alternate views of what constitutes “ancillary data” certainly exist

*Outside of SPICE it is often the case the term “coordinate system” is used instead of “reference frame

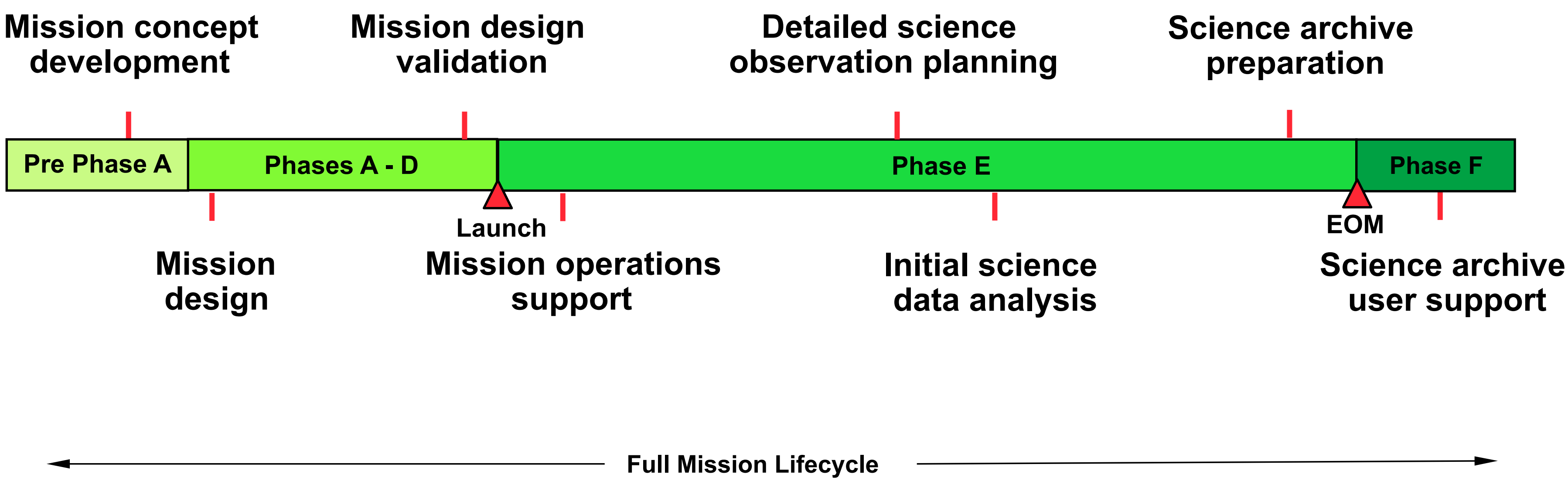
A View of Ancillary Data



When are Ancillary Data Used?
A Minimal View



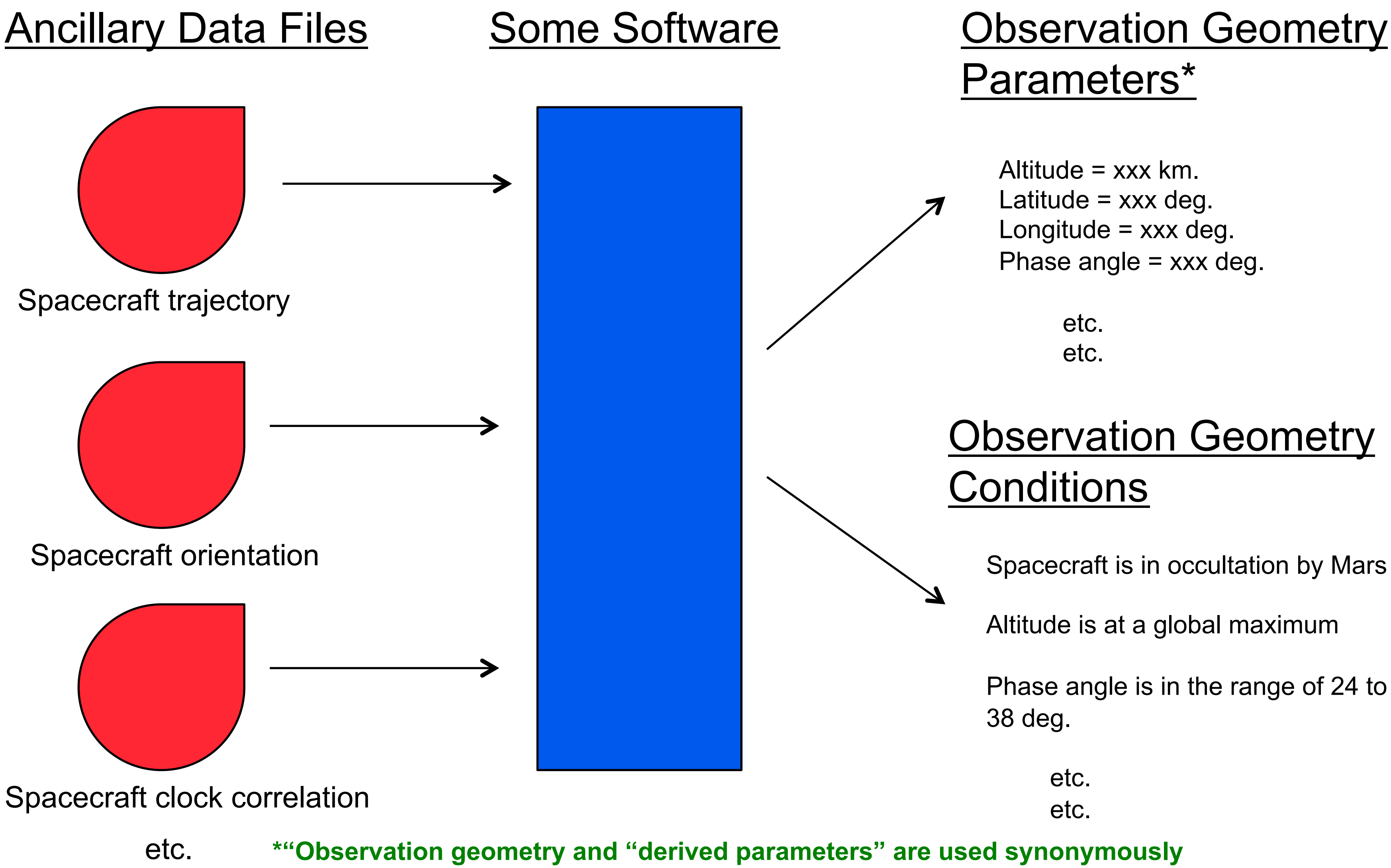
When are Ancillary Data Used?
A Far More Practical and Common View



Purposes for Ancillary Data

- **To inform ground communications/tracking stations of the planned spacecraft trajectory**
- **To compute observation geometry parameters and conditions needed by mission engineers for tasks such as…**
  - communications station view period calculations
  - communications station antenna pointing and tuning
  - thermal and telecom analyses
- **To compute observation geometry parameters and conditions needed by instrument teams for tasks such as…**
  - approval of a mission (trajectory) design
  - science observation planning
  - science data analysis
  - science archive preparation

Contrast "Ancillary Data" and "Observation Geometry*"



*"Observation geometry and "derived parameters" are used synonymously

What Approach Might Be Taken to Producing Ancillary Data?

- At one end of the spectrum the project might provide:
  - an ASCII table of reconstructed, time-tagged spacecraft position vectors
  - an ASCII table of reconstructed, time-tagged spacecraft orientation quaternions

  with the above tables using UTC time tags (sometimes called SCET)

  - Then leave it to end users to use these data, perhaps some other data as well, along with fully user-built software to compute needed observation geometry parameters
- At the other end of the spectrum the project might provide a complete “SPICE” capability as described later on
- Certainly other, middle-ground approaches exist

What Skills are Needed to Produce Ancillary Data?

