X-ray Pulsar Navigation (XNAV) for Missions to Mars (M2M)

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M2M XNAV Agenda

Part 1: What do we need to do

- **Typical Mission to Mars Profile**
- **Non-spherical gravitational fields**
- **Navigation basics**

Part 2: One way we might be able to do it

- **Pulsar Theory and Background**
- **X-ray Receivers for Spacecraft**
- **Useful Coordinate Systems and Conversions**
- **Time of Arrival (TOA) and Timing Residuals**
- **Navigation and Kalman Filtering**
- **Motion control in arbitrary gravitational fields**
- **Navigation System Components**
- **Summary & Conclusions**
- **Way forward / what's next**

Part 1: Problem Definition

The problem of navigating to Mars

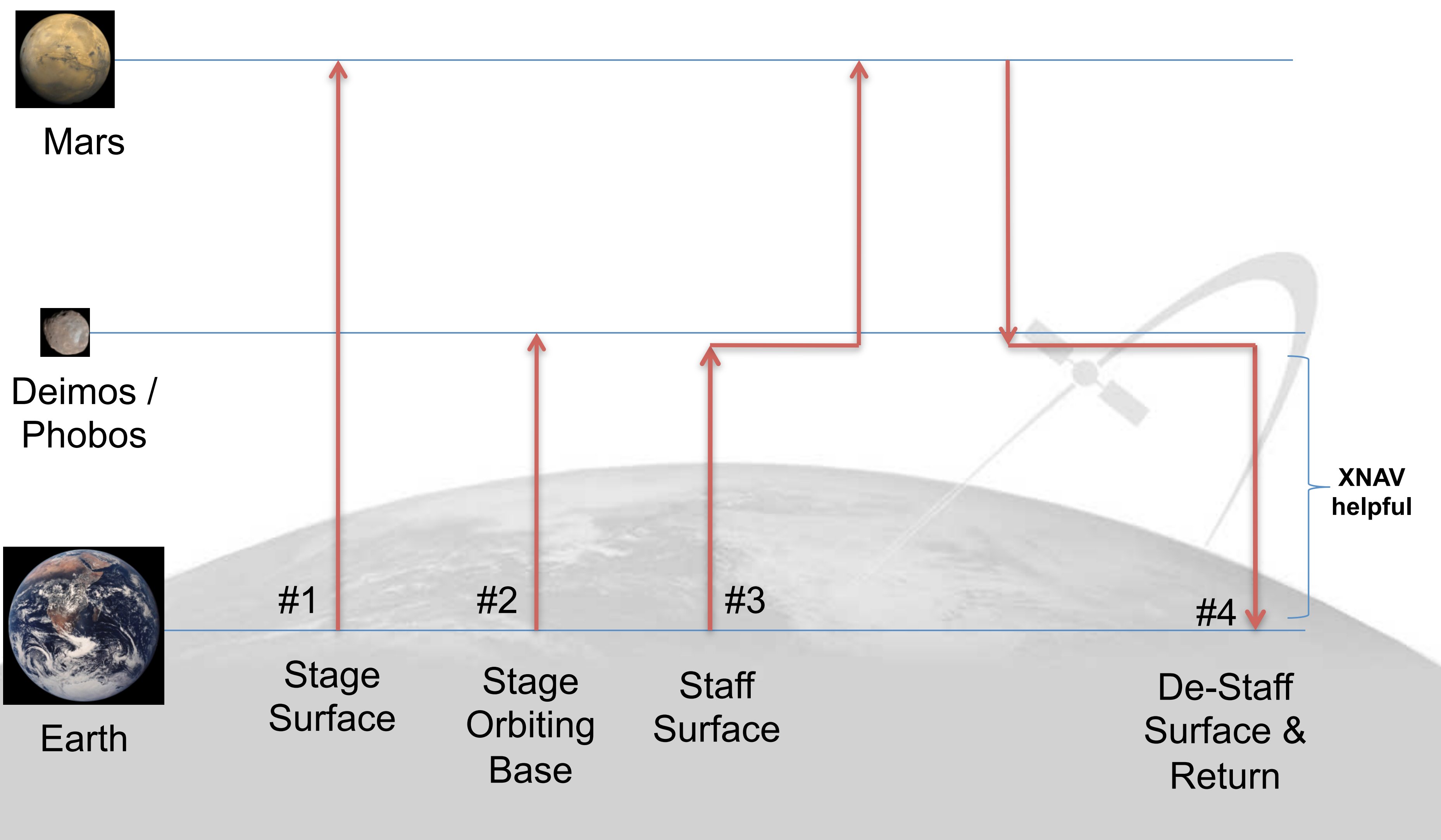
Typical Mission to Mars Profile

- Interplanetary Transfer – patched conic OK for est but not nav
  - Non-spherical gravitational (NSG) profile
  - Solar wind may be an issue (solar radiation pressure)

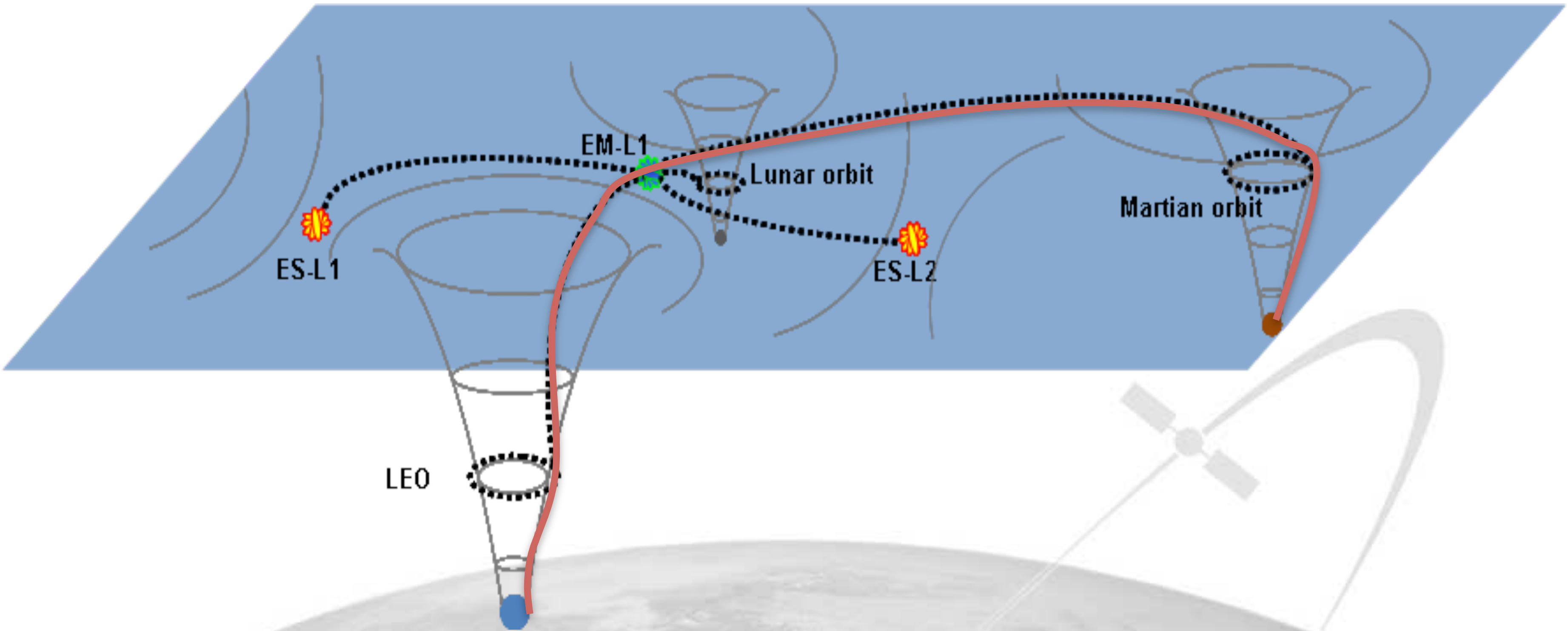
- Staging (Conjunction Class) Trajectories
  - Minimum energy for unmanned prestaging of equipment
- Staffing (Fast Transit) Trajectories
  - Minimum transit time to minimize exposure to radiation

- Mission sequencing – one option:
  - #1. Staging to surface (surface hab, fuel gen, spare rtn vehicle)
  - #2. Staging to Deimos/Phobos (orbital hab, com relay & remote sensors, landing & return "D/A" vehicle, spare provisions)
  - #3. Staffing to Deimos/Phobos (CEV, transit hab, staff, spare Descent/Ascent "D/A" vehicle)
  - #4. De-staff Martian surface and return to Earth.

Mission Profile: Segment Timeline



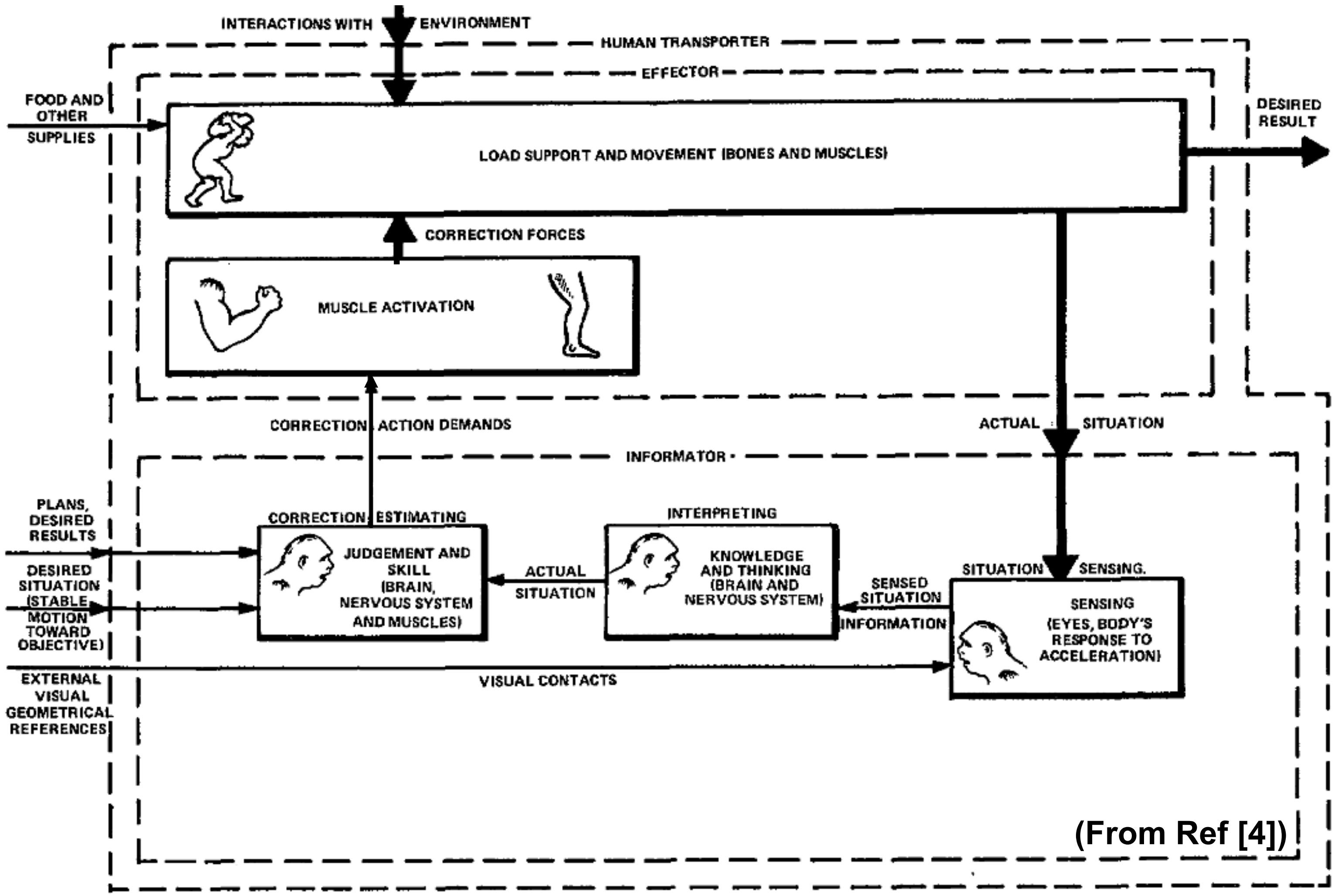
Non-Spherical Gravitational (NSG) Profile



- Interplanetary Transfer occurs in NSG environment:
  - Two body and Restricted 3 body problem (RTBP) simplifications insufficient (need gravity gradient description)
  - May also need drag term, for Solar Radiation Pressure (SRP)
- Question: how do we navigate arbitrary NSG fields?

Navigation: So easy a caveman can do it

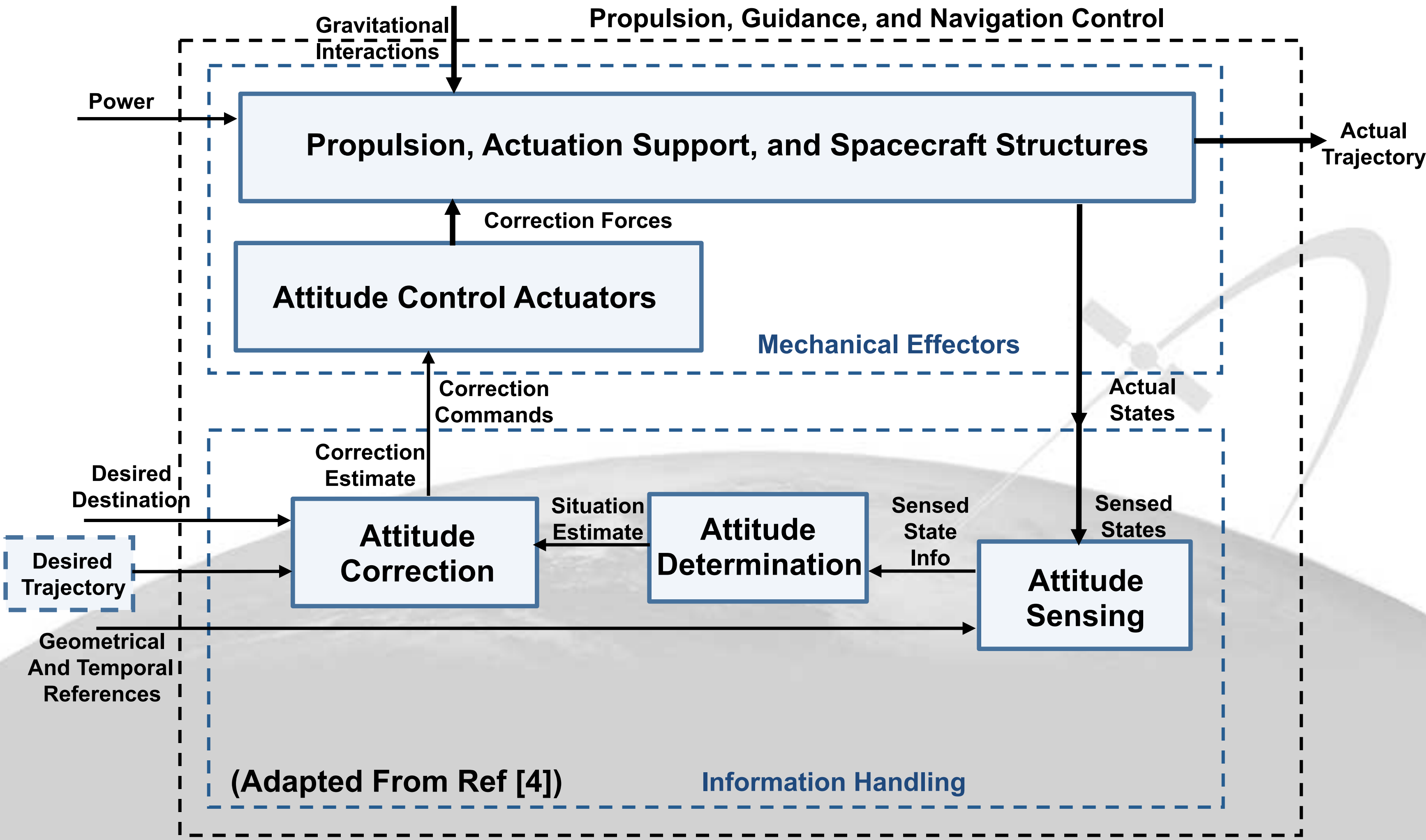
- Charles Stark Draper's 1981 example of caveman navigation:



(From Ref [4])

Navigation: So easy a spacecraft can do it

- Charles Stark Draper's example applied to spacecraft navigation:



Part 2: One Approach to a Solution

Navigation to Mars with the aid of X-ray Pulsars

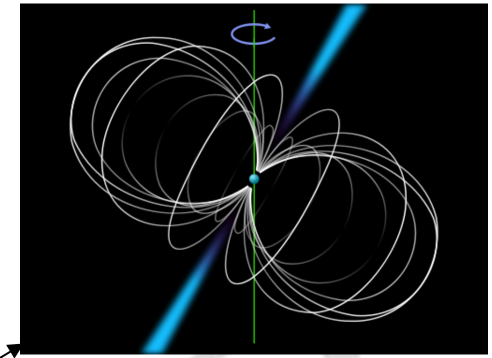
Pulsar Theory and Background

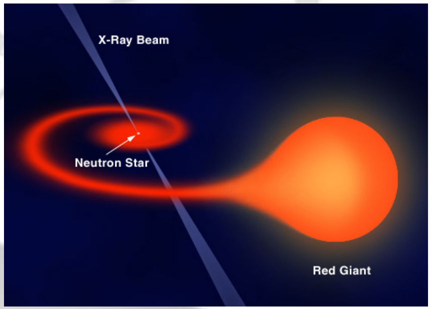
- **Neutron Stars** – pulsars are rotating neutron stars (collapsed supernova remnants with residual angular momentum)
  - "**Lighthouse Effect**" - A beam of radiation is emitted along the magnetic axis, which is not in general aligned with the spin axis
    - can emit in a range of wavelengths (RF, IR, visible, UV, and Xray)
  - Can suffer from "glitches" in period

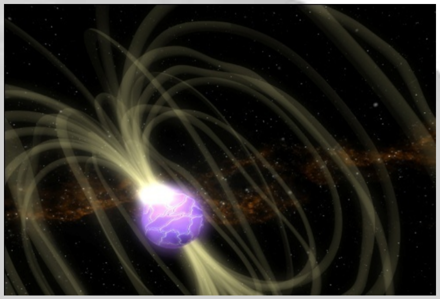
- **Types of Pulsars**:
  - Rotation Powered (spin down in 10-100M years)
  - Accretion Powered (binary, with one accreting matter into the other)
  - Magnetars (magnetic field powered, ~10 GT field strength, live only ~10,000 years)

- **X-ray Pulsar Sources**, a.k.a. MSPs, or millisec pulsars:
  - Rival Atomic Clocks for accuracy
  - Unaffected by Interstellar medium (ISM)
  - Easier to detect with smaller antennas than RF
  - Xray only pulsars with buried magnetic fields can live billions of years

(Refs [1], [2], [3], art from Wikipedia)







Important Pulsar Parameters

- **Spatial position of Pulsar (cataloged by Pulsar name)**
  - Ecliptic lat/long, Galactic lat/long, right ascension/declination (J2000)
- **Pulsar Frequency of emission and spin down derivatives**
  - Rotational frequency and derivations f [t], df /dt [t], d^2f/dt^2 [t], epoch of pulse ephemeris (Modified Julian Date), spin down power (for rotation powered)
- **Pulse emission spectrum characteristics**
  - Spectral index, spectral content per energy band, pulsed luminosity, pulse width at 50%, 10% of peak
- **Pulse strength: amplitude, form, and quality**
  - Noise temperature, SNR (assuming a collecting area), quality factor per 10^9 samples
- **Pulsar Catalog Content Example:**

Table 2.1: 50 best Q pulsars: coordinates, flux density, SNR, Q

Name	l_E [a] (deg)	b_E [a] (deg)	l [b] (deg)	b [b] (deg)	α [c] (h)	δ [c] (deg)	DM [d] (cm^{-3} pc)	Spectral [e] Index	$S_{\nu,T}$ [f] (mJy)	T_{gal} [g] (K)	T_{sys} [h] (K)	SNR [i] (dB)	Q [j] (dB)
B1937+21	301.82	42.30	57.51	−0.29	19.661	21.58	71.04	−2.2	33.1	10.8	43.3	−55.6	11.8
B0329+54	65.19	34.26	145.00	−1.22	3.550	54.58	26.83	−1.6	347.4	9.2	41.9	−45.2	4.5
B1642−03	250.19	18.86	14.11	26.06	16.751	−3.30	35.73	−2.3	46.1	6.4	39.4	−53.7	1.3
B0950+08	147.71	−4.62	228.91	43.70	9.886	7.93	2.96	−1.2	127.7	2.6	35.9	−48.9	−0.7
B0740−28	125.33	−48.71	243.77	−2.44	7.714	−28.38	73.76	−2.4	33.4	5.2	38.3	−55.0	−2.3

(Extracted from Ref [2])

Maps of Useful X-ray Pulsars

- Best 15 pulsars

  in Galactic Plane: & in Ecliptic Plane:

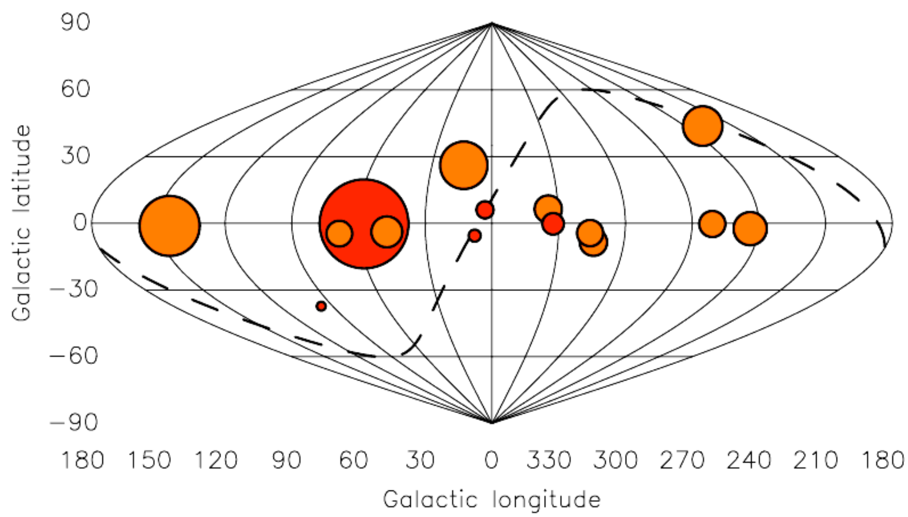


Figure 2.1: Position of the 15 best Q pulsars, in galactic coordinates. The sizes of the circles indicate the pulsar quality factor Q. Dark color circles indicate pulsars with periods under 100 ms, and light color circles correspond to pulsars with periods longer than 100 ms. The dashed line shows the ecliptic plane.

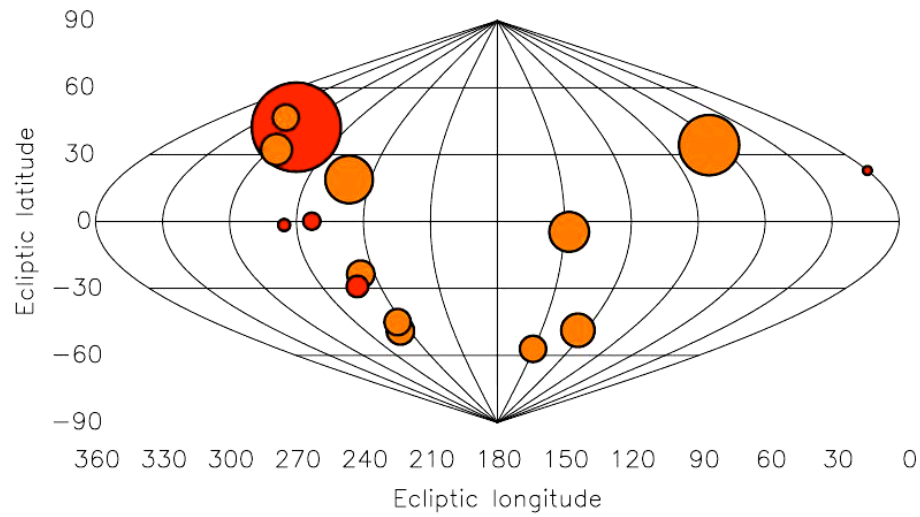


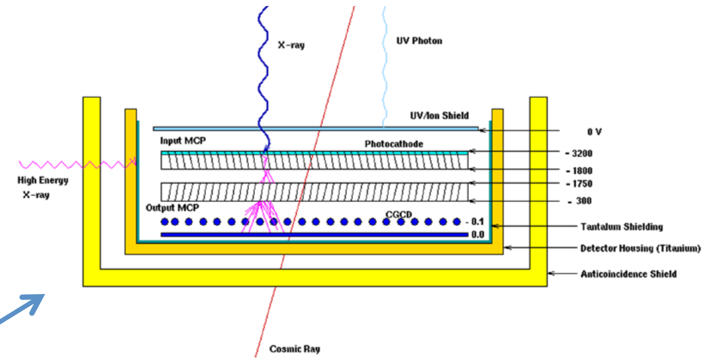
Figure 2.3: Same as Fig. 2.1, in ecliptic coordinates.

(Extracted from Ref [2])

X-ray Receivers for Spacecraft

Design considerations:

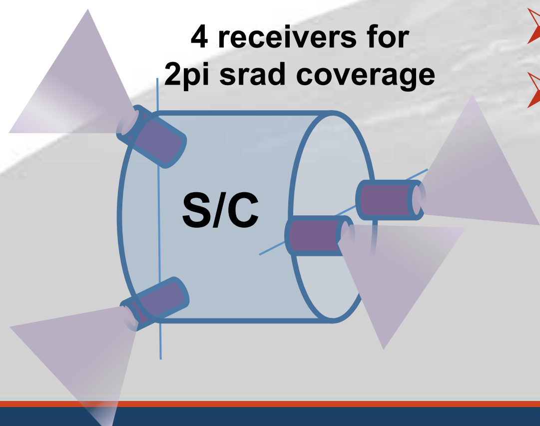
- ➢ Operation (pulse integration, etc)
  - Integrate N pulses for higher Q
- ➢ Design of detectors:
  - Use MicroChannel Plate (MCP) for superior time resolution (50 pS)
  - Can operate with a coded mask for wider Field of View (FOV)



(MCP flown on CHANDRA, coded mask flown on Integral Sat, Ref [10])

- ➢ Orientation on Spacecraft:
  - ➢ Gimbal each receiver for wider FOV coverage
  - ➢ Overlap coverages to allow for fault tolerance of at least one X-ray receiver

4 receivers for 2pi srad coverage



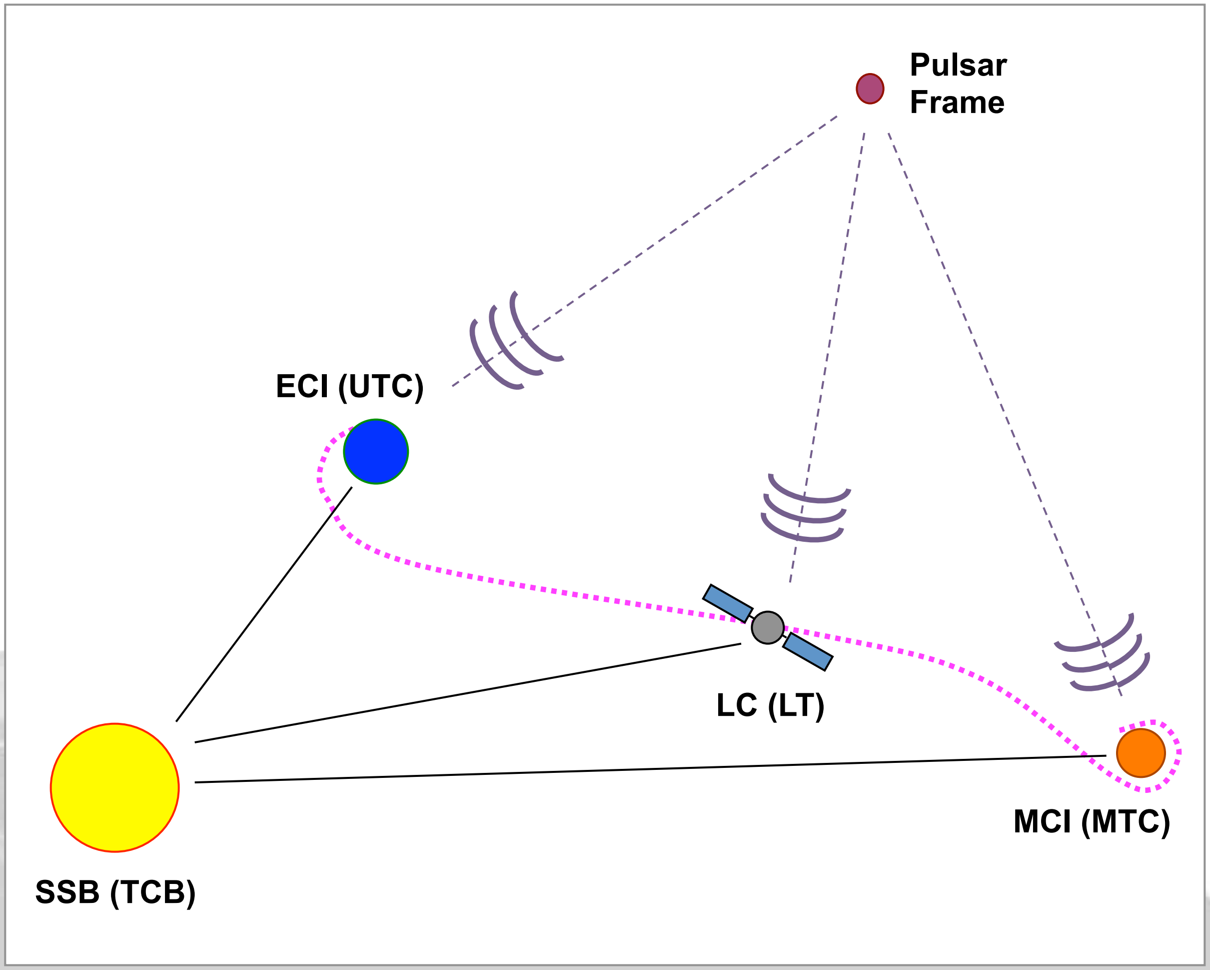
(Refs [9] - [14])

Useful Coordinate and Time Systems

- ECI = Earth Centered Inertial Coordinates
  - (UTC time)
- SSB = Solar System Barycenter Coordinates
  - (TCB time)
- LC = Local Coordinates
  - (Local Time)

- MCI = Mars Centered Inertial Coordinates, i.e.
- Mars-centered Mars Mean Equator and Equinox of Epoch
  - (MTC time)

- <u>Strategy</u>: translate everything to SSB/TCB for Interplanetary Navigation



(See Refs [1], [6] for more details)

Pulse Processing and Timing Estimation

(Ref [1])

Pulse Timing Model, aka "Spin down eqn" – unique for each Pulsar

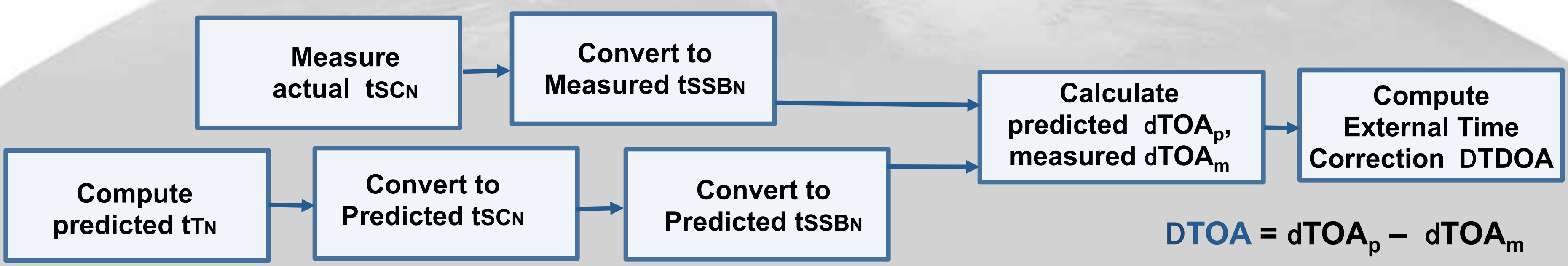
- "Pulsar Centric"- it describes pulse train timing (phase evolution) at the Pulsar
- Expressed in terms of total phase: $F(t) = F(t_o) + f\,[t-t_o] + (1/2)df/dt\,[t-t_o]^2 + (1/6)d^2f/dt^2\,[t-t_o]^3$
  - Frequency *f* and spin down derivatives are unique to each pulsar and are catalog lookups

TOA, Time of Arrival estimate of pulse at Spacecraft (S/C)

- Includes time of flight along null geodesic from the Pulsar center to S/C, as well as Doppler delay, annual parallax, pulsar proper motion & transverse motion, and Shapiro delay (i.e. gravitational time dilation).
- Covert from Pulsar centric Coordinates – need to apply barycentric time transfer to correct to SSB coordinates: $(t_{SSBN} - t_{TN}) - (t_{SCN} - t_{TN}) = t_{SSBN} - t_{SCN}$, and this latter term must be applied to S/C measured pulse times to get them to SSB coordinates and TCB time.

Timing Residuals:

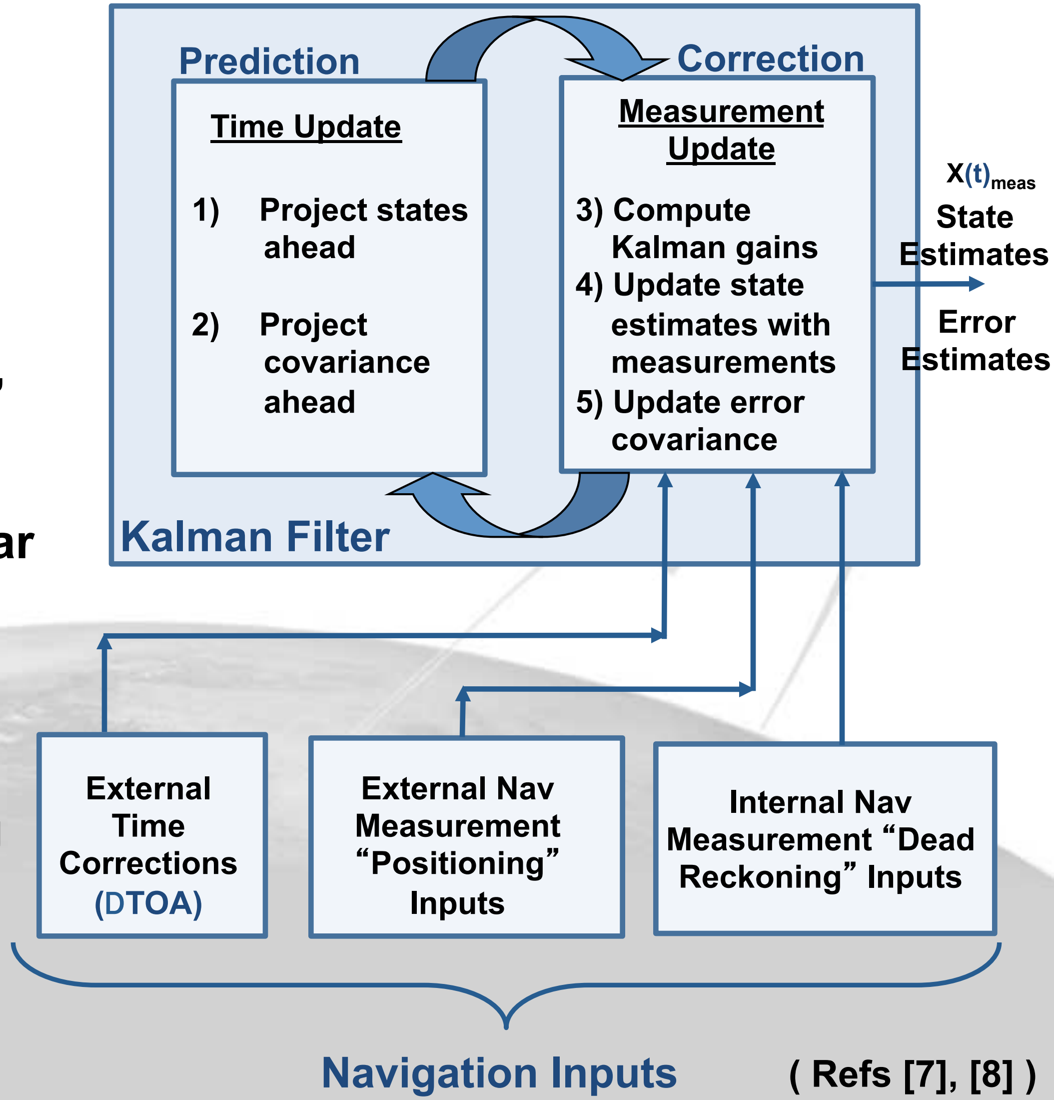
- The difference between the total TOA and the integer value of TOA is the timing residual
  - $dTOA = \{ F(t_{doa}) - \mathrm{nint}\,[F(t_{doa})] * [\text{Pulse period}] \}$
- Measured versus corrected timing residuals can be compared to compute time corrections:



$DTOA = dTOA_p - dTOA_m$

Attitude Determination and Kalman Filtering

- **Kalman Filters**
  - **Theory of Operation:**
    - ***A recursive, weighted algorithm for estimating the states* (physical parameters) *of a system***
    - **5 eqns: 2 for predictions, and 3 for corrections**
  - **Typical Nav Inputs: angular position est, velocity, acceleration, & time corrections**
- **Sources of errors & handling of residuals:**
  - **Time series of nav measurement inputs allows KF to estimate**

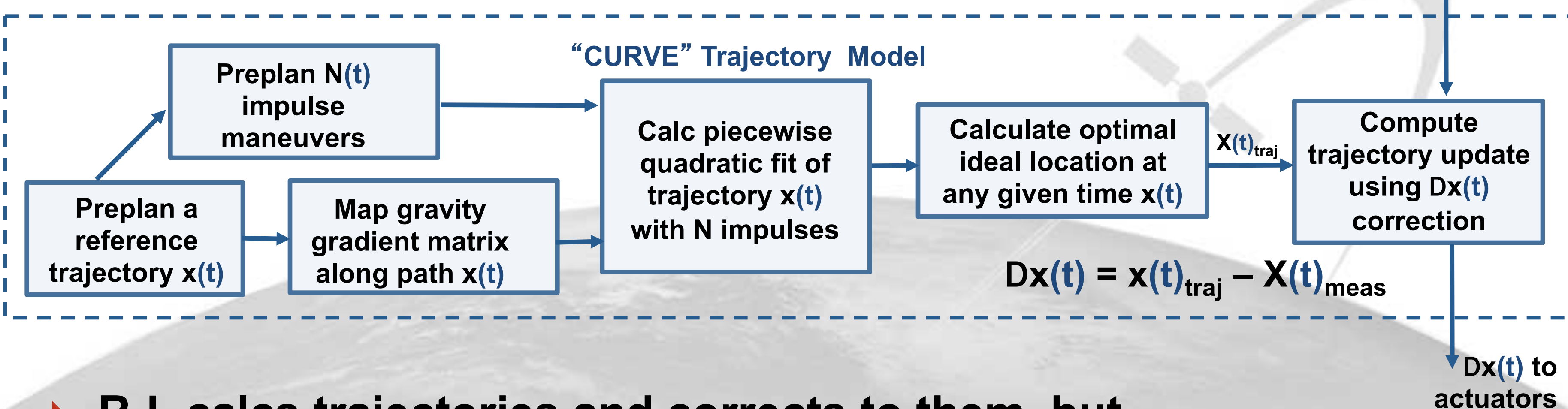


(Refs [7], [8])

Motion Control in Arbitrary Gravitational Fields

- **Motion Control:** (See Ref [5] for more details)
  - **Picking a desired trajectory (plan the work)**
  - **Following the trajectory you've picked (work the plan)**

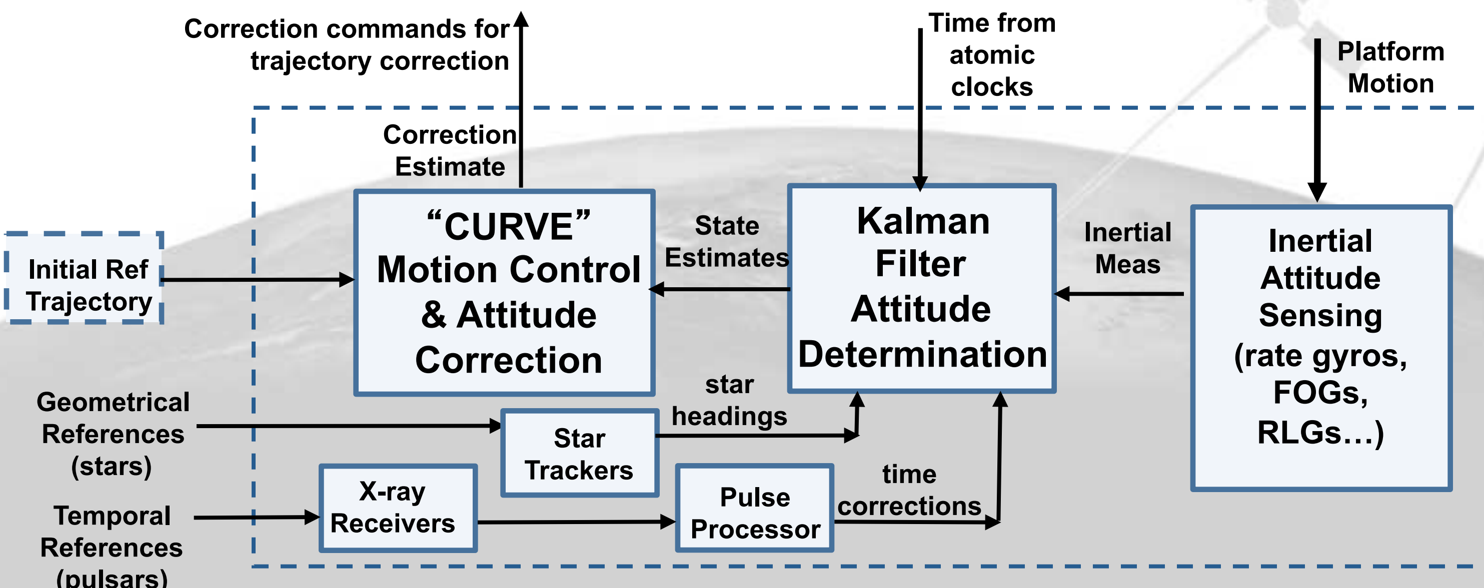
- **Russell-Lantoine Optimal Control of Relative Motion in Arbitrary Fields as Attitude Correction Algorithm:**



- **R-L calcs trajectories and corrects to them, but…**
  - Need to accurately know relative inertial orientation of S/C (from Inertial Sensors)
  - Need to accurately know absolute location of S/C in space (from Star trackers)
  - Need to accurately know absolute time (from Atomic Clocks &/or X-ray Pulsars)

Suggested GNC Block Diagram

- **Inertial References**: Accelerometers, rate gyros (fiber-optic or ring laser gyros)
- **Position**: "M" Star Trackers, possibly supplemented with sun sensor
- **Time**: "N" X-ray Telescopes (Receivers) with pulse processing / disambiguation, possibly supplemented with on-board atomic clocks for free-running backup
- **Attitude Determination Processor**: Kalman Filtering
- **Attitude Correction Processor**: "CURVE" Optimized Motion Control (Ref [5])



Guidance, and Navigation Control Information Handling, (Ref [4])

Benefit Summary & Conclusions

- **Beneficial improvements in navigation performance**
  - **Lower absolute time errors should improve Kalman Filter Attitude Determination & Russell-Lantoine Trajectory Correction**

- **Lower risk / higher redundancy**
  - **The addition of X-ray pulsar receivers and pulse processing backs up and improves the time keeping of on-board atomic clocks, as well as the position estimates derived from star trackers**

- **Less Infrastructure / higher autonomy**
  - **Enables fully autonomous absolute correction of on-board time and position without any data relay or communication from Earth or other control stations**

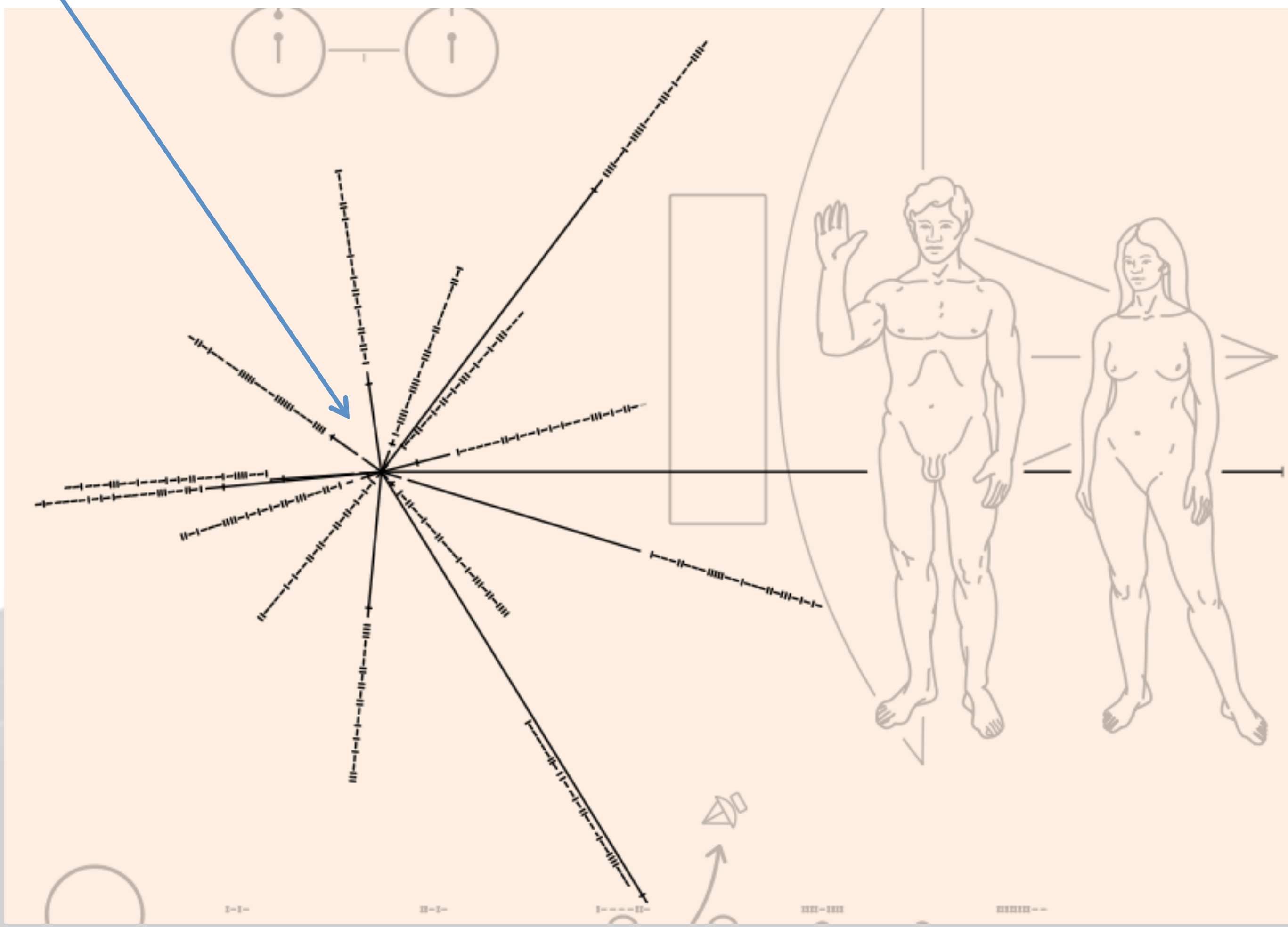
- **Possible Side benefit: Could act as a com relay sync source**
  - **If communication with Earth is required for mission data relay both the spacecraft and Earth orbit communication relays could synchronize with the same designated pulsar, thus providing a snyc source**

Suggestions for Future Work

- XNAV configuration dependent Kalman Filtering simulations
- Optimal trajectory control for various missions to Mars with XNAV inputs
- X-ray sensor simulation, and spaceborne X-ray sensor specification development, design development, prototyping, and demonstration
- Let’s shake out the system by practicing with Lunar missions

Any Questions?

- You are here



(Pulsar map of Earth on Pioneer 10 plaque)

Acknowledgements

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- Thanks to Dr J Russell Carpenter of the Flight Dynamics Analysis Lab at NASA GSFC for helpful correspondence on Tschauner-Hempill solutions for motion control.

References, 1 of 3

1. Sheikh, Hellings, & Matzner, *Higher Order Pulsar Timing for Navigation*, Proceedings of ION 63rd Annual Meeting, 2007, Cambridge, MA.

2. Sala, Urruela, & Villares, *Feasibility Study for a Spacecraft Navigation System relying on Pulsar Timing Information*, Final Report of the ARIADNA Study #03/4202, 2004, Barcelona.

3. Bernhardt, et al., *Timing X-ray Pulsars with Application to Spacecraft Navigation*, Proceedings of HTRA-IV, 2010, Crete.

4. Draper, Charles Stark, Origins of Inertial Navigation, IEEE Control Systems Magazine, 1981, reprinted from AIAA Journal of Guidance and Control, 4: 339-63.

5. Russell and Lantoine, Optimal Control of Relative Motion in Arbitrary Fields: Applications at Deimos, Paper AAS 10-313, Proceedings of KT Alfriend Astrodynamics Symposium, 2010, Monterey, CA.

References, 2 of 3

6. Burkhart, P. Daniel, *MSL Update to Mars Coordinate Frame Definitions*, JPL Interoffice Memorandum 343B-2006-004, August 15, 2006.

7. Welsh & Bishop, *An Introduction to the Kalman Filter*, TR 95-041, Department of Computer Science, University of North Carolina at Chapel Hill, NC 27599-3175, July 24, 2006.

8. Williams, Michael, *Introduction to Kalman Filters*, June 5, 2003, users.cecs.anu.edu.au/~hartley/Vision-Reading-Course/Kalman-filters.ppt, accessed August 2nd, 2011.

9. Ray, Wood, & Philips, *Spacecraft Navigation Using X-ray Pulsars*, Featured Research in the NRL Review, 2006.

10. Neustroev, Vitaly, *X-ray Detectors*, Observational Astrophysics and Data Analysis, http://vitaly.neustroev.net/teaching/Observational_Astrophysics_05.pdf, accessed August 2nd, 2011.

References, 3 of 3

11. Ray, et al., *The USA X-ray Timing Experiment*, ARGOS XDS 9911236.

12. Wood, et al., The USA Experiment on the ARGOS Satellite, http://xweb.nrl.navy.mil/usa/publications/usa-spie-94.html, accessed August 2nd, 2011.

13. Qiao, et al., Integration of Ultraviolet Sensor and X-ray Detector for Navigation Satellite Orbit Estimation, ref# 04570027.

14. Sheikh & Matsakis, Spacecraft Navigation Using X-ray Pulsars, Presentation to International Astronomical Union XXVIth General Assembly, August 21, 2006, Prague.