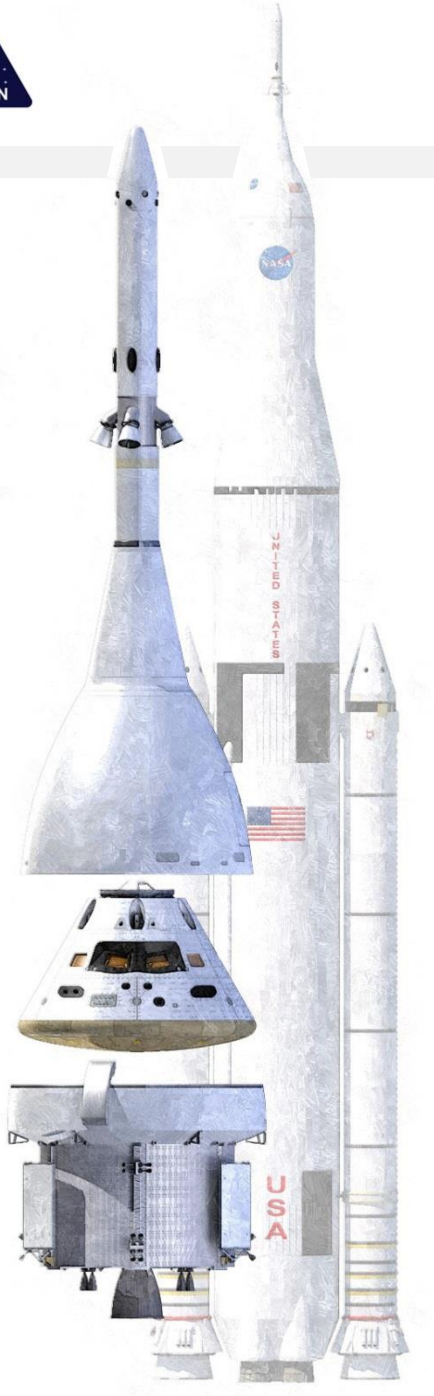


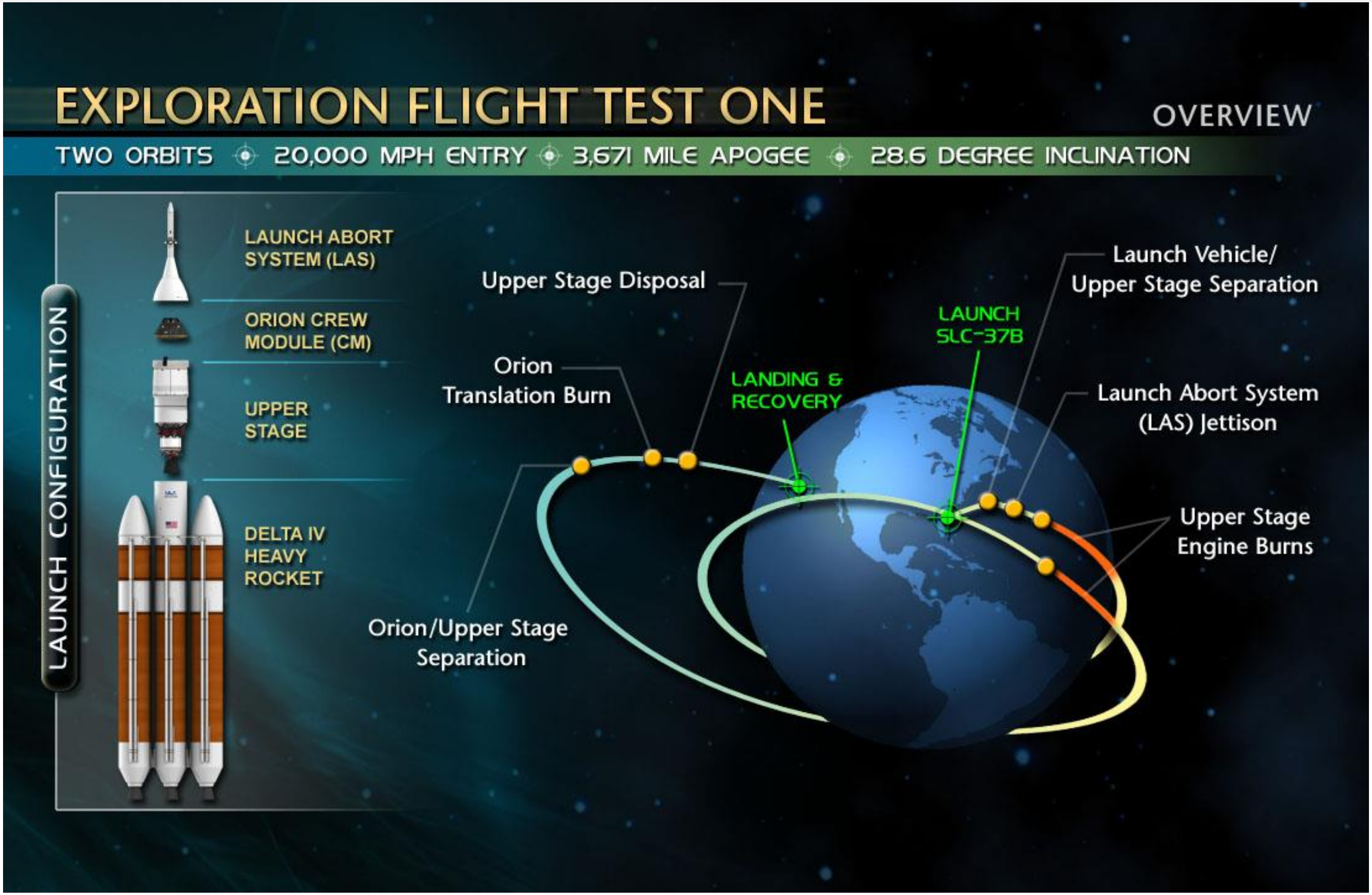
Navigation Design and Performance of the First NASA Orion Flight Test

