

A large, bold, black number '42' is centered on a dark blue background. The number has a soft, glowing blue aura around it, giving it a three-dimensional appearance.

A General-Purpose
Multi-body, Multi-spacecraft
Simulation

Eric Stoneking
2014

What kind of a name is 42?

- 42 is a tongue-in-cheek reference to the “answer to Life, the Universe, and Everything”, as proclaimed by Douglas Adams in his Hitchhiker's Guide to the Galaxy stories
 - The first book is spent seeking this answer, which had taken a special computer and millions of years to compute. But by the time they had it, nobody knew what the question was anymore.
 - The next two books are spent seeking the question, which turns out to be: “What do you get when you multiply six by nine?”
- The reader may draw a number of lessons from this story...

So what is it really?

- A simulation of spacecraft attitude and orbital dynamics and control
- Intended for use from concept studies through ops
 - Rapid prototyping makes it useful for MDL studies
 - Environment models support actuator sizing, performance studies
 - High-fidelity dynamics handle multi-body, flexible-body spacecraft
 - Portability (Mac, linux, Windows) minimizes infrastructure requirements
 - Clean interface aids progression from flight software “model” to dropping in actual flight software
 - Visualization aids situational awareness from concept to operations
- Designed to be powerful, but easy to get started

Features

- Multiple spacecraft, anywhere in the solar system
 - Two-body, three-body orbit dynamics (with seamless transition between)
 - One sun, nine planets, 45 major moons
 - Minor bodies (comets and asteroids) added as needed
 - RQ36 (aka Bennu), Eros, Itokawa, Wirtanen, etc
- Multi-body spacecraft
 - Tree topology
 - Kane's dynamics formulation
 - Each body may be rigid or flexible
 - Flexible parameters taken (by m-file script) from Nastran output (.f06 file)
 - Joints may have any combination of rotational and translational degrees of freedom

More Features

- Supports precision formation flying
 - Several S/C may be tied to a common reference orbit
 - Used by FACET, Stellar Imager studies
 - Encke's method or Euler-Hill equations used to propagate relative orbit states
 - Precision maintained by judicious partitioning of dynamics
 - Add big things to big things, small things to small things
- Clean FSW interface facilitates FSW validation
 - Used by GLAST project for independent validation of vendor's (autocoded) GNC flight software
- Open Source, available on sourceforge and github
 - [Sourceforge.net/projects/fortytwospacecraftsimulation](https://sourceforge.net/projects/fortytwospacecraftsimulation)
 - [Github.com/ericstoneking/42](https://github.com/ericstoneking/42)

42 Software Overview

Architecture, Interfaces with Matlab

42 is Written in C for Speed, Portability

- The C language has a well-deserved reputation for giving you enough rope to hang yourself. Like any sharp tool, some care in handling is needed.
 - If it weren't fast, powerful, portable, ubiquitous, and free, we wouldn't put up with it.
- The good news is, you can get a quick prototype running in 42 with zero C coding
 - Use “prototype FSW”, command script
- The next steps are to add your own sensor, FSW, and actuator models
 - Simple existing models show where to insert yours
 - Global data structures make needed signals easy to find
 - Choose your level of fidelity and difficulty: n00b -> l33t
- You can get into the guts of the environment and dynamics if you want to, but you probably won't ever need to

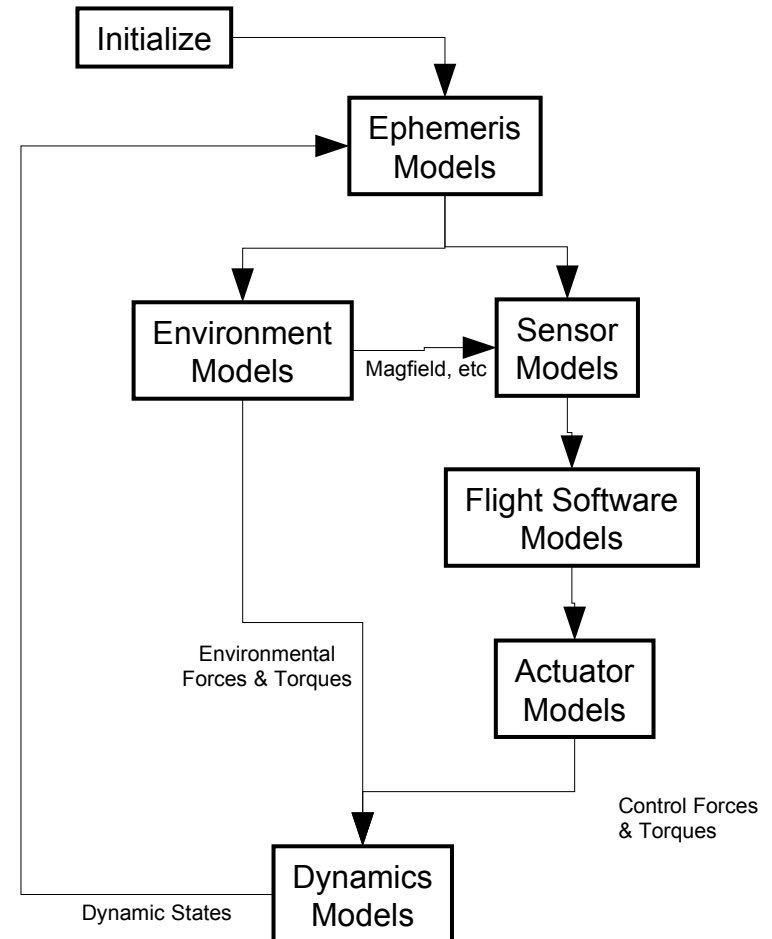
Command Script

- The command script allows changing configuration (sim, FSW, or GUI) in the course of a sim run, from an ASCII input file.
- Good for rapid prototyping
- Inject sensor or actuator failures
- Model ground commands
- Script graphics for movie generation

