US End User Perspective

Orbital Uncertainty Working Group

January 29, 2024

Perspective

- I’m the end user …
  - Handed a “pile of observations”
  - “Make something”

“I’ve never met a sensor I didn’t like …

… just some I can’t afford.”

Processed

- Full US Space Surveillance Network (ground and space-based)
- Civil
  - SLR
  - NASA
    - Near Earth Network
    - TDRS
    - Deep Space Network
  - ISON
  - NEOSSat
- Operator
  - Ranging, doppler, angles
  - GNSS
- Commercial
  - Comspoc
  - Thoth Technology
  - Exo Analytics
  - Slingshot
  - Spaceflux
  - LeoLabs
  - Silentium Defence
  - GEOST
  - SAFRAN
  - KRATOS
  - Deimos
  - Raytheon

Measurement Types

Ground Based

- Traditional
  - 2-way range
  - Bistatic range
  - Doppler (1-way and 2-way)
  - Bistatic Doppler (1-way and 2-way)
  - Az /El angles
  - RA /Dec angles
  - Delta RA/DEC angles
  - X / Y angles
  - Direction cosines
  - Phased array face U, V
- Deep Space Network
  - 1, 2, and 3-way Doppler
  - 1, 2, and 3-way TCP
  - 2 and 3-way Sequential Range
  - DOR, Delta DOR, QDOR
  - PN Range
- Normal point range
- TDRS
  - BRTS range / Doppler
  - DOWD

Either

- GNSS receiver (GPS, Galileo, QZSS, GLONASS)
  - 2L CA pseudo-range
  - Pseudo-range
    - Multiple frequencies
    - Single and double differenced
  - Phase
    - Multiple frequencies
    - Single and double differenced
  - CA and DF nav solution (X, Y, Z)
- TDOA, FDOA, TDOA-dot, single differenced TDOA and FDOA

Space Based