- The skills needed could vary depending on:
  - the scope and requirements the project has agreed to
  - the approach taken
  - end-user expectations

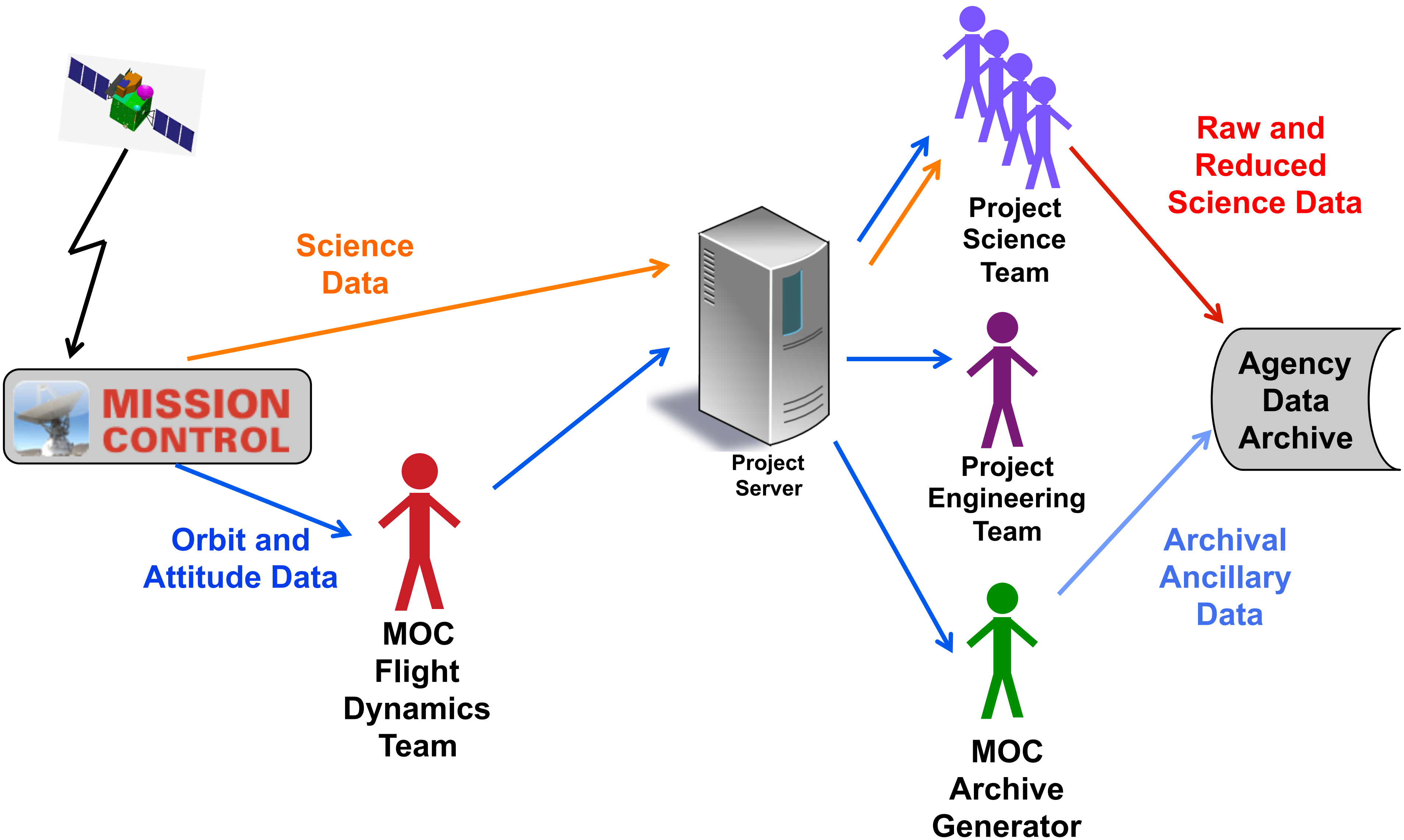
- Generally speaking, doing a good job is not trivial and often requires some knowledge of:
  - astrodynamics (orbital mechanics)
  - spacecraft dynamics
  - spacecraft and ground-based time systems
  - software programming and testing
  - ground data system workings and automation
  - insight and tools needed to validate ancillary data
  - ability to help end users resolve problems in using ancillary data

Ancillary Data Production Functions: A Minimal Model

- As a minimum, project personnel will need to produce, validate, distribute and archive reconstructed (“definitive”) spacecraft orbit and attitude data
  - Perhaps the production, validation and distribution would be accomplished by a Mission Operations Center (MOC) flight dynamics team
  - Perhaps the archive preparation would be accomplished by another member of the MOC
  - The next graphic depicts this minimal approach

Ancillary Data Production & Use

A Minimal Model



Advantages and Disadvantages of the Minimal Model

- Advantages
  - May be built upon local processes already in place
  - Minimizes the direct cost to the mission
- Disadvantages
  - Some ancillary data needed by some end users is not provided in the simple model shown
    - » Users must find the rest for themselves
    - » The archive will be extremely sparse: not much help to scientists after the mission is over
  - How to use the provided ancillary data, along with other data, to compute needed geometry parameters is largely left as an exercise for the end user
    - » Requires special effort on the part of each instrument team, maybe even individual team members
    - » Easy for them to make mistakes

A Somewhat Maximal Model: The SPICE Approach

- NASA's Planetary Science Division, NASA's Planetary Data System (PDS) and the multi-national Interplanetary Data Alliance (IPDA) <u>recommend</u> planetary projects use the "SPICE" approach
  - But using SPICE is *NOT* a requirement

- "SPICE" is described later on in this presentation

Your Considerations

- When selecting an approach to providing ancillary data, consider several points

Planetary Ancillary Data are Complex

- Almost everything is moving and/or rotating
  - Often with multiple sources providing different values
- Many reference frames are used
  - There may be multiple definitions
  - The data/parameters used to realize them may be changing
- Many coordinate systems are used
  - Standard definitions may not exist
- Size and shape estimates for target bodies abound and are constantly evolving
  - The various mechanisms used for modeling size/shape also evolve
- Several time systems are used
  - Mishandling of time tags is a common problem
- National interests can complicate matters

End Users Haven’t Much Patience

- **Many–perhaps most–end users of ancillary data don’t want to be bothered dealing with these data**
  - **Using ancillary data is just one of many steps along the way to achieving science or engineering results**
  - **Using ancillary data is generally viewed as difficult**
  - **Many users simply want *the* answer, or even *an* answer, readily available to them**

Ancillary Data Production Often Gets Little Attention

- Ownership of the job is often distributed among several entities
- The job is often not well understood
- When, where and how the data will be used is often not well understood
- Producing ancillary data is often seen as just a rather simple and boring archiving job

Takes Real Effort

- No matter the approach used for producing and using ancillary data, doing so requires non-trivial resources
  - Smart, interested, motivated people
  - Planning
  - Time
  - Funding
  - Training/consulting

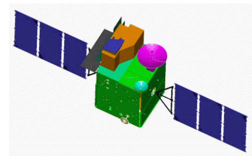
- Giving only “ancillary attention” to producing ancillary data can result in frustrated engineers, angry scientists, incorrect science results and a poor archive
  - Could even jeopardize a mission

How does SPICE Differ from a Minimal Ancillary Data System?

- More kinds of ancillary data are provided
- SPICE provides users a large suite of software used to read SPICE ancillary data files and to compute observation geometry (a.k.a. derived quantities)
  - End users have a great deal of help in writing their own software to determine geometry parameters
- SPICE is fully multi-mission: can be and has been used on every kind of planetary mission
- SPICE is supported with tutorials and programming lessons
  - NAIF offers an approximately annual training class for end users
- SPICE is the recommended means of archiving ancillary data by NASA's Planetary Data System and by the International Planetary Data Alliance

From Where do SPICE Ancillary Data Come?