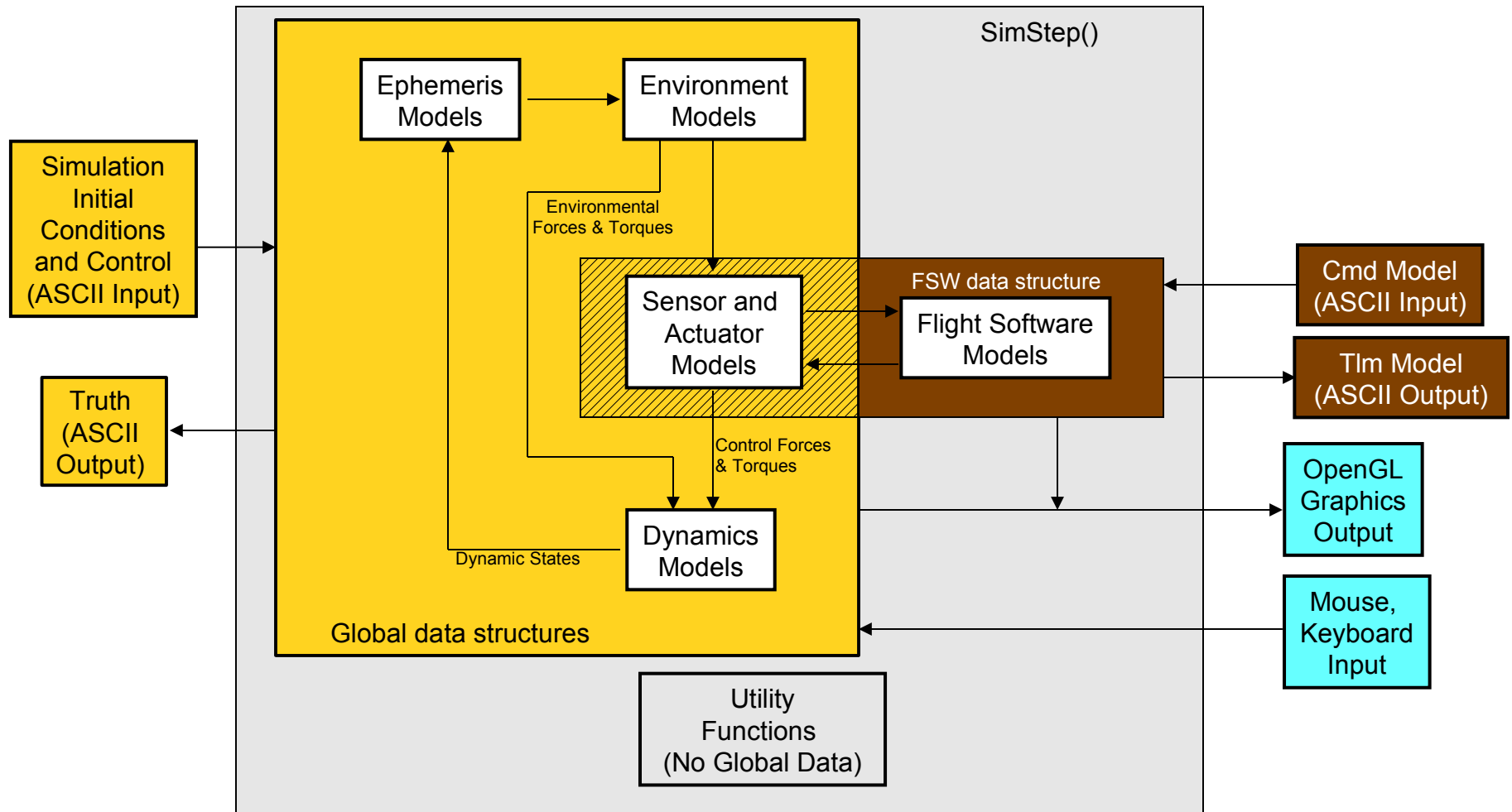
[illegible]

A Basic Simulation Loop

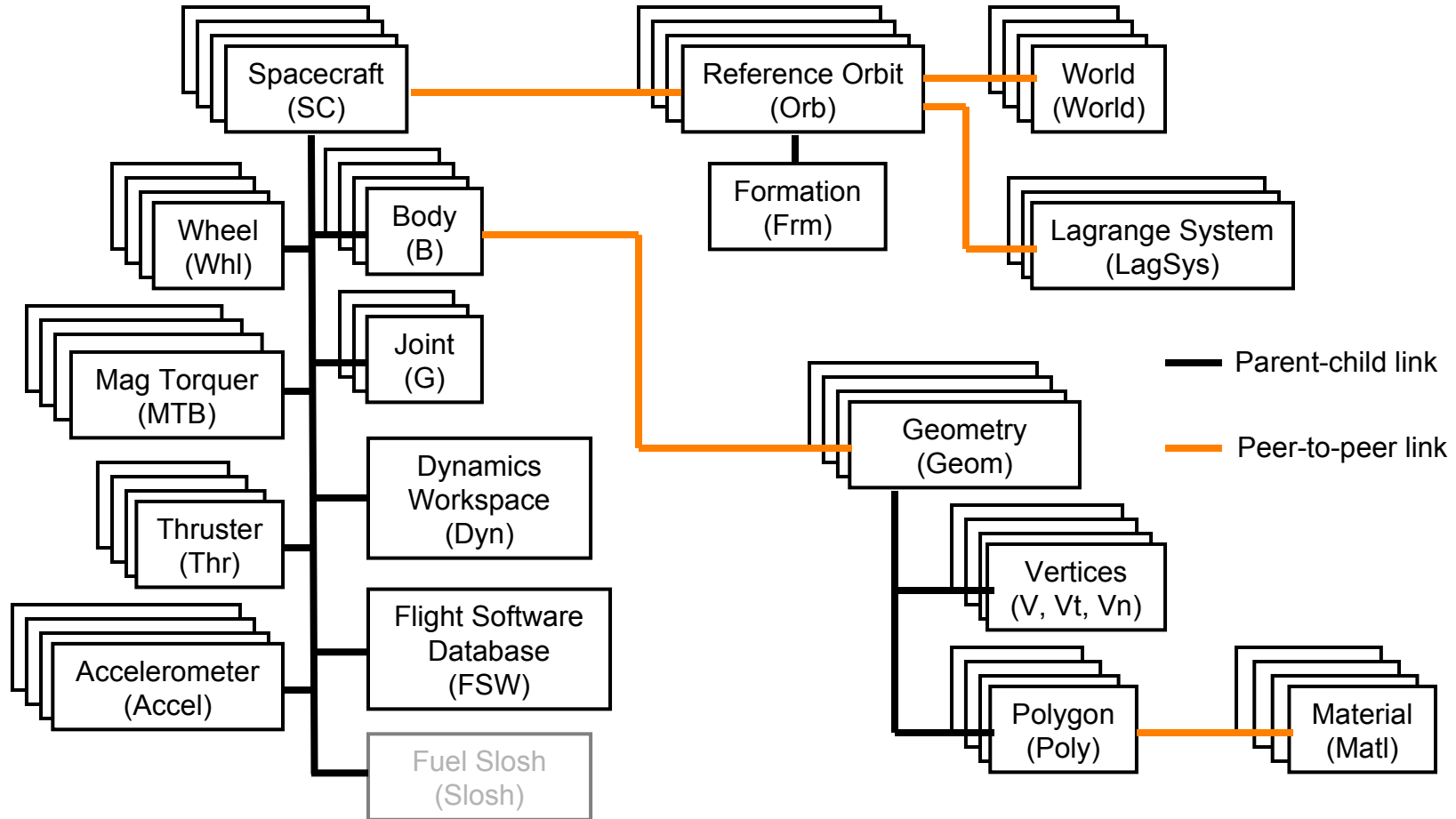
- Initialize
 - Read user inputs
 - Set up
- Ephemeris: Where is everything?
 - Sun, Earth, Moon, etc
 - Orbits
 - Spacecraft
- Environment Models: What forces and torques exerted by the environment?
- Sensor Models
 - Input truth
 - Output measurements
- Flight Software Models
 - Input Measurements
 - Process Control Laws, etc
 - Output Actuator Commands
- Actuator Models
 - Input Commands
 - Output Forces and Torques
- Dynamics: How does S/C respond to forces and torques?
 - Integrate dynamic equations of motion over a timestep
 - Advance time to next step



42's Architecture



Global Data Structure Relationships



The Three Layers of Code

- 42 uses three “layers” of code:
 - Low-level toolkit functions:
 - Everything comes in and goes out through arguments and return value
 - No global variables
 - Segregated into *kit.c files (mathkit.c, dcmkit.c, etc)
 - Top-level frame outline:
 - Follows outline, does minimal math/logic itself
 - Access to all global variables
 - Mid-level workhorse functions
 - Most likely to be tailored to a particular need
 - Access to global variables

Toolkit Code Example

```

/*****
/*  Convert quaternion to direction cosine matrix  */
void Q2C(double Q[4], double C[3][3])
{
    C[0][0] = 1.0-2.0*(Q[1]*Q[1]+Q[2]*Q[2]);
    C[0][1] = 2.0*(Q[0]*Q[1]+Q[2]*Q[3]);
    C[0][2] = 2.0*(Q[2]*Q[0]-Q[1]*Q[3]);
    C[1][0] = 2.0*(Q[0]*Q[1]-Q[2]*Q[3]);
    C[1][1] = 1.0-2.0*(Q[2]*Q[2]+Q[0]*Q[0]);
    C[1][2] = 2.0*(Q[1]*Q[2]+Q[0]*Q[3]);
    C[2][0] = 2.0*(Q[2]*Q[0]+Q[1]*Q[3]);
    C[2][1] = 2.0*(Q[1]*Q[2]-Q[0]*Q[3]);
    C[2][2] = 1.0-2.0*(Q[0]*Q[0]+Q[1]*Q[1]);
}

```

Top-level Code Example

```
ReportProgress();
ManageFlags();

/* Read and Interpret Command Script File */
CmdInterpreter();

/* Update Dynamics to next Timestep */
for(Isc=0;Isc<Nsc;Isc++) {
    if (SC[Isc].Exists) Dynamics(&SC[Isc]);
}
OrbitMotion();
SimComplete = AdvanceTime();

/* Update SC Bounding Boxes occasionally */
ManageBoundingBoxes();

Ephemerides(); /* Sun, Moon, Planets, Spacecraft, Useful Auxiliary Frames */
for(Isc=0;Isc<Nsc;Isc++) {
    S = &SC[Isc];
    if (S->Exists) {
        Environment(S); /* Magnetic Field, Atmospheric Density */
        Perturbations(S); /* Environmental Forces and Torques */
        Sensors(S);
        FlightSoftWare(S);
        Actuators(S);
        PartitionForces(S); /* Orbit-affecting and "internal" */
    }
}
Report(); /* File Output */
```

Mid-level Code Example

```
/* Find Attitude Command */
FindCLN(FSW->PosN,FSW->VelN,CRN,wln);
C2Q(CRN,qrn);
MxV(CRN,FSW->svn,svr);

/* Form Error Signals */
QxQT(FSW->qbn,qrn,qbr);
RECTIFYQ(qbr);

/* PD Control */
for(i=0;i<3;i++) {
    FSW->Tcmd[i] = -FSW->Kr[i]*FSW->wbn[i]-FSW->Kp[i]*(2.0*qbr[i]);
    FSW->Twhlcmd[i] = -FSW->Tcmd[i];
}

/* Momentum Management */
for(i=0;i<3;i++) {
    Herr[i]=FSW->Hw[i]-FSW->Hwcmd[i];
}
VxV(Herr,FSW->bvb,HxB);
for(i=0;i<3;i++) FSW->Mmtbcmd[i] = FSW->Kunl*HxB[i];
```

Interfaces to Matlab

- 42 generates ASCII output files, which may be loaded into Matlab (or whatever) for post-processing and plotting
- Using Matlab's `mcc` utility, m-files may be translated into C, and compiled and linked into 42
 - As done by FACET

Matlab + 42 = Monte Carlo

- 42 can be called from within Matlab using the `system` command
- Use Matlab as the MC executive
 - Generate initial conditions, parameters
 - Write to 42's input files
 - Run 42
 - Process and save data
 - Repeat
- Use 42 as the high-speed, high-fidelity component

Matlab/42 Example

```
for Irun=1:Nrun,

    % Compute initial attitude
    CRN = TRIAD(tvn(Irun,:),svn,[0 0 1],[1 0 0]);
    qrn = C2Q(CRN);

    % Write target to file
    Outdata = [TrgRA(Irun) TrgDec(Irun)];
    save -ascii ./MOMBIAS/TargetRaDec.inp Outdata

    % Write initial attitude to file
    line = sprintf('%f %f %f %f ! Quaternion\n', qrn(1),qrn(2),qrn(3),qrn(4));
    OverwriteLineInFile('./MOMBIAS/GLAST.inp',21,line);

    % Run 42 for three days.
    system('./42 MOMBIAS');

    % Record pointing histogram.
    load ./MOMBIAS/AngleToGo.42
    [HistCount(Irun,:),HistAng(Irun,:)] = hist(AngleToGo,20);

end
```

42 Walkthrough

Models, Terminology, Input Files

Environment Models

- Planetary Ephemerides
 - Mean Elements
 - From Meeus, “Astronomical Algorithms”
 - Expressed in heliocentric ecliptic frame
 - Good enough for GNC validation, not intended for mission planning
 - DE430 Chebyshev Coefficients
 - From JPL
 - Expressed in ICRS frame (aka J2000 equatorial frame)
 - More accurate than mean elements
- Gravity Models have coefficients up to 18th order and degree
 - Earth: EGM96
 - Mars: GMM-2B
 - Luna: GLGM2
- Planetary Magnetic Field Models
 - IGRF up to 10th order (Earth only)
 - Tilted offset dipole field
- Earth Atmospheric Density Models
 - MSIS-86 (thanks to John Downing)
 - Jacchia-Roberts Atmospheric Density Model (NASA SP-8021)
- Simple exponential Mars atmosphere density model
 - New models easily incorporated as the state of the art advances

Time

- 42 makes use of several time systems
 - Terrestrial Dynamical Time (TT or TDT) is used for all internal models (DE430, ephemerides, orbits, etc)
 - DynTime variable is seconds since J2000 (TT) epoch
 - Universal Time, Coordinated (UTC) is wall-clock time, used for synchronization with external sources
 - CivilTime variable is seconds since J2000 (UTC)
 - UTC drifts from other time systems via Leap Seconds
 - +37 leap seconds as of Dec 2016
 - Atomic Time (TAI) is used as an intermediary between TT and UTC
 - $TAI = TT - 32.184 \text{ sec} = UTC + \text{Leap Seconds}$
 - AtomicTime variable is seconds since J2000 (TAI) epoch
 - GPS Time = TAI – 19 sec
- You will mostly interact with TT and UTC
 - Be aware that they differ by 32.184+LeapSeconds
 - Be aware that the true, official J2000 epoch is the TT one. The others are not the same instant in time, and are only included as conveniences.

Dynamics Models

- Full nonlinear “6DOF” (actually N-DOF) dynamics
- Attitude Dynamics
 - One or many bodies
 - Tree topology (no kinematic loops)
 - Each body may be rigid or flexible
 - Joints may combine rotational and translational DOFs
 - May be gimbaled or spherical
 - Slosh may be modeled as a pendulum (lo-fi, quick to implement and run)
 - 42 may run concurrently with Star-CCM CFD software for hi-fi slosh
 - Wheels embedded in Body[0]
 - Torques from actuators, aerodynamic drag, gravity-gradient, solar radiation pressure, joint torques
- Orbit Dynamics
 - Two- or three-body orbits
 - Encke or Euler-Hill (Clohessy-Wiltshire) for relative orbit motion (good for formation flying, prox ops)
 - Forces from actuators, aerodynamic drag, non-spherical gravity, third-body gravity, solar radiation pressure

Reference Frames are Important!

- In any dynamics problem beyond the spinning top, a systematic approach to reference frames and the relationships between them is vital
- For 42, we define several fundamental reference frames, and notational conventions to keep quaternions and direction cosines sorted out

Reference Frames (1 of 2)

- Heliocentric Ecliptic (H)
 - Planet positions expressed in this frame
- Each world has an inertial (N) and rotating (W) frame
 - For Earth, N = ECI (J2000), W = ECEF
 - N is the bedrock for orbits, S/C attitude dynamics

Reference Frames (2 of 2)

- Each reference orbit has a reference point R
 - For two-body orbit, R moves on Keplerian orbit
 - For three-body orbit, R propagates under influence of both attracting centers (as point masses)
 - S/C orbit perturbations integrated with respect to R
- Associated with each R is a LVLH frame (L) and a formation frame (F)
 - F is useful for formation-flying scenarios
 - F may be offset from R, may be fixed in N or L
- Each spacecraft has one or more Body (B) frames and one LVLH frame (L)
 - L(3) points to nadir, L(2) points to negative orbit normal
 - SC.L is distinct from Orb.L, since SC may be offset from R

Notation for Quaternions, DCMs

- The rotation from frame A to frame B may be described by the direction cosine matrix

$${}^B C^A_{ij} = \hat{b}_i \cdot \hat{a}_j$$

- Given the components of a vector in A , its components in B may be found by the multiplication

$${}^B \mathbf{v} = {}^B C^A \mathbf{v}$$

- In C, we write the DCM as CBA to preserve order of superscripts, eg

$$\text{MxV}(\text{CBA}, \mathbf{v}_a, \mathbf{v}_b)$$

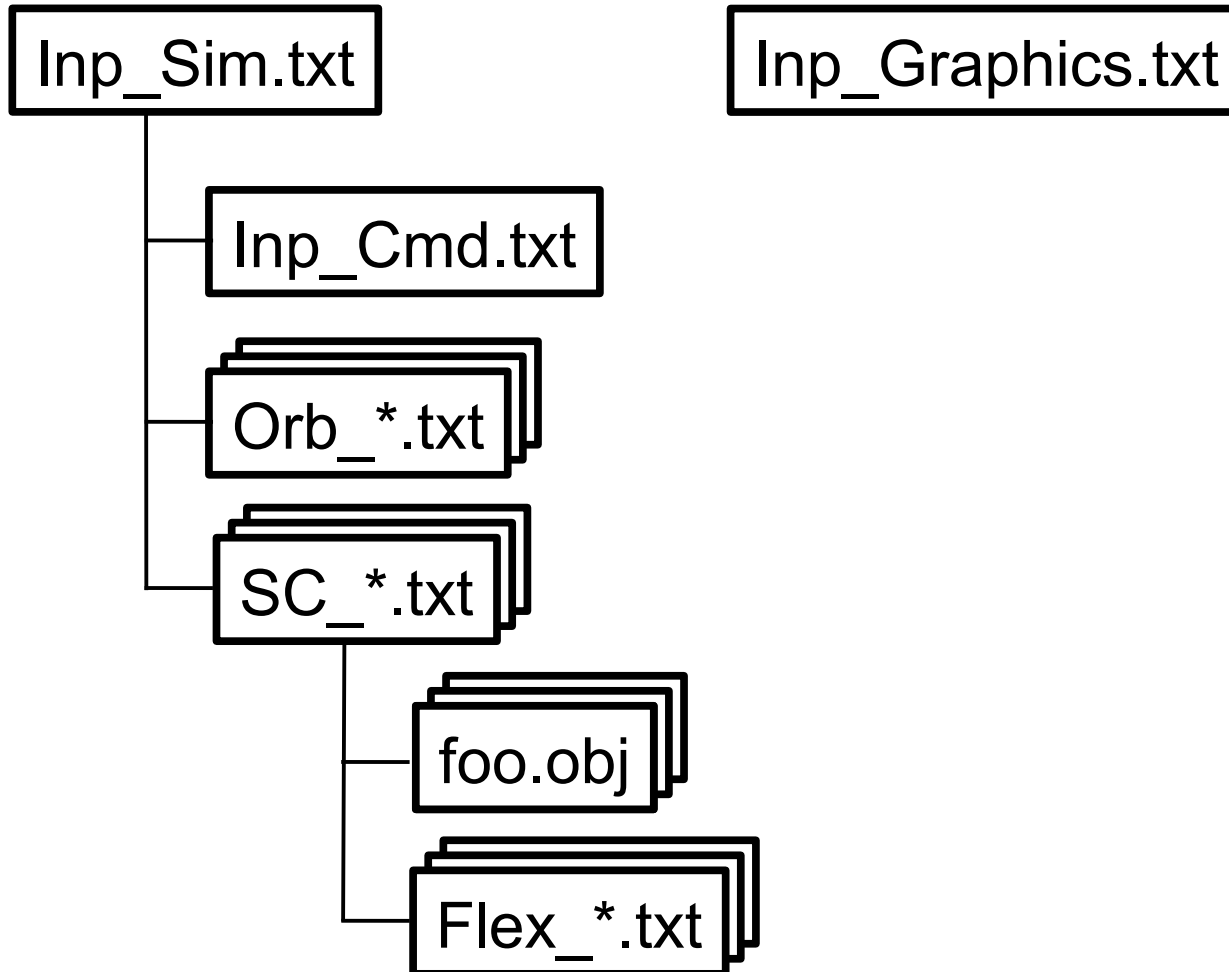
- Quaternions are another way to describe rotations. We use a parallel notation:

$$\text{QxV}(\text{qba}, \mathbf{v}_a, \mathbf{v}_b)$$

- These and similar conventions promote concise, *unambiguous* code

Input File Overview

Input File Hierarchy



Top-level Input File (Slide 1 of 3)

[illegible]

Top-level Input File (Slide 2 of 3)

```
***** Environment *****
06 28 2011      ! Date (Month, Day, Year)
16 45 00.00     ! Greenwich Mean Time (Hr,Min,Sec)
0.0            ! Time Offset (sec)
USER_DEFINED    ! Solar Flux, AP values (TWO SIGMA_KP, NOMINAL ...)
230.0          ! If USER_DEFINED, enter desired F10.7 value
100.0          ! If USER_DEFINED, enter desired AP value
IGRF           ! Magfield (NONE,DIPOLE,IGRF)
8 8            ! IGRF Degree and Order (<=10)
2 0            ! Earth Gravity Model N and M (<=18)
2 0            ! Mars Gravity Model N and M (<=18)
2 0            ! Luna Gravity Model N and M (<=18)
TRUE           ! Aerodynamic Forces & Torques
FALSE          ! Gravity Gradient Torques
FALSE          ! Solar Pressure Forces & Torques
FALSE          ! Gravity Perturbation Forces
FALSE          ! Passive Joint Torques
FALSE          ! Thruster Plume Forces & Torques
FALSE          ! Output Environmental Torques to Files
```

Top-level Input File (Slide 3 of 3)

```
***** Celestial Bodies of Interest *****
TRUE          ! Mercury
TRUE          ! Venus
TRUE          ! Earth and Luna
TRUE          ! Mars and its moons
TRUE          ! Jupiter and its moons
TRUE          ! Saturn and its moons
TRUE          ! Uranus and its moons
TRUE          ! Neptune and its moons
TRUE          ! Pluto and its moons
TRUE          ! Asteroids and Comets
***** Lagrange Point Systems of Interest *****
FALSE         ! Earth-Moon
TRUE          ! Sun-Earth
FALSE         ! Sun-Jupiter
***** Ground Stations *****
5             ! Number of Ground Stations
TRUE EARTH   -77.0  37.0  "GSFC"          ! Exists, World, Lng, Lat, Label
TRUE EARTH   -155.6 19.0  "South Point"    ! Exists, World, Lng, Lat, Label
TRUE EARTH   115.4 -29.0  "Dongara"        ! Exists, World, Lng, Lat, Label
TRUE EARTH   -71.0 -33.0  "Santiago"       ! Exists, World, Lng, Lat, Label
TRUE LUNA     45.0  45.0  "Moon Base Alpha" ! Exists, World, Lng, Lat, Label
```

Reference Orbit Definition (1 of 2)

[illegible]

Reference Orbit Definition (2 of 2)

```

:.....: Use these lines if Three-Body Orbit :.....:
SUNEARTH          ! Lagrange system
LAGDOF_MODES      ! Propagate using LAGDOF_MODES or LAGDOF_COWELL
MODES             ! Initialize with MODES or XYZ
L2               ! Libration point (L1, L2, L3, L4, L5)
800000.0         ! XY Semi-major axis, km
45.0            ! Initial XY Phase, deg
CW              ! Sense (CW, CCW), viewed from +Z
0.0            ! Second XY Mode Semi-major Axis, km (L4, L5 only)
0.0            ! Second XY Mode Initial Phase, deg (L4, L5 only)
CW              ! Sense (CW, CCW), viewed from +Z (L4, L5 only)
400000.0         ! Z Semi-axis, km
60.0           ! Initial Z Phase, deg
1.05  0.5  0.0  ! Initial X, Y, Z (Non-dimensional)
0.0   0.0  0.0  ! Initial Xdot, Ydot, Zdot (Non-dimensional)
***** Formation Frame Parameters *****
L          ! Formation Frame Fixed in [NL]
0.0  0.0  0.0  123 ! Euler Angles (deg) and Sequence
L          ! Formation Origin expressed in [NL]
0.0  0.0  0.0  ! Formation Origin wrt Ref Orbit (m)

```

Example Spacecraft Input File (1 of 4)

[illegible]

Example Spacecraft Input File (2 of 4)

```
*****
***** Body Parameters *****
*****
1                               ! Number of Bodies
===== Body 0 =====
200.0                           ! Mass
100.0  200.0  300.0            ! Moments of Inertia (kg-m^2)
0.0  0.0  0.0                  ! Products of Inertia (xy,xz,yz)
0.0  0.0  0.0                  ! Location of mass center, m
IonCruiser.obj                 ! Geometry Input File Name
NONE                           ! Flex File Name
```

Example Spacecraft Input File (3 of 4)

```
*****
***** Joint Parameters *****
*****
      (Number of Joints is Number of Bodies minus one)
===== Joint 0 =====
0 1                                ! Inner, outer body indices
1 213 GIMBAL                       ! RotDOF, Seq, GIMBAL or SPHERICAL
0 123                              ! TrnDOF, Seq
FALSE FALSE FALSE                 ! RotDOF Locked
FALSE FALSE FALSE                 ! TrnDOF Locked
0.0 0.0 0.0                       ! Initial Angles [deg]
0.0 0.0 0.0                       ! Initial Rates, deg/sec
0.0 0.0 0.0                       ! Initial Displacements [m]
0.0 0.0 0.0                       ! Initial Displacement Rates, m/sec
0.0 0.0 0.0 312                   ! Bi to Gi Static Angles [deg] & Seq
0.0 0.0 0.0 312                   ! Go to Bo Static Angles [deg] & Seq
0.0 0.0 0.0                       ! Position wrt inner body origin, m
0.0 0.0 0.0                       ! Position wrt outer body origin, m
0.0 0.0 0.0                       ! Rot Passive Spring Coefficients (Nm/rad)
0.0 0.0 0.0                       ! Rot Passive Damping Coefficients (Nms/rad)
0.0 0.0 0.0                       ! Trn Passive Spring Coefficients (N/m)
0.0 0.0 0.0                       ! Trn Passive Damping Coefficients (Ns/m)
```

Example Spacecraft Input File (4 of 4)

```

***** Wheel Parameters *****
0                                ! Number of wheels
===== Wheel 0 =====
0.0                              ! Initial Momentum, N-m-sec
1.0    0.0    0.0                ! Wheel Axis Components, [X, Y, Z]
0.14    50.0                    ! Max Torque (N-m), Momentum (N-m-sec)
0.012                                ! Wheel Rotor Inertia, kg-m^2
***** MTB Parameters *****
0                                ! Number of MTBs
===== MTB 0 =====
180.0                            ! Saturation (A-m^2)
1.0    0.0    0.0                ! MTB Axis Components, [X, Y, Z]
***** Thruster Parameters *****
0                                ! Number of Thrusters
===== Thr 0 =====
1.0                              ! Thrust Force (N)
-1.0    0.0    0.0                ! Thrust Axis
1.0    1.0    1.0                ! Location in B0, m
***** CMG Parameters *****
0                                ! Number of CMGs
===== CMG 0 =====
1                                ! CMG DOF (typically 1 or 2)
0.0    0.0    0.0    123          ! Initial Gimbal Angles [deg] and Seq
0.0    0.0    0.0                ! Initial Gimbal Angle Rates, deg/sec
-90.0    0.0    -54.74    123     ! Static Mounting Angles [deg] and Seq
0.12                                ! Rotor Inertia, kg-m^2
75.0                                ! Momentum, Nms
1.0    0.0    0.0                ! Max Gimbal Angle Rates, deg/sec

```

Geometry Definition

- Geometry uses Wavefront “Object” format
 - ASCII, human-readable
 - Can hand-generate models *in theory*
 - In practice, you’ll want mechanical help
- I use Wings3D solid modeling software
 - Free, multi-platform
- 42 can support myriad-polygon models, limited mainly by your patience
 - I get impatient at about 10,000 polys
- Note that aerodynamic and solar-pressure force and torque computations use these models
 - Interior polygons, self-shadowing are error sources

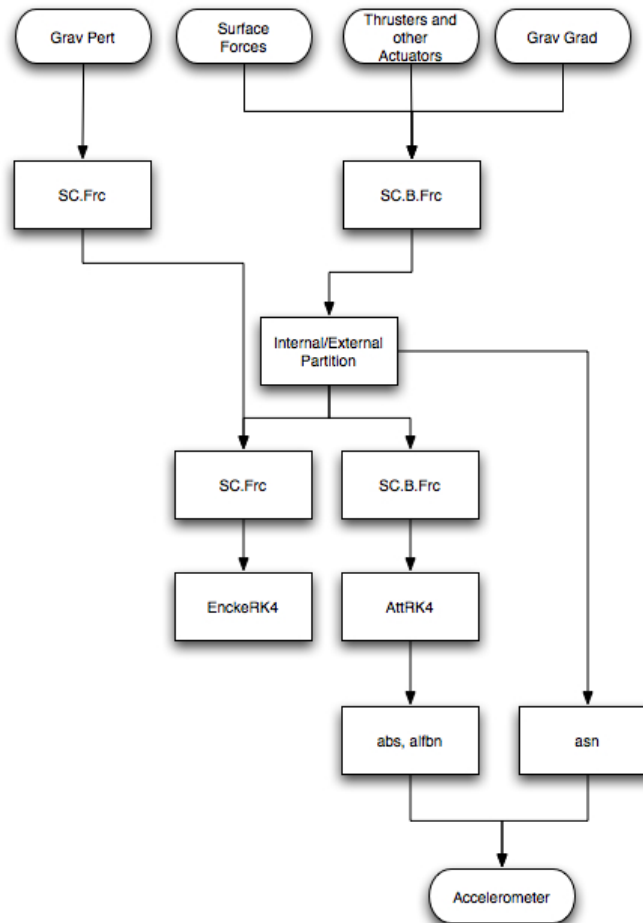
```
# Exported from Wings 3D 0.99.00b
mtllib Altair.mtl
o cylinder9
#12 vertices, 8 faces
v 2.11050391 1.21850000 -1.80666667
v 2.11050391 -1.21850000 -1.80666667
[...]
vn 0.00000000e+0 9.1113913e-17 1.00000000
vn 0.50000000 0.86602540 0.00000000e+0
[...]
g cylinder9_SHINY_WHITE
usemtl SHINY_WHITE
f 1//1 6//16 5//13 4//10 3//7 2//4
f 1//2 7//20 12//35 6//17
[...]
```

Excerpt from Altair.obj

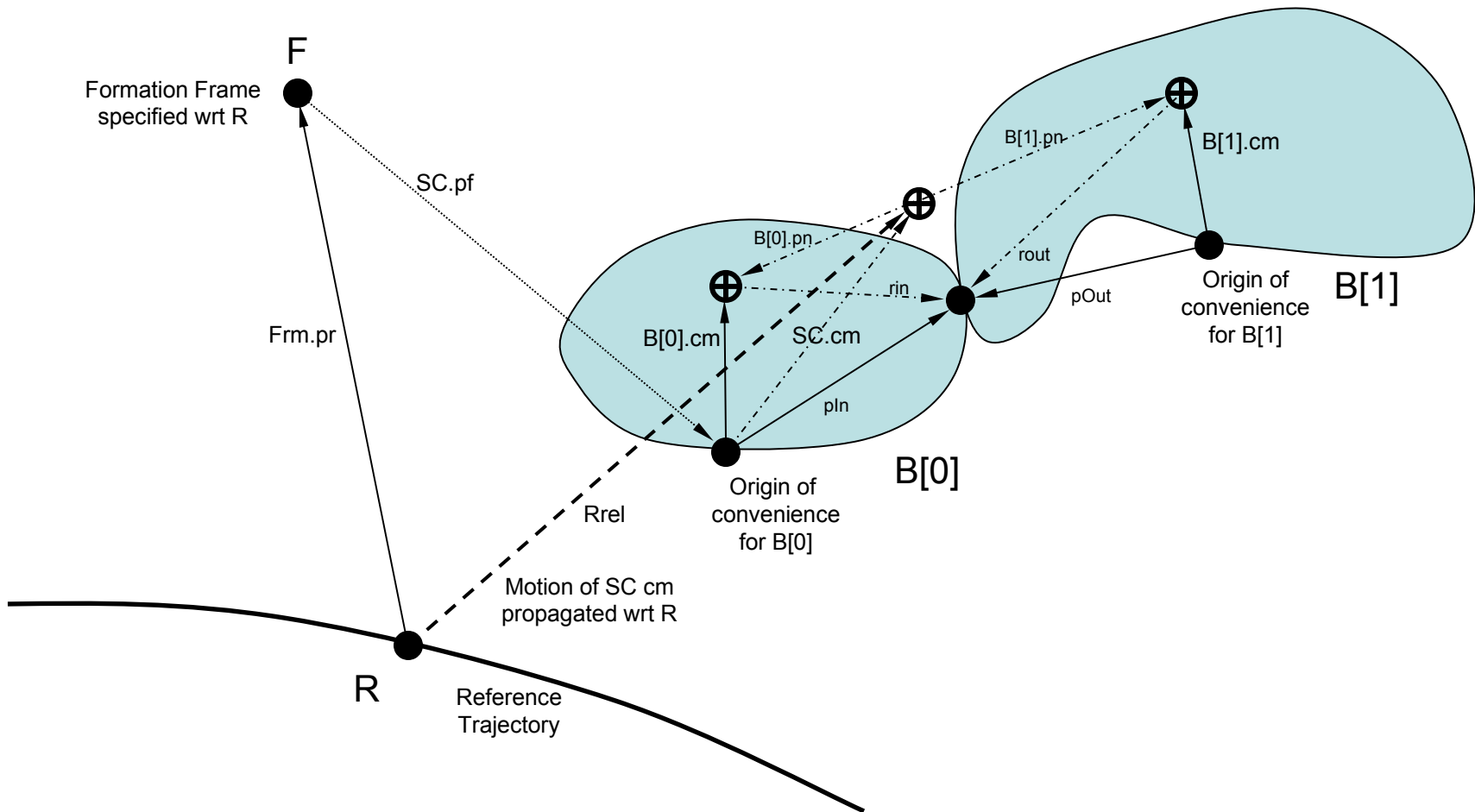
Reference Slides

Force Flow

- Careful accounting needed to decouple orbit and attitude equations of motion
- Accelerometer model also requires careful accounting



Bookkeeping of Translational States



Geometry for Surface Forces

Moment of forces taken about
Body's mass center