October 28, 2015

Renato Zanetti
Orion Absolute Navigation Team

renato.zanetti@nasa.gov

EFT1 Summary

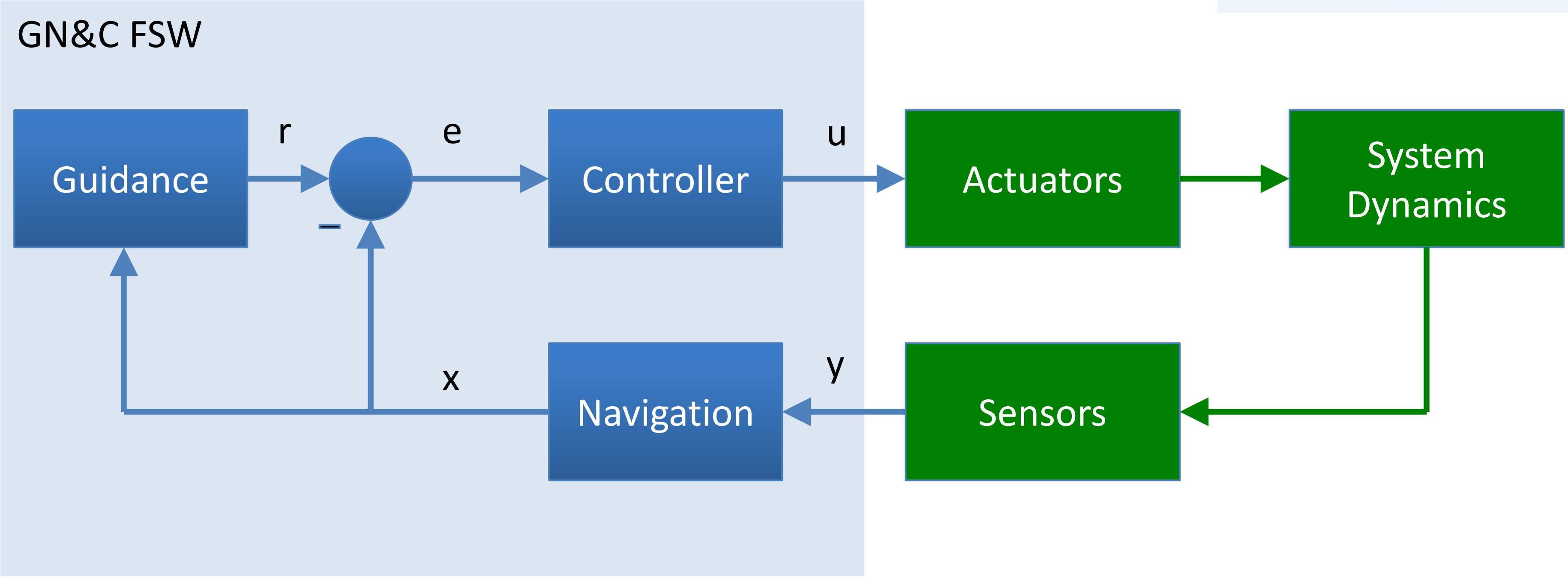


EFT1 Launch – December 5th, 2014

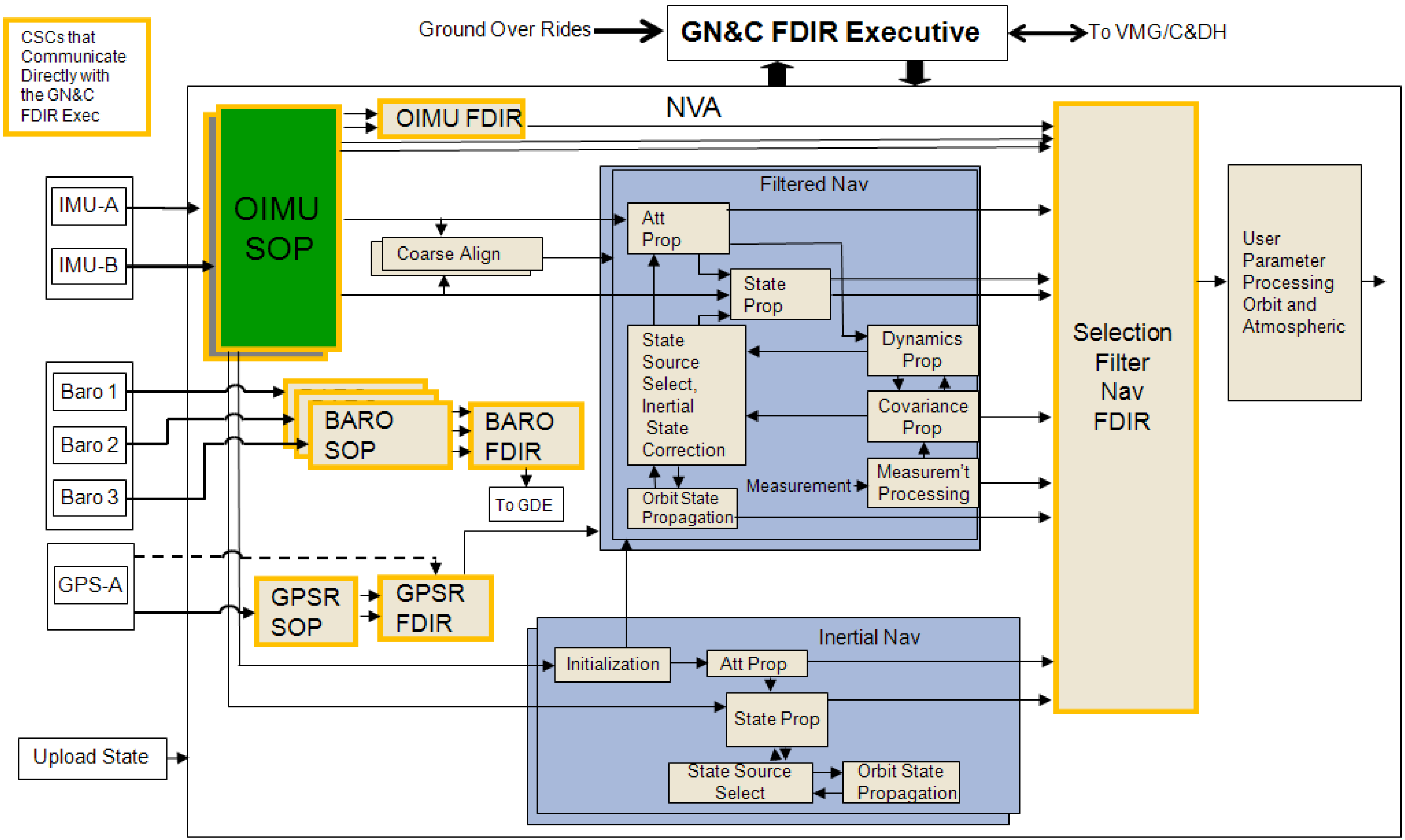
- **This slide will show the video "Orion Soars on First Flight Test" from www.nasa.gov/exploration/systems/orion/videos**

Orion GN&C Flight-Software

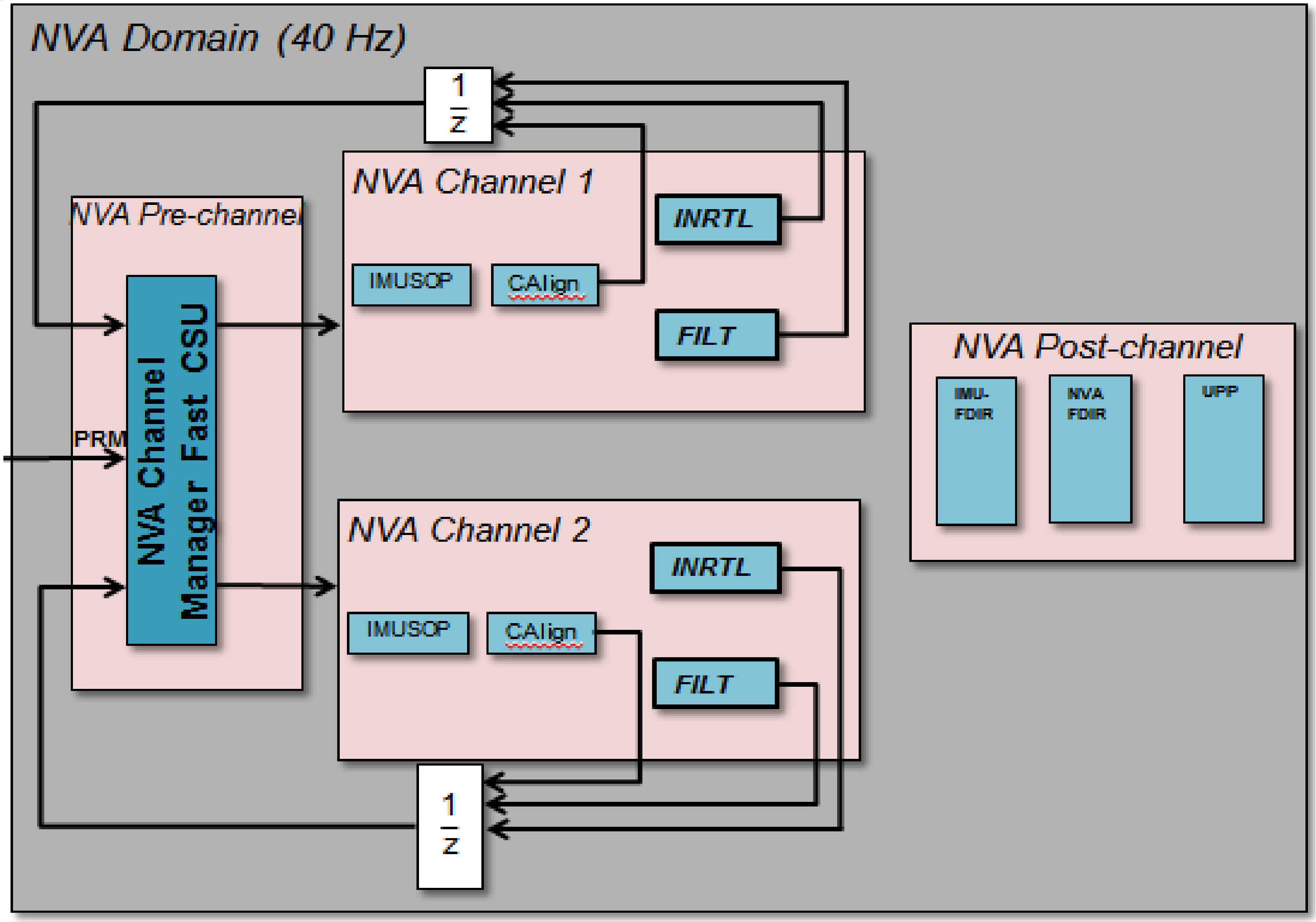
- **The EFT-1 Orion Guidance, Navigation, and Control Flight-software was selected as the 2014 co-winner of the NASA Software of the Year Award**
  - Guidance: Tells us how to get there
  - Navigation: Tells us where we are
  - Control: Puts us there



Absolute Navigation Architecture



Navigation Channels



EFT1 Navigation Computer Software Units

- **The Navigation CSUs implemented for EFT1 are**
  - Coarse Align
  - Filtered Navigator
  - Extended Kalman Filter
  - Inertial Navigator
  - User Parameter Processor
- **Additionally, the following FDIR CSUs were part of the NVA Domain**
  - IMU Sensor Operating Program
  - GPS Sensor Operating Program
  - Barometric Altimeter Sensor Operating Program
  - IMU FDIR
  - GPS FDIR
  - BALT FDIR
  - NVA FDIR