- From the spacecraft



- From the mission control center

- From the spacecraft and instrument builders

- From science organizations

- SPICE is used to organize and package these data in a collection of stable file types, called "kernels.” SPICE includes software for writing some kernels, and for reading all kernels and computing observation geometry (derived quantities)

SPICE System Components

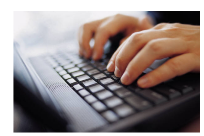
Ancillary data files (“kernels”)…………………..

Software (SPICE Toolkit) …………..

Documentation ……..

Tutorials ……………………………….

Programming lessons …………………………..



SPICE Data Overview

Logical Components	Data Files	Contents*
S Spacecraft	SPK	Spacecraft and target body ephemerides
P Planet	SPK, PcK	Target body size, shape and orientation
I Instrument	IK	Instrument field-of-view size, shape and orientation
C Camera-matrix	CK	Orientation of spacecraft and any articulating structure on it
E Events	~~EK ESP ESQ ENB~~ No longer used	Events information: - Science Plan (ESP) - Sequence of events (ESQ) - Experimenter’s Notebook (ENB)
	Others: FK	Reference frame specifications
	Others: LSK	Leapseconds tabulation
	Others: SCLK	Spacecraft clock coefficients
	Others: DSK	Digital shape models

* See the Backup section for details

SPICE Toolkit Software Overview

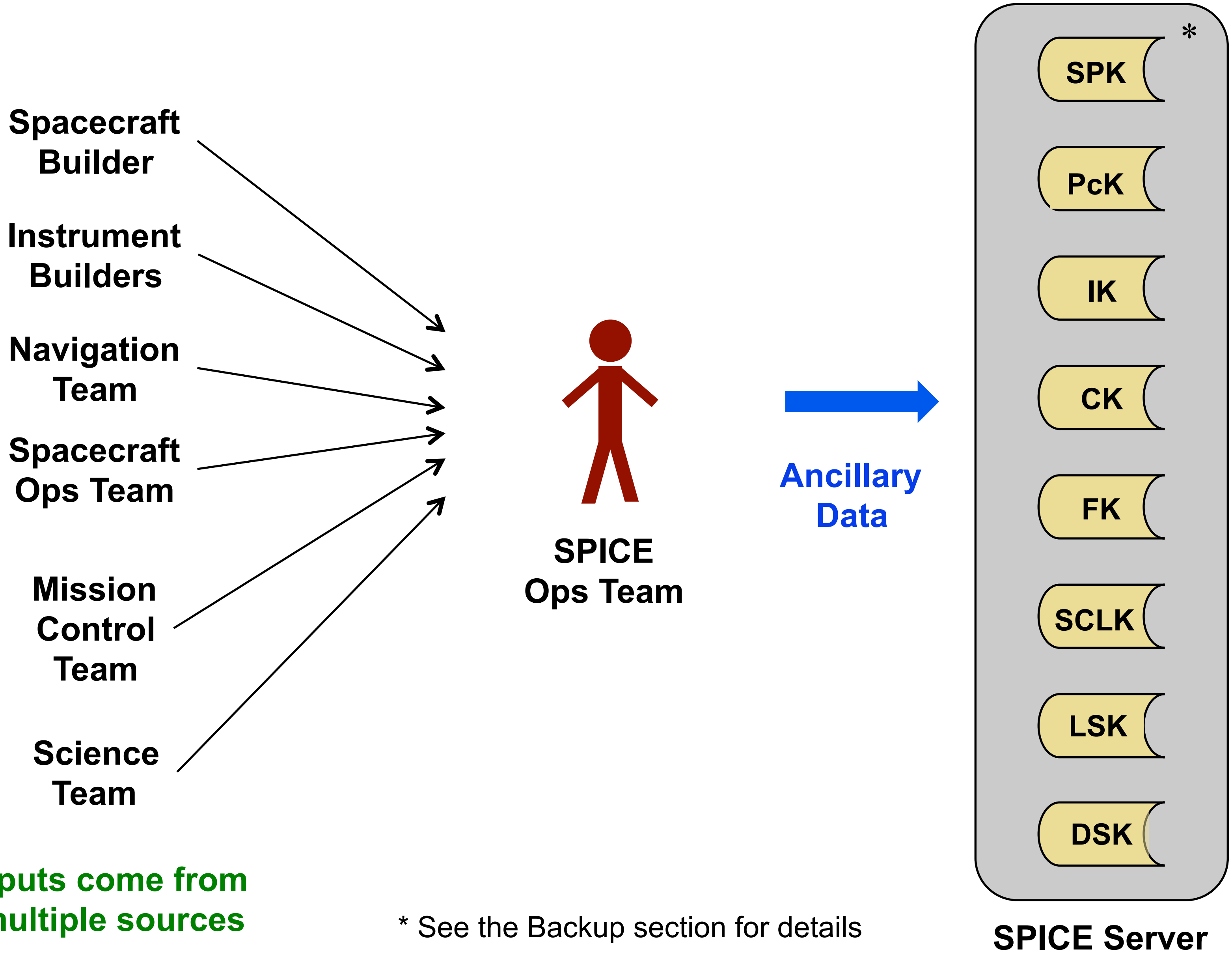
Contents

- Library of subroutines (~1500)
  - Just a few used within a customer's program to compute quantities derived from SPICE data files
- Programs (19)
  - SPICE data production
  - SPICE data management
- Documentation
  - Highly annotated source code
  - Technical Reference Manuals (23)
  - User Guides

Versions

- Four languages
  - Fortran
  - C
  - Interactive Data Language (IDL)
  - MATLAB
  - Under development:
    - Java Native Interface (JNI)
    - Python
- Five platforms
  - PC/Linux
  - PC/Windows
  - Sun/Solaris
  - Mac/OSX
- Several compilers
  - For the Fortran and C Toolkits

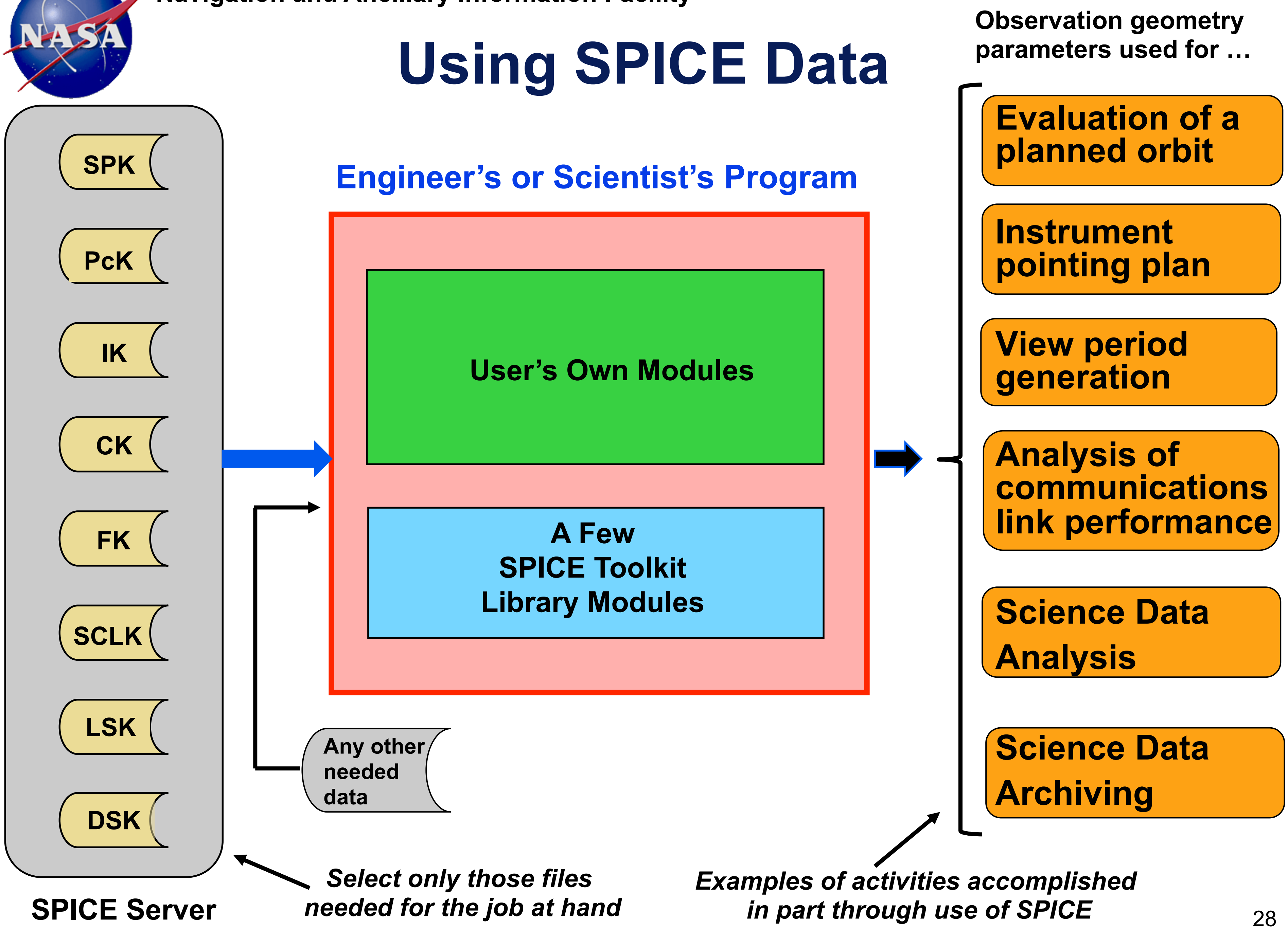
Producing SPICE Data



Inputs come from multiple sources

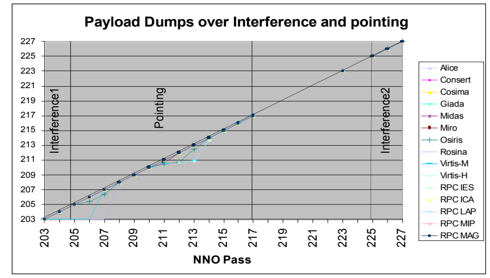
* See the Backup section for details

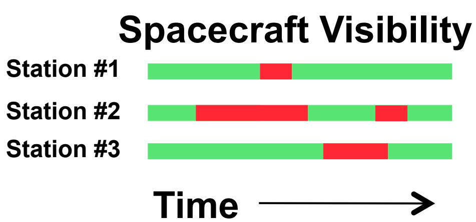
Using SPICE Data



How is SPICE Typically Used?

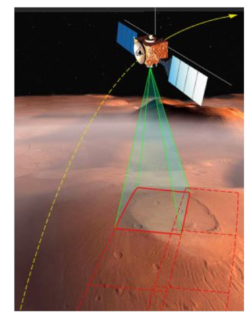
Evaluation of a planned trajectory

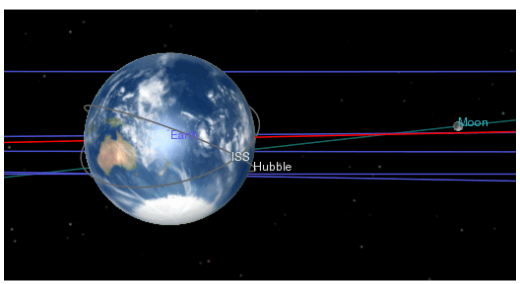




Mission engineering analyses

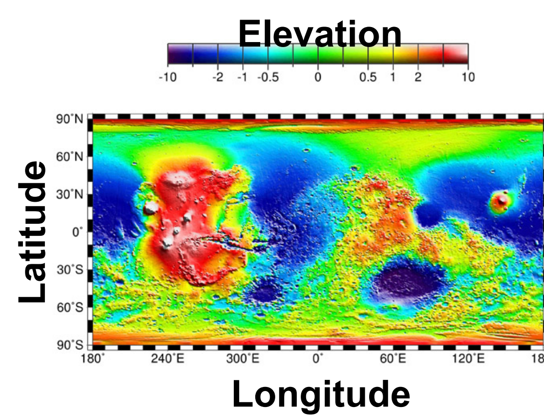
Planning an instrument pointing profile





Observation geometry visualization

Science data archiving and analysis



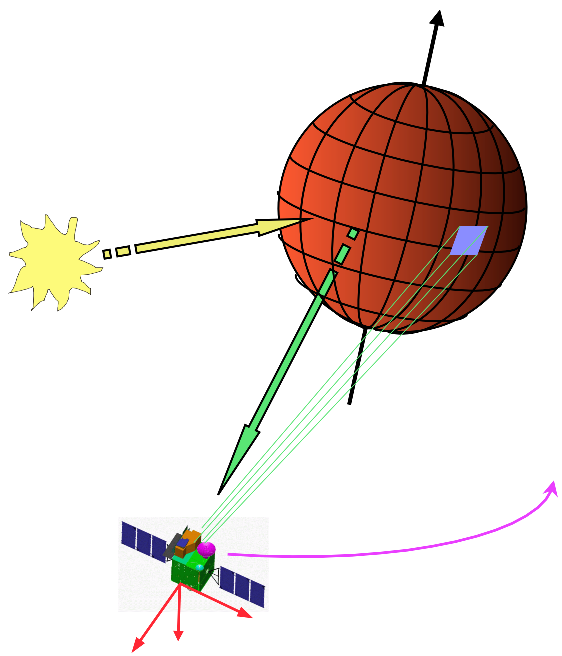
Kinds of Missions Using SPICE

- **Cruise/Flyby**
  - Remote sensing
  - In-situ measurement
  - Instrument calibration
- **Orbiters**
  - Remote sensing
  - In-situ measurement
  - Communications relay
- **Landers**
  - Remote sensing
  - In-situ measurements
  - Rover or balloon relay
- **Rovers**
  - Remote sensing
  - In-situ sensing
  - Local terrain characterization

What Can One Do With SPICE?

Compute many kinds of observation geometry parameters at selected times

A Few Examples

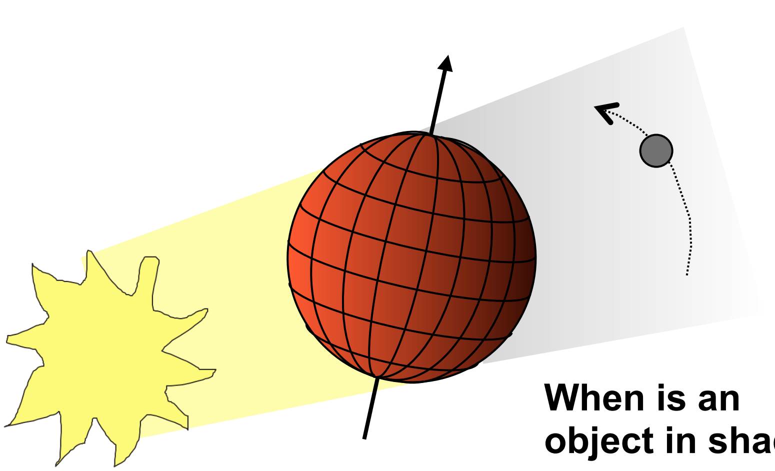


- **Positions and velocities of planets, satellites, comets, asteroids and spacecraft**
- **Size, shape and orientation of planets, satellites, comets and asteroids**
- **Orientation of a spacecraft and its various moving structures**
- **Instrument field-of-view location on a planet's surface or atmosphere**

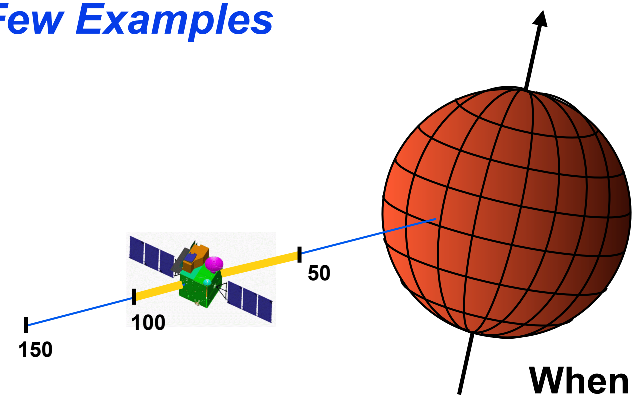
What Can One Do With SPICE?

Find times when a selected "geometric event" occurs, or when a selected "geometric condition" exists

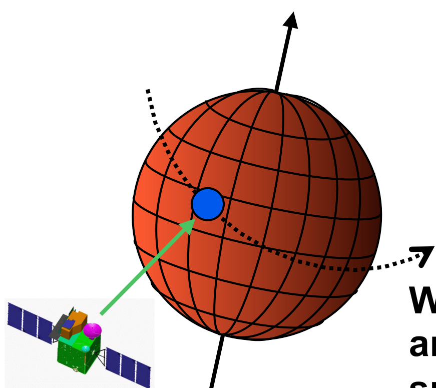
A Few Examples



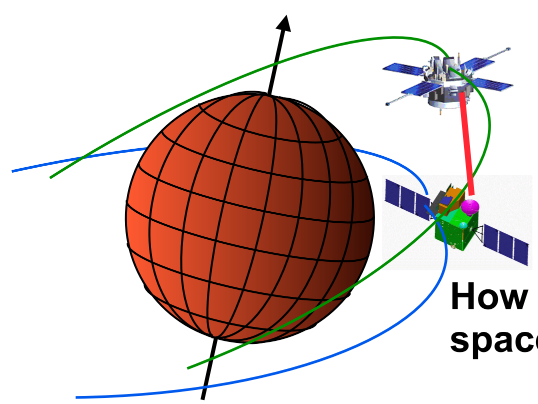
When is an object in shadow?



When is the spacecraft's altitude within a given range? (say 50 to 100 km)



When is an object in front of another, as seen from a spacecraft?



How close will two spacecraft get?

Advantages of Using SPICE

- SPICE provides a great deal of space geometry computational capability–end users need not invent this themselves
- SPICE software is very well tested and extensively used; bugs are rarely found
- Having proven, extensive and reusable means for producing and using ancillary data can reduce cost and risk, and can help scientists and engineers achieve more substantive, accurate and timely results
- Many scientists and engineers around the world are already familiar with SPICE; it is truly multi-mission
- SPICE is free to individual users
- No ITAR restrictions, no licensing
- SPICE is the NASA-preferred archive mechanism

Disadvantages of Using SPICE

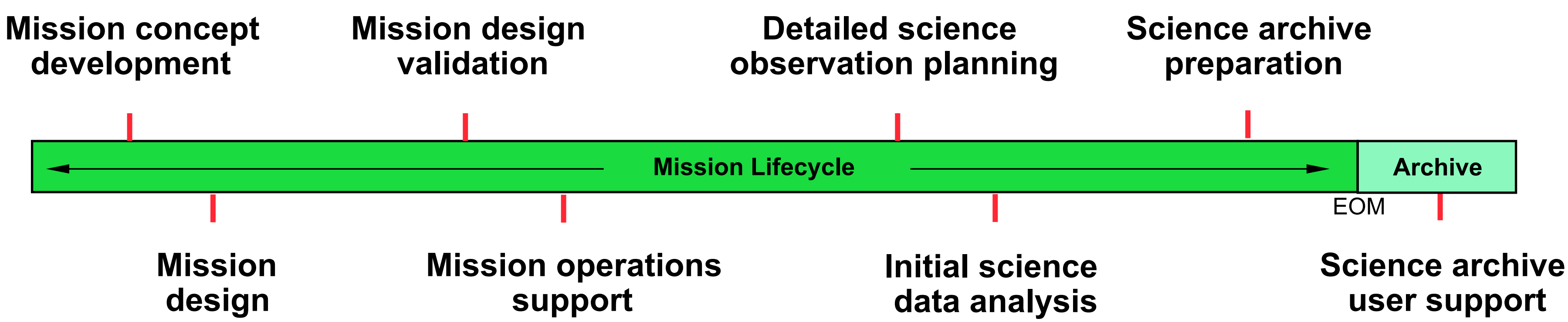
- Production and use of SPICE data requires use of SPICE software
  - Maybe your project doesn't wish to count on "outside" software
  - Maybe the SPICE Toolkit is not available in the language(s) or for the operating system(s) you use
- Learning to correctly <u>produce</u> SPICE data requires effort and at least some domain knowledge
- Learning to correctly <u>use</u> SPICE data and software also takes effort
  - Some scientists and engineers don't wish to take the time to do so
- Documentation of mission event information within the SPICE paradigm has not proved successful
- You'll need to provide SPICE-aware problem solving and user consultation services throughout the life of the mission
- Use of SPICE is not a requirement of any space agency or standards group

If you are considering use of SPICE …

read on

Timeline Big Picture

- **SPICE is frequently used throughout the mission life cycle and beyond: from pre-Phase A to well past EOM**



- **You'll need to plan and budget for various components of SPICE support consistent with the extent of your project's planned use of SPICE**
- **Your agency should have an archive willing to ingest SPICE data and to support future users of the SPICE archive**

Who Needs to Learn What?

- Mission Ops people need to learn: SPICE data production
- Scientists and Mission Ops people need to learn: SPICE data use
  - How to write SPICE-aware software used for mission and science planning, science data analysis, and mission engineering
- Someone needs to learn: SPICE archive production
  - Possibly a single product, but more often a pipeline operation with incremental deliveries every 3 to 6 months
- Someone needs to learn: User consulting
  - Know enough about SPICE…
    - » to be able to provide advice to your project on how to use SPICE
    - » to be able to help solve user's problems

- See the next three pages for some details

SPICE Data Production

- Time-invariant SPICE data files are made once, with perhaps a few subsequent updates
  - Mission Frames Kernel (FK)
  - Instrument Kernels, one for each instrument (IK)
  - Planetary Constants Kernel (PCK)*
  - Leap seconds kernel (LSK)*
  - Digital Shape Kernel (DSK)*, if useful to the project (optional)
- Time varying SPICE data files are produced regularly
  - Spacecraft trajectory (SPK)
  - Spacecraft orientation (CK)
    - » Possibly also orientation of antennas, solar arrays and other articulating structures
  - Spacecraft clock correlation (SCLK)

* Generic versions provided by NAIF may be all that is needed

SPICE Archive Production

- Involves numerous details, especially for production of the very first increment
- Examples…
  - Ensure no missing files
  - Validate all files
  - Get orbit (SPK) and attitude (CK) data producers to fill in gaps where possible
  - Ensure any updates from instrument teams are included in the FK and IKs
  - Produce/complete descriptive documentation of all files
  - Produce needed archive labels
  - Conduct a peer review
  - Fix liens from peer review and deliver final version
- This is much more than a crank-turning activity

SPICE User Consultation

- Have someone trained to be able to help scientists and engineers use SPICE correctly and effectively

What Does NAIF Provide for Free?

- **The SPICE Toolkit, available at the NAIF website**
  - http://naif.jpl.nasa.gov/naif/toolkit.html
  - Includes numerous utilities useful in making, validating and managing SPICE data files
  - Includes a large amount of user-focused documentation
- **Access to all archived and generic SPICE data available at the NAIF website: http://naif.jpl.nasa.gov/naif/data.html**
- **A collection of SPICE tutorials and "open book" SPICE programming lessons, also available at the NAIF website**
  - http://naif.jpl.nasa.gov/naif/tutorials.html
  - http://naif.jpl.nasa.gov/naif/lessons.html
- **For NASA's planetary missions:**
  - a SPICE Archive Preparation Guide and some related tools
  - peer review of archive submissions and archiving of the peer reviewed SPICE data in the PDS*
  - consultation on using SPICE for NASA-funded scientists using planetary mission SPICE data archived at the NAIF Node of the PDS*
- **About once every year and a half, a three day SPICE training class, usually held in the Pasadena CA area**
  - This class is focused on "beginners": people largely new to using SPICE data and software
  - To date there are no classes for SPICE data producers

*PDS = NASA's Planetary Data System

What You'll Need to Provide

- Capable personnel who are motivated to learn how to produce and validate SPICE kernels
- A data production infrastructure for producing and distributing SPICE kernels
- Any needed SPICE training for your scientists and engineers intending to use your SPICE data
  - If the timing works out, perhaps they can attend the public NAIF class mentioned on the previous page
- Careful oversight of the SPICE production process
- Analysis and correction of problems encountered in SPICE production
  - Often requires good knowledge of your spacecraft and/or its ground data system
- Consultation for your project's SPICE users

What Could NAIF Provide if Funded to do so?

- Many flight projects at JPL and elsewhere within NASA elect to fund NAIF to do:
  - SPICE data production
  - training and consultation for project team members
  - archive production
- A few times NASA has funded NAIF to provide some support for a foreign flight project
- NAIF could provide training for others on data production or archive production

- What's the cost for such support?
  - There's not a simple answer, but for recent projects NAIF ops support has ranged from about $25K to $60K per year, usually spanning from Phase C into Phase F

To learn more

- To learn more about technical or programmatic details please contact the NAIF manager

Charles Acton

charles.acton (at) jpl.nasa.gov

Backup

Ancillary Data Production Challenges

Contents of SPICE Kernels

Graphics Depicting SPICE Data

Backup

Ancillary Data Production Challenges

Ancillary Data Production and Usage Challenges
Introduction

- No matter what approach is selected for providing engineers and scientists (and an archive) with ancillary data, real effort is needed to provide an effective system, and to detect and resolve the inevitable problems that arise
- Even when good ancillary data are made available, end users often have trouble using these data
- The next several charts provide some examples

Examples of Ancillary Data Production & Usage Challenges
Spacecraft Trajectory

- Will users need both predicted as well as reconstructed ("definitive") trajectory data?
  - Both types need be readily available
  - How to distinguish between these?
  - How to manage the many files needed?
- Need to reduce or eliminate gaps in coverage
- How avoid "jumps" between adjacent trajectory solutions?
- How to handle improved trajectory solutions:
  - resulting from long arc fits
  - resulting from use of better gravity model
- How to notify end users when new data are available, and for what purpose?
- Will the time system used be a problem for end users?
- Any special requirements placed by tracking stations?
- Any issues resulting from a changing time step size?
- Need you provide end users an evaluation/interpolation algorithm?

Examples of Ancillary Data Production & Usage Challenges
Spacecraft Attitude

- Are predicted attitude data needed? With what fidelity? How to achieve that fidelity?
- Are the accuracy and frequency of downlinked attitude data sufficient for all users?
- How accurate are attitude data time tags?
- How does the attitude file producer deal with gaps in downlinked attitude telemetry?
- How do end users deal with gaps in reconstructed attitude data?
- Is attitude data volume too excessive for end users?
- How to "name" and document attitude data files so as to meet end user needs?

Examples of Ancillary Data Production & Usage Challenges
Spacecraft Clock Calibration

- Often the science data and the spacecraft attitude data returned from a spacecraft have time tags determined by an on-board clock
- If this is the case, the ground system must be able to convert such time tags to another time system, such as UTC or TAI or ???
  – Requires the flight system generate and downlink time correlation “packets,” and that these be used to calibrate the spacecraft clock to the accuracy required by the mission.
  – Doing this sort of calibration well can be quite difficult
  – Calibration can be complicated by inadequate frequency of returned calibration packets, clock temperature changes, unplanned clock resets, and planned clock “jumping”

Examples of Ancillary Data Production & Usage Challenges
Reference Frames and Coordinate Systems

- **Planetary missions tend to make use of multiple reference frames and coordinate systems**
- **In many cases the definition of the frame or coordinate system is not a true standard**
  - **For some reference frames the defining data are not well documented, and/or are disputed, and/or are evolving over time**
  - **For some coordinate systems what is meant by a name can be uncertain or totally left up to the creator**
- **Some end users do not know how to write code to convert between frames or between coordinate systems**
- **The above can result in confusion, inconsistencies and outright errors in geometry parameter computations**

Examples of Ancillary Data Production & Usage Challenges
Instrument Geometry

- **Geometry pertaining to "instruments" is important to understanding the science data acquired**
  - Where the instrument is mounted, and with what orientation
    - » Could involve multiple "view ports"
  - If applicable, also need to know the instrument's field-of-view size and shape
- **Such data are often built-in to an instrument's ground software, and thus hidden from other flight team members and users of the instrument archive**
- **A good ancillary information system makes these data readily available and clearly documented**
  - Must be checked using real flight observations, since errors of 90 or 180 degrees often crop up
- **The same info is often needed, or useful, for antennas, solar arrays, star trackers, etc.**

Examples of Ancillary Data Production & Usage Challenges
Target Body Shape Data

- Gone are the days when every target body was modeled as a sphere, spheroid or tri-axial ellipsoid
  - Either tessellated plate models for small, irregular objects, or digital elevation models, for large bodies are the norm
- Estimating such shapes is generally in the purview of instrument experiments
  - But making such shapes readily available to other scientists, and to mission engineers, is increasingly important. This is complicated due to:
    - » multiple methods used for modeling
    - » rapidly evolving model data
    - » lack of standard software for using models
- A modern ancillary data system should address these challenges, where appropriate

Backup

Contents of SPICE Kernels

SPICE Data Details- 1

SPK

- Space vehicle ephemeris (trajectory)
- Planet, satellite, comet and asteroid ephemerides
- More generally, position of something relative to something else

PcK

- Planet, satellite, comet and asteroid orientations, sizes, shapes
- Possibly other similar “constants” such as parameters for gravitational model, atmospheric model or rings model

IK

- Instrument field-of-view size, shape, orientation
- Possibly additional information, such as internal timing

SPICE Data Details- 2

CK

- Instrument platform (e.g. spacecraft) attitude
- More generally, orientation of something relative to a specified reference frame

EK
3 components

- "Events," broken into three components:
  - ESP: Science observation plans
  - ESQ: Spacecraft & instrument commands
  - ENB: Experiment "notebooks" and ground data system logs

EK is not much used

SPICE Data Details - 3

FK

- **Frames**
  - Definitions of and specification of relationships between reference frames (coordinate systems)
    - Both “fixed” and “dynamic” frames are available

LSK

- **Leap seconds Tabulation**
  - Used for UTC <--> TDB (ET) time conversions

SCLK

- **Spacecraft Clock Coefficients**
  - Used for SCLK <--> TDB (ET) time conversions

DSK

- **Shape models (digital elevation model and tessellated plate model) (DSK)**

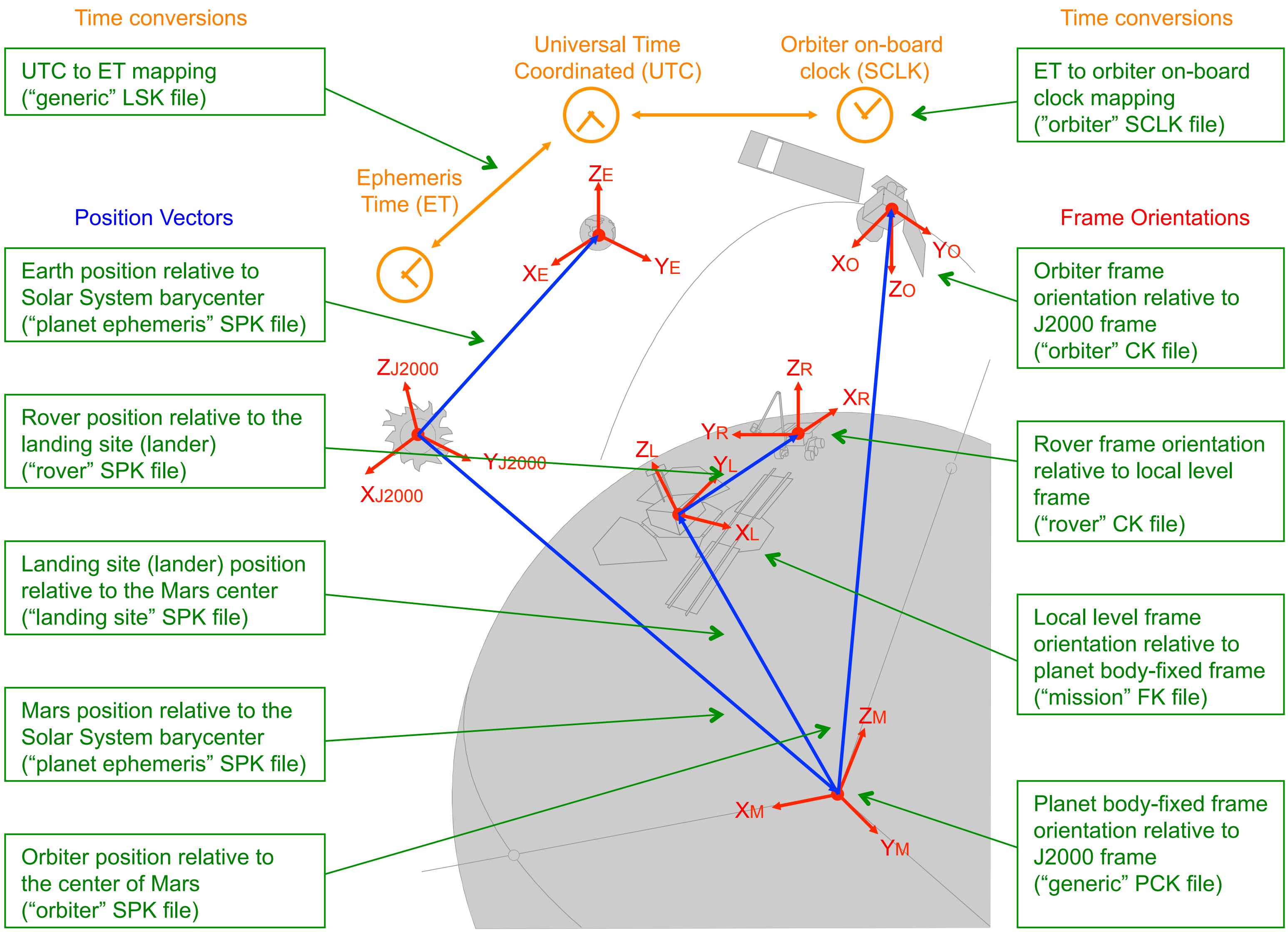
  Under development now

UTC = Coordinated Universal Time   ET = Ephemeris Time   SCLK = Spacecraft Clock Time

Backup

Graphics Depicting SPICE Data

Global SPICE Geometry



Orbiter Geometry

Position Vectors

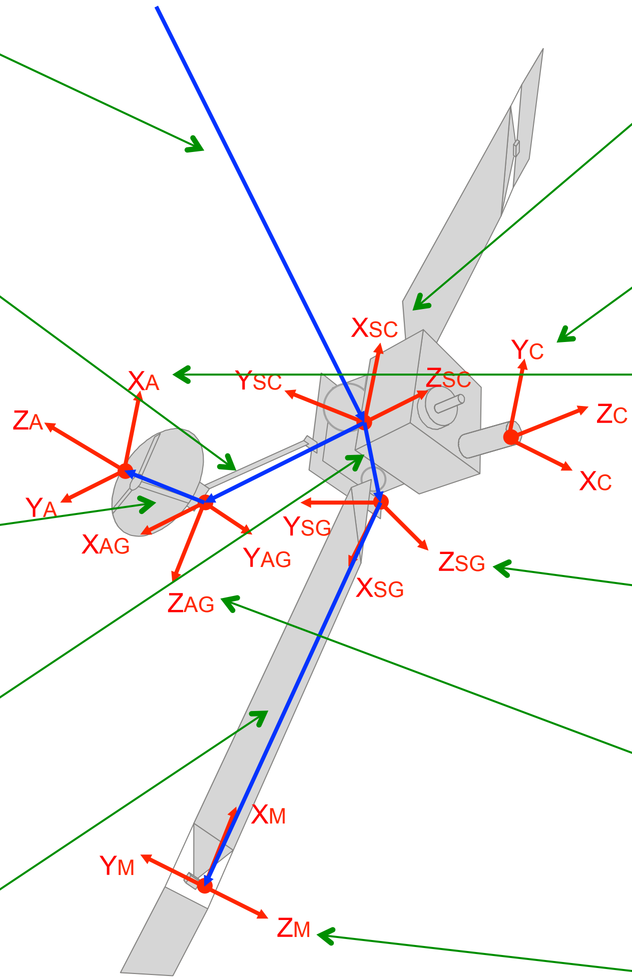
Spacecraft position relative to planet center (“spacecraft” SPK file)

High gain antenna gimbal position relative to spacecraft (“structures” SPK file)

High gain antenna phase center location relative to high gain antenna gimbal (“structures” SPK file)

Solar array gimbal position relative to spacecraft center (“structures” SPK file)

Magnetometer position relative to solar array gimbal (“structures” SPK file)



Frame Orientations

Spacecraft frame orientation relative to inertial frame (“spacecraft” CK file)

Camera frame orientation relative to spacecraft frame (“mission” FK file)

High gain antenna frame orientation relative to high gain antenna gimbal frame (“mission” FK file)

Solar array gimbal frame orientation relative to spacecraft frame (“solar array” CK file)

High gain antenna gimbal frame orientation relative to spacecraft frame (“antenna” CK file)

Magnetometer frame orientation relative to solar array gimbal frame (“mission” FK file)

Lander Geometry

Position Vectors

Left and right mast camera positions relative to camera head (“structures” SPK file)

Robotic arm gimbal and camera relative positions (“structures” SPK file)

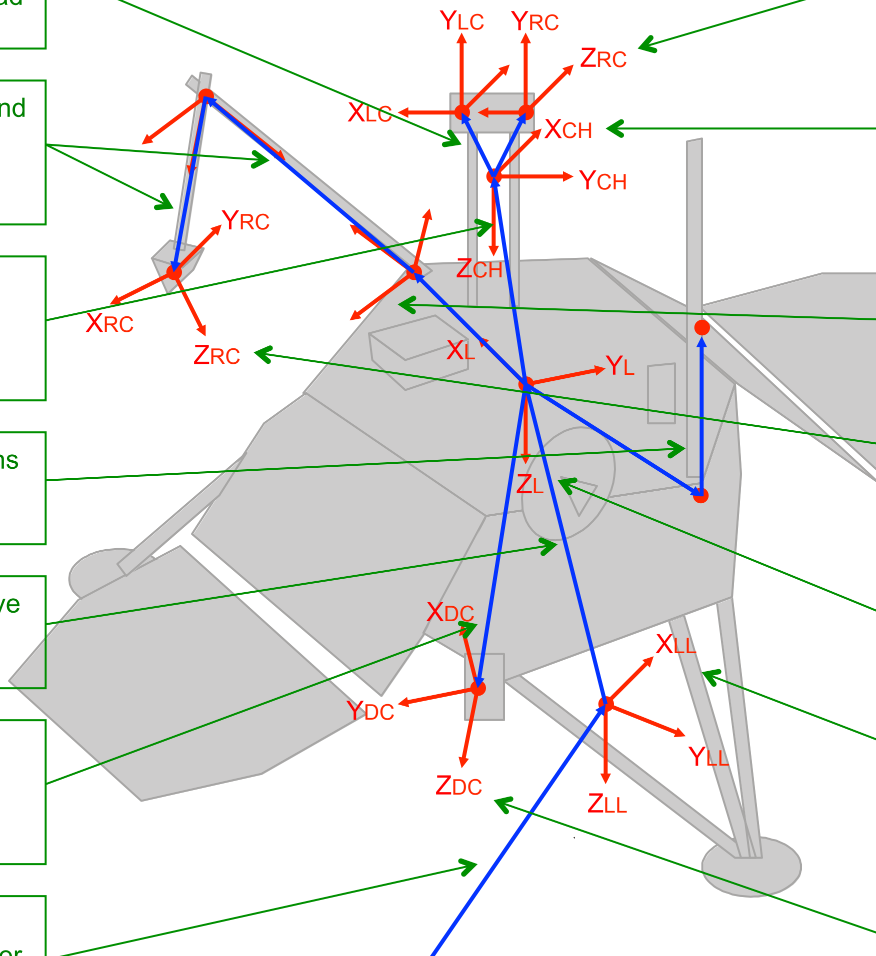
Mast camera head position relative to lander (“structures” SPK file)

Meteo sensor positions relative to lander (“structures” SPK file)

Lander position relative to landing site (“lander” SPK file)

Descent camera position relative to lander (“structures” SPK file)

Landing site position relative to planet center (“landing site” SPK file)



Frame Orientations

Left and right mast camera frame orientations relative to camera head frame (“mission” FK file)

Mast camera head frame orientation relative to lander frame (“mast camera” CK file)

Robotic arm gimbal frames orientations relative to each other (“arm” CK file)

Robotic arm camera frame orientation relative to last gimbal frame (“mission” FK file)

Lander frame orientation relative to local level frame (“lander” CK file)

Local level frame orientation relative to planet body-fixed frame (“mission” FK file)

Descent camera frame orientation relative to lander frame (“mission” FK file)

Rover Geometry

Position Vectors

Left and right mast camera center positions relative to end of mast (“structures” SPK file)

End of mast position relative to elbow gimbal (“structures” SPK file)

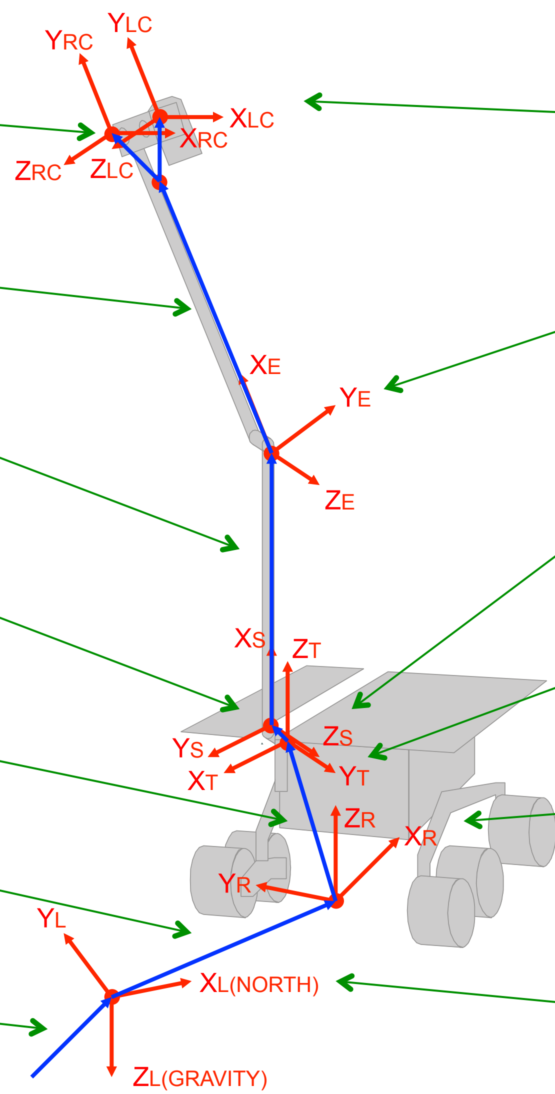
Mast elbow gimbal position relative to shoulder gimbal (“structures” SPK file)

Mast shoulder gimbal position relative to torso gimbal (“structures” SPK file)

Mast torso gimbal position relative to rover (“structures” SPK file)

Rover position relative to landing site (“rover” SPK file)

Landing site position relative to planet center (“landing site” SPK file)



Frame Orientations

Left and right mast camera frames orientation relative to mast elbow frame (“mission” FK file)

Mast elbow frame orientation relative to mast shoulder frame (“mast” CK file)

Mast shoulder frame orientation relative to mast torso frame (“mast” CK file)

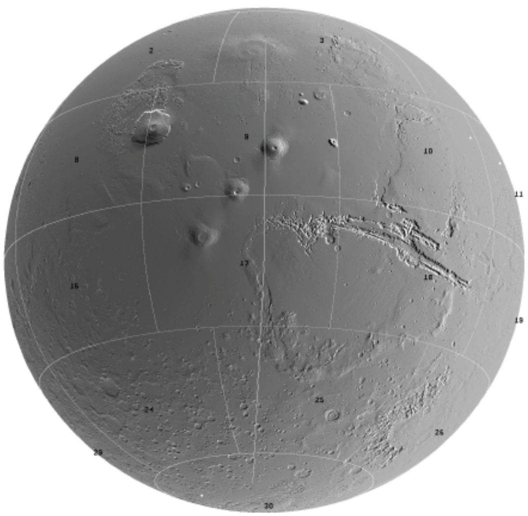
Mast torso frame orientation relative to rover frame (“mast” CK file)

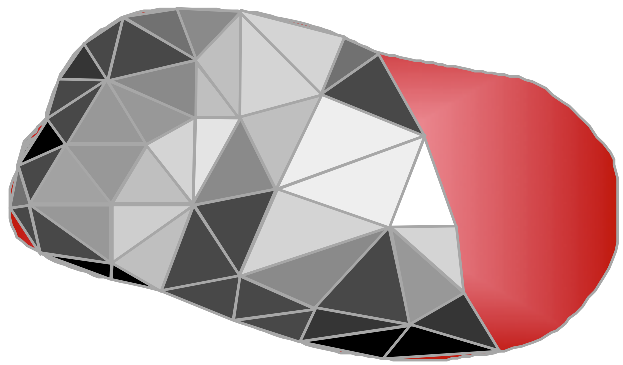
Rover frame orientation relative to local level frame (“rover” CK file)

Local level frame orientation relative to planet body-fixed rotating frame (“mission” FK file)

Digital Shape Kernel

The two DSK types shown here are used to provide high fidelity shape models needed by modern experiments. Would be used instead of, or in addition to, the spherical, spheroidal and ellipsoidal models available in a PCK.





Digital elevation model

For large, regular bodies such as the earth, moon and Mars

Tessellated plate model

For small, irregular bodies such as asteroids and small satellites