Overall Navigation Filter Characteristics

- **The algorithm is the standard extended Kalman filter**
- **Each filter is founded on the UDU matrix factorization**
  - Computationally stable
  - Efficient
- **Computational stability ensures positive definiteness of the covariance matrix as well as retaining numerical precision**
- **All measurements are processed as scalars and their residual are tested before being incorporated into the solution**
- **Efficiency is obtained by partitioning the filter state-space into *states* and *parameters***
  - States vary dynamically (i.e. position, velocity, attitude)
  - Parameters are sensor parameters modeled as first-order Gauss-Markov processes
    - The State Transition Matrix can be obtained analytically
  - Most of the filter state-space is populated by sensor parameters
    - The Agee-Turner rank-one time-update ensures computational efficiency

From MCC: “Looks good. Go Orion!”

State Vector Update Comparison

Comparison Epoch

Dryden (1:37:34)

MCC Vector Source

No Kwajalein #1

585

P(Inside Limits | NoUpdate) = 99.976% / P(Inside Limits | SVU) = 100%

-494

P(Inside Limits | NoUpdate) = 100% / P(Inside Limits | SVU) = 100%

501

P(Inside Limits | NoUpdate) = 100% / P(Inside Limits | SVU) = 100%

1.60

P(Inside Limits | NoUpdate) = 100% / P(Inside Limits | SVU) = 100%

-0.38

P(Inside Limits | NoUpdate) = 93.73% / P(Inside Limits | SVU) = 97.467%

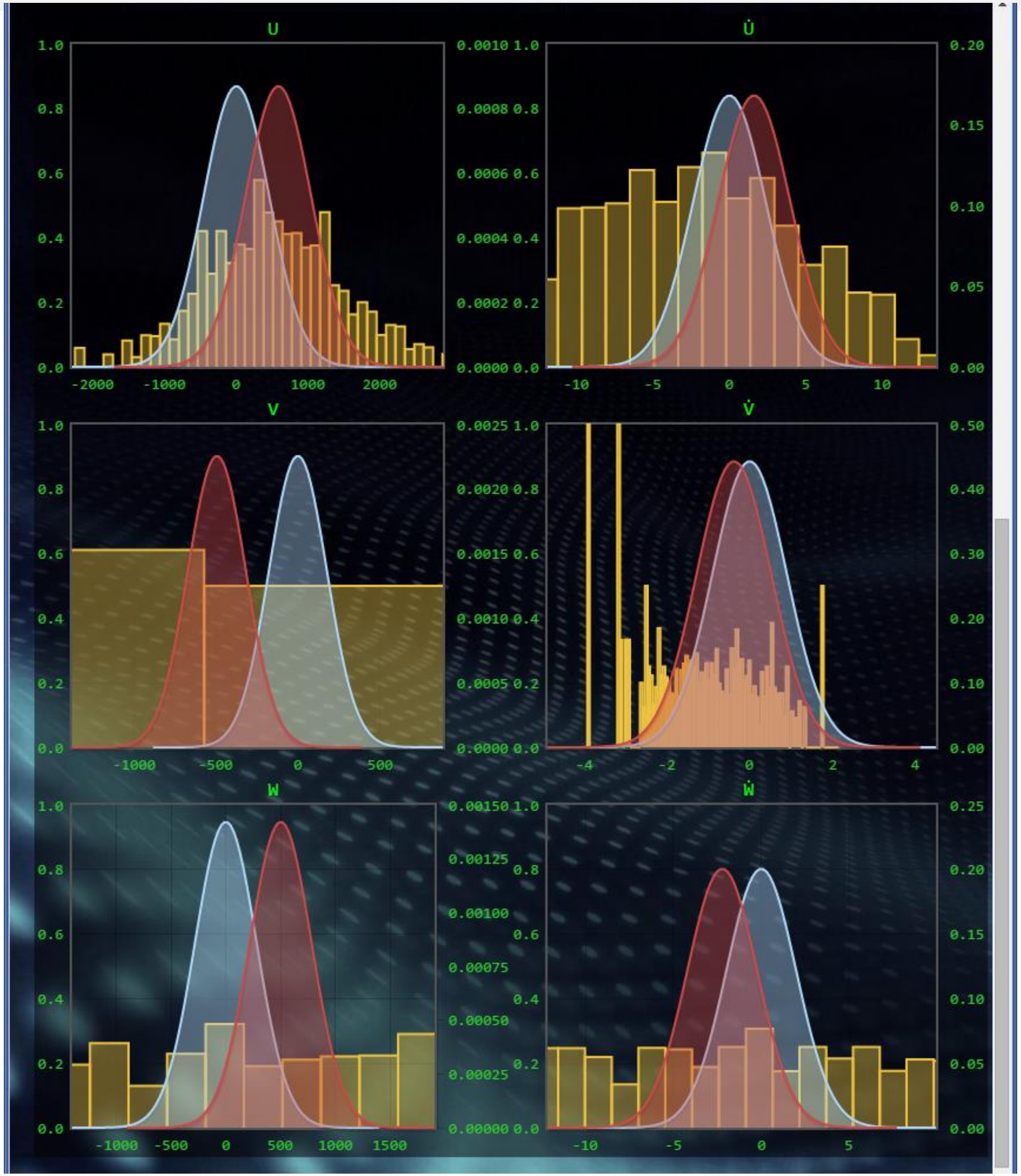
-2.22

P(Inside Limits | NoUpdate) = 100% / P(Inside Limits | SVU) = 100%

PainFactor = 4

Dimension	$3\sigma_G$	Limits
$3\sigma_U$	1376 ft	-3205 ft < ΔU < 2185 ft
$3\sigma_V$	530 ft	-28343 ft < ΔV < 22073 ft
$3\sigma_W$	842 ft	-17562 ft < ΔW < 14067 ft
$3\sigma_{UDot}$	7.12 ft/s	-22.55 ft/s < ΔUDot < 26.11 ft/s
$3\sigma_{VDot}$	2.7 ft/s	-1.76 ft/s < ΔVDot < 3.89 ft/s
$3\sigma_{WDot}$	5.97 ft/s	-62.47 ft/s < ΔWDot < 76.45 ft/s
Covariance Scaling Factor	8	

From MCC: “Looks good. Go Orion!”



Summary of Navigation Filter Design

Extended Kalman Filter (1Hz)				
Type	**States**	**Parameters**	**Measurement**	**Comments**
Translation& Attitude	Position (3) Velocity (3) Attitude (3) GPS clock (2)	IMU (24)	Integrated Velocity GPS PR and DR	- IV processed during fine align - GPS processing starts after LAS disposal

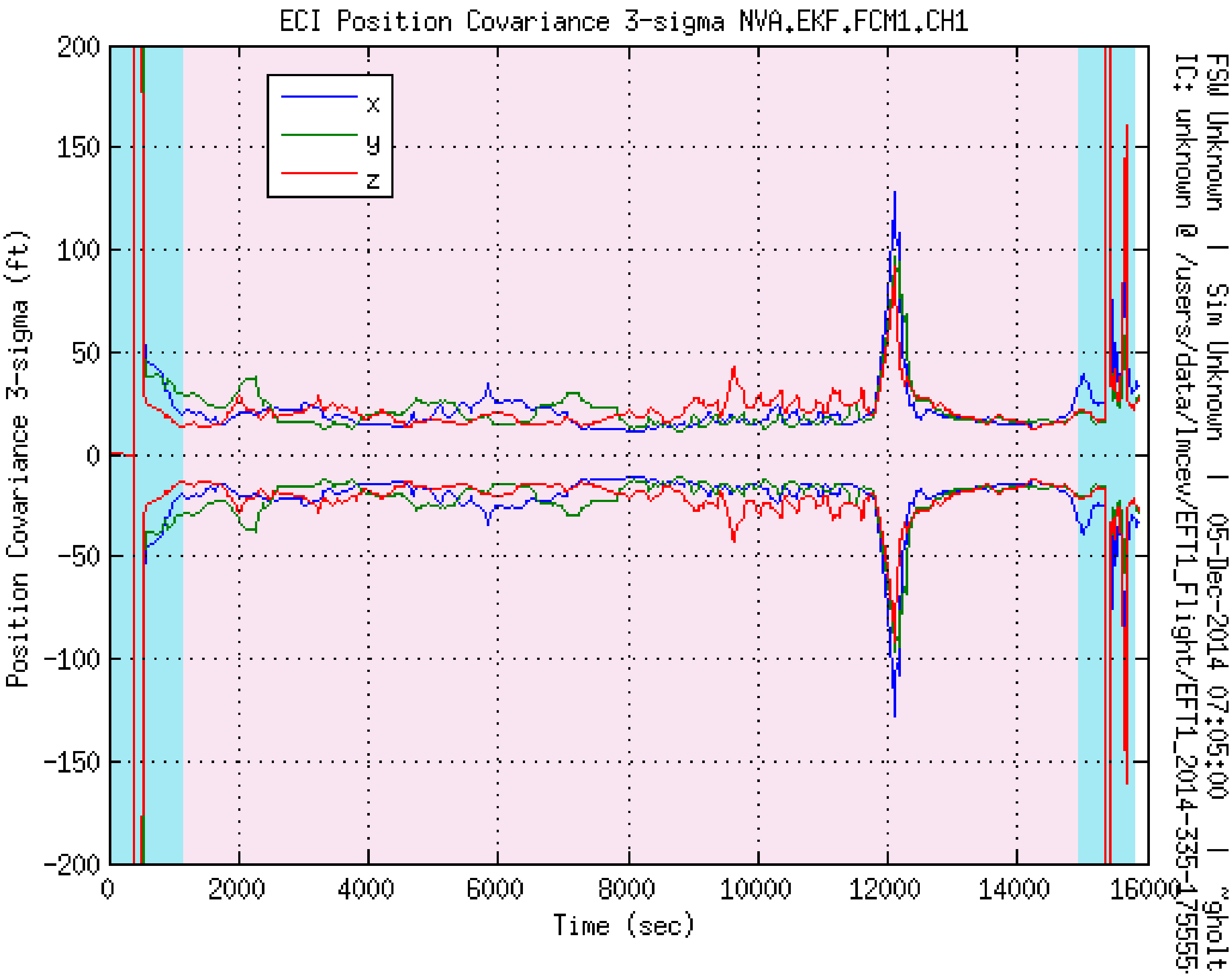
- **X** is the vector containing all 35 states, **Y** is the vector containing all measurements, which are a function of the state **X** and the measurement error (noise) **N**
- The estimates of the state and measurement are represented with a “^”, a superscript “+” indicates the updated estimate after the knowledge from a new measurement is incorporated

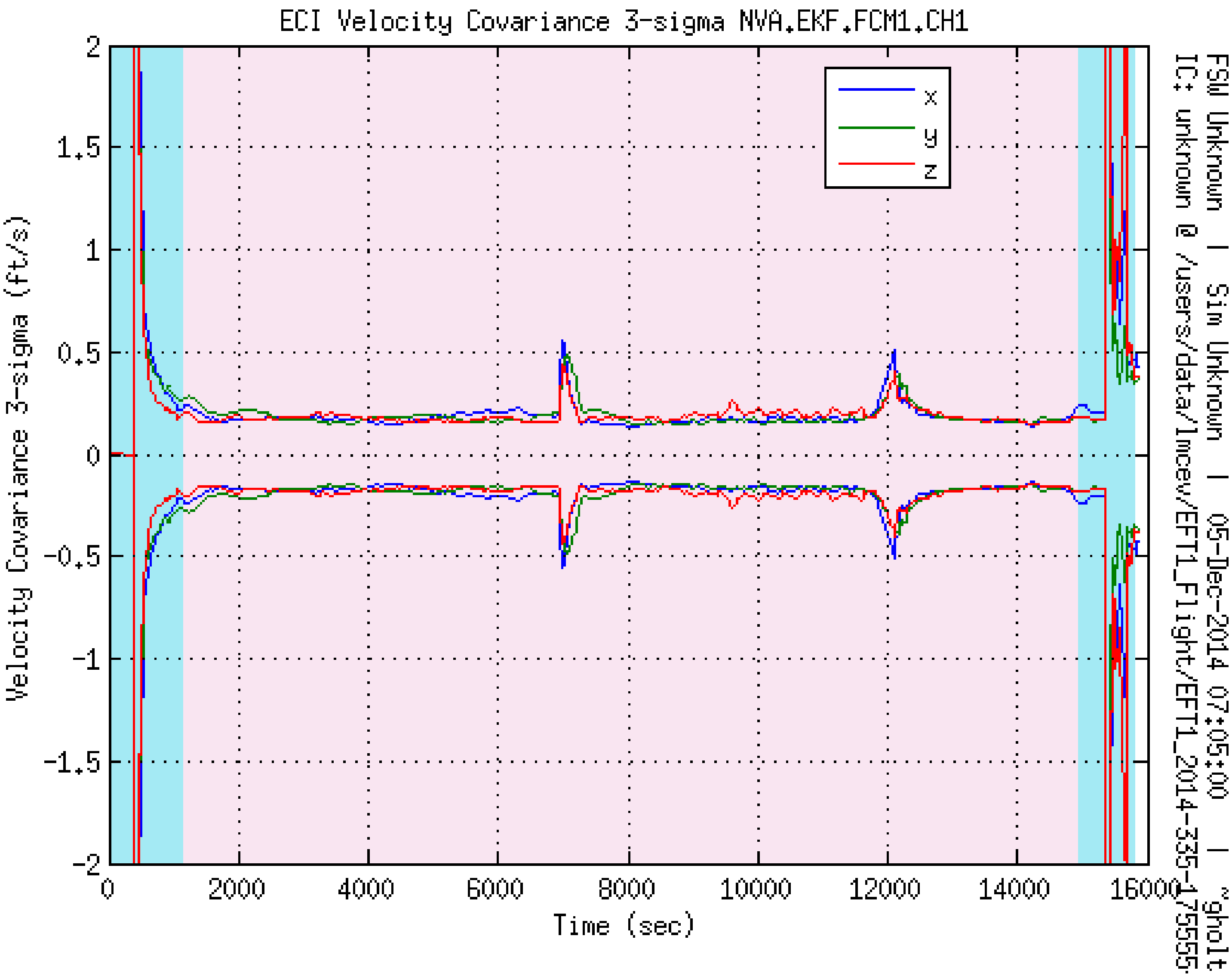
$$\hat{X}^{+} = \hat{X}^{-} + K(Y - \hat{Y})$$

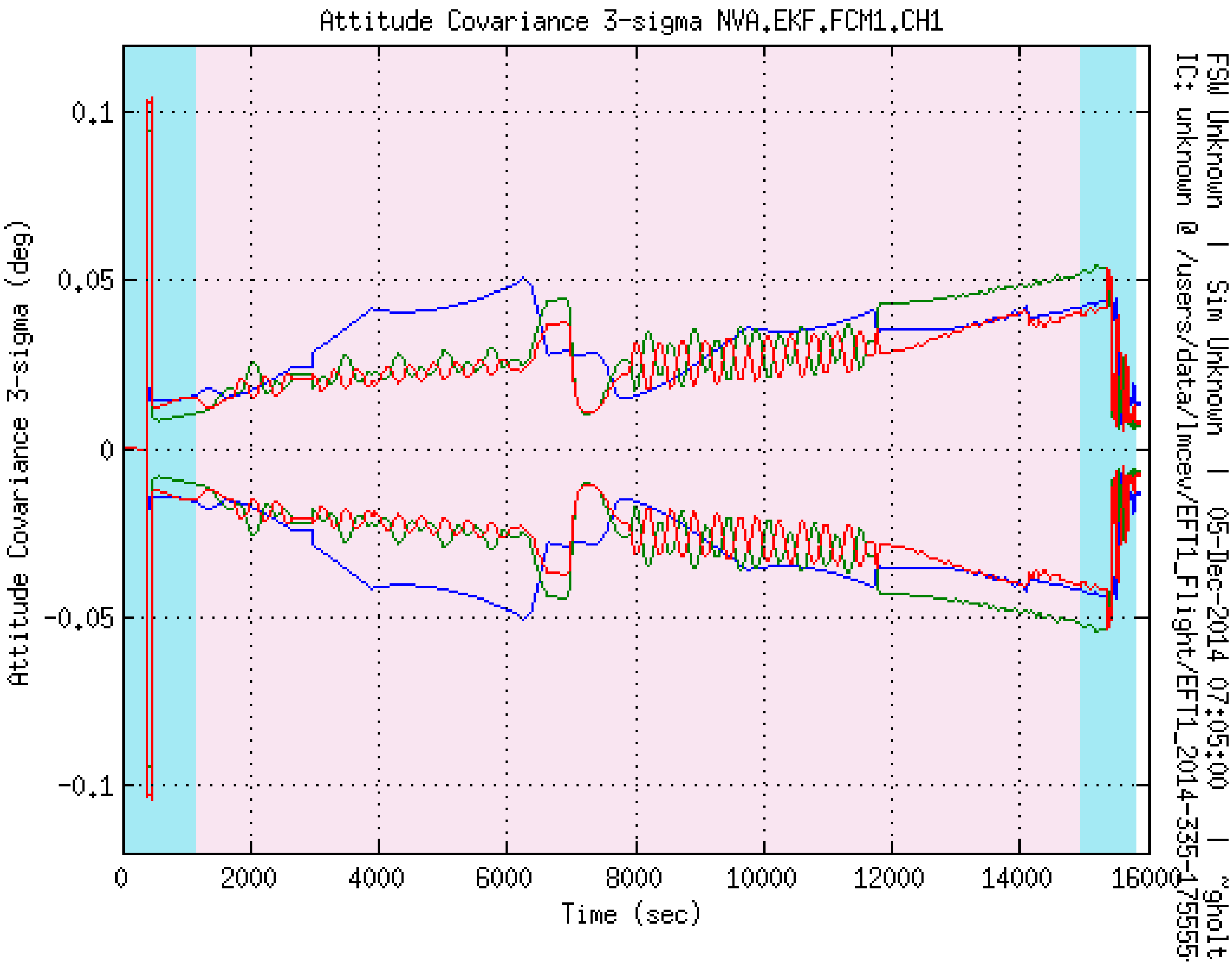
- The difference between the actual measurement **Y** and the estimated measurement is called measurement residual

Filter Design - Continued

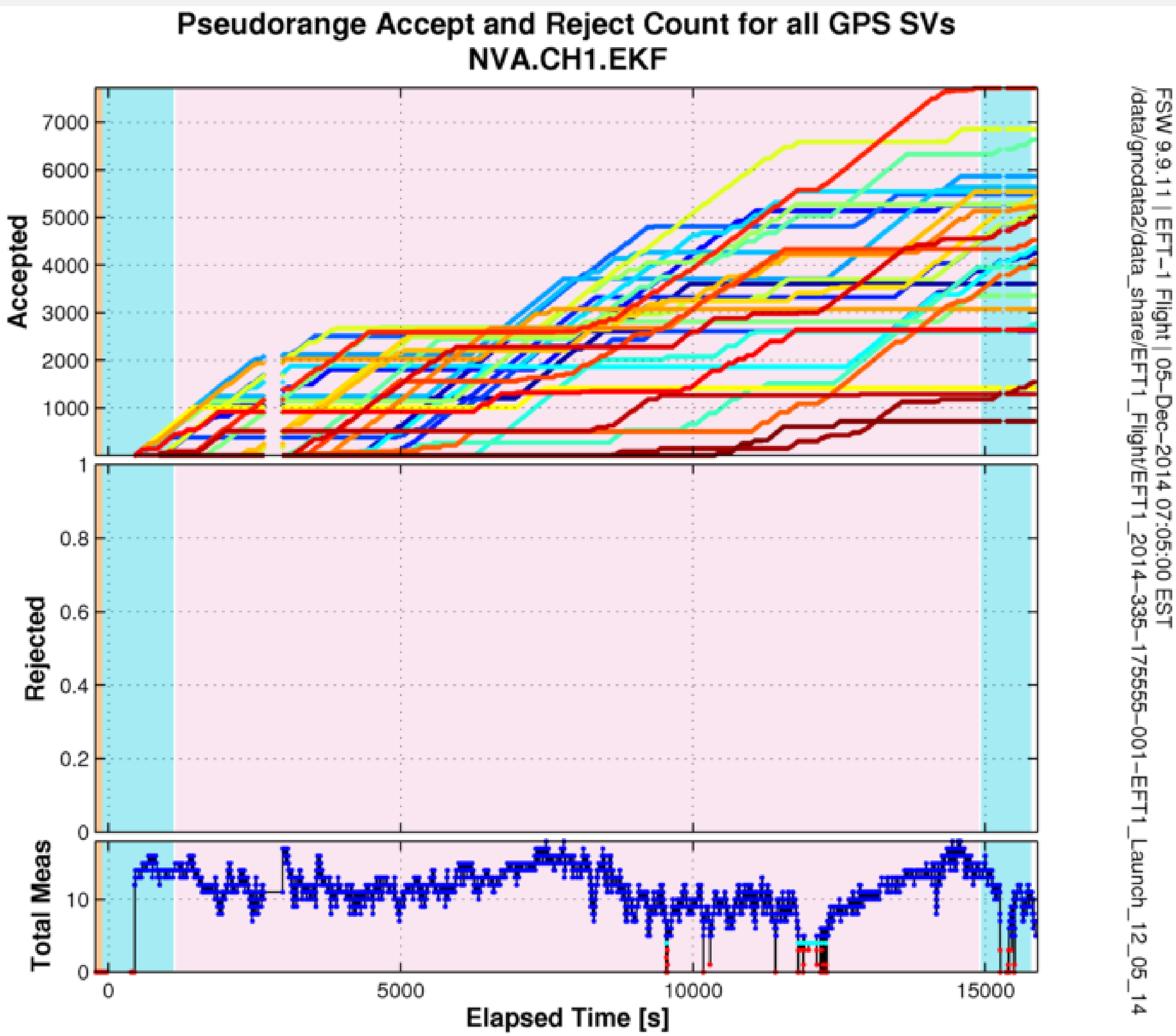
- Together with an estimate of the state, the EKF carries an estimate of the covariance matrix of the estimation error
  - During flight, we cannot check the accuracy of this covariance directly, we checked it previously with simulations and many Monte Carlo runs
  - During flight we check that the measurement residual is consistent with its predicted covariance
- The measurements processed by the navigation system are
  - Coarse Align – gyro compassing
  - Fine Align – Integrated Velocity
  - Flight – GPS Pseudorange and Delta Range

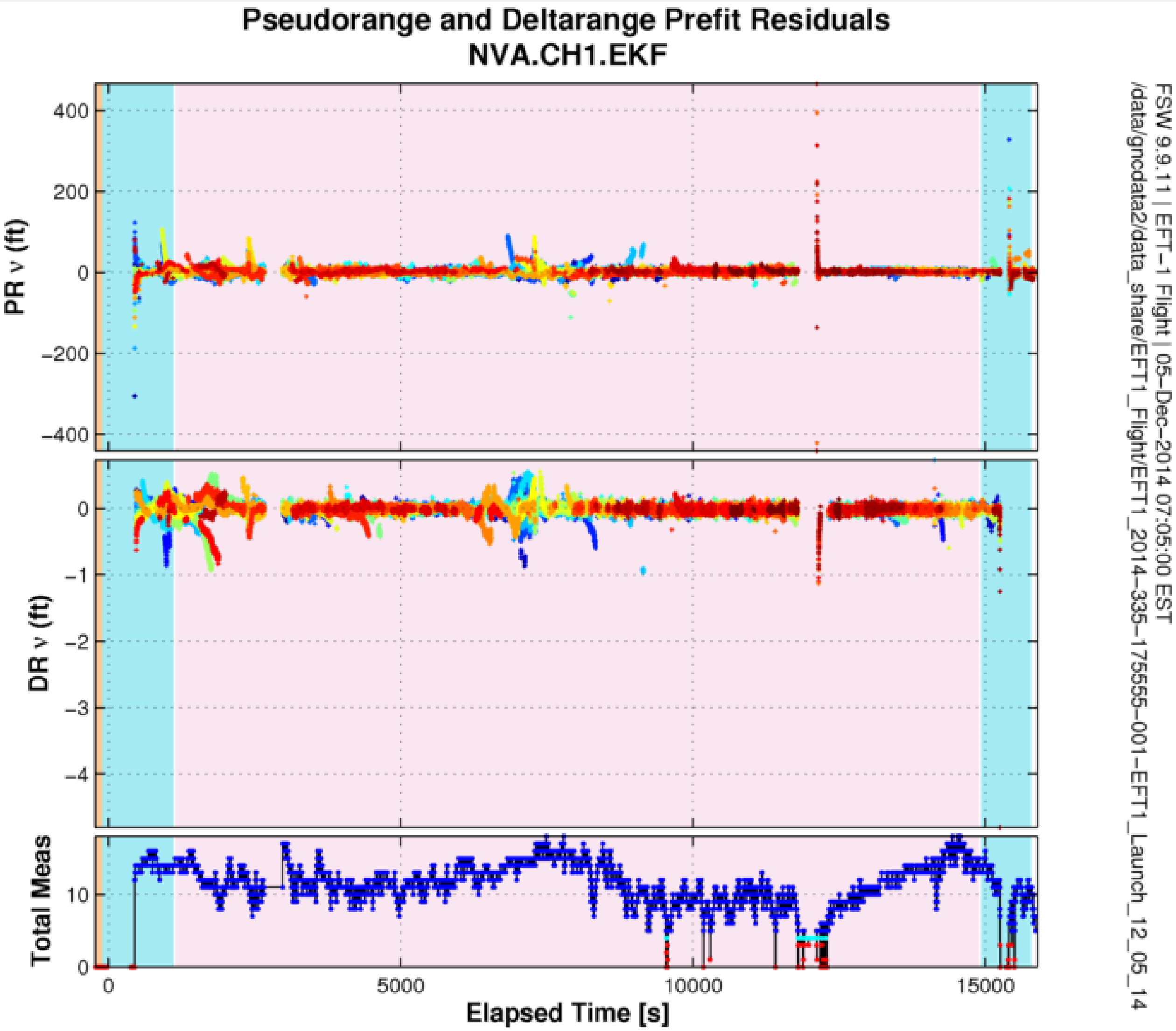

ECI Position Covariance 3-sigma NVA.EKF.FCM1.CH1
Position Covariance 3-sigma (ft)
Time (sec)
x
y
z
200
150
100
50
0
−50
−100
−150
−200
0
2000
4000
6000
8000
10000
12000
14000
16000
FSW Unknown | Sim Unknown | 05-Dec-2014 07:05:00 | ~gholt
IC: unknown @ /users/data/lmcev/EFT1_Flight/EFT1_2014-335-175555.


ECI Velocity Covariance 3-sigma NVA.EKF.FCM1.CH1
Velocity Covariance 3-sigma (ft/s)
Time (sec)
x
y
z
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
2000
4000
6000
8000
10000
12000
14000
16000
FSW Unknown | Sim Unknown | 05-Dec-2014 07:05:00 | ~gholt
IC: unknown @ /users/data/lmcev/EFT1_Flight/EFT1_2014-335-175555



Attitude Covariance 3-sigma NVA.EKF.FCM1.CH1
Attitude Covariance 3-sigma (deg)
0.1
0.05
0
-0.05
-0.1
0
2000
4000
6000
8000
10000
12000
14000
16000
Time (sec)
FSW Unknown | Sim Unknown | 05-Dec-2014 07:05:00 | ~gholt
IC: unknown @ /users/data/lmcev/EFT1_Flight/EFT1_2014-335-175555


Pseudorange Accept and Reject Count for all GPS SVs
NVA.CH1.EKF
Accepted
7000
6000
5000
4000
3000
2000
1000
Rejected
1
0.8
0.6
0.4
0.2
0
Total Meas
10
0
0
5000
10000
15000
Elapsed Time [s]
FSW 9.9.11 | EFT−1 Flight | 05−Dec−2014 07:05:00 EST
/data/gncdata2/data_share/EFT1_Flight/EFT1_2014−335−175555−001−EFT1_Launch_12_05_14



Pseudorange and Deltarange Prefit Residuals
NVA.CH1.EKF
PR ν (ft)
400
200
0
−200
−400
DR ν (ft)
0
−1
−2
−3
−4
Total Meas
10
0
0
5000
10000
15000
Elapsed Time [s]
FSW 9.9.11 | EFT−1 Flight | 05−Dec−2014 07:05:00 EST
/data/gncdata2/data_share/EFT1_Flight/EFT1_2014−335−175555−001−EFT1_Launch_12_05_14

EFT-1 Re-entry

- **This slide will show the video "Astronaut's-Eye View of NASA's Orion Spacecraft" from www.nasa.gov/exploration/systems/orion/videos**

Questions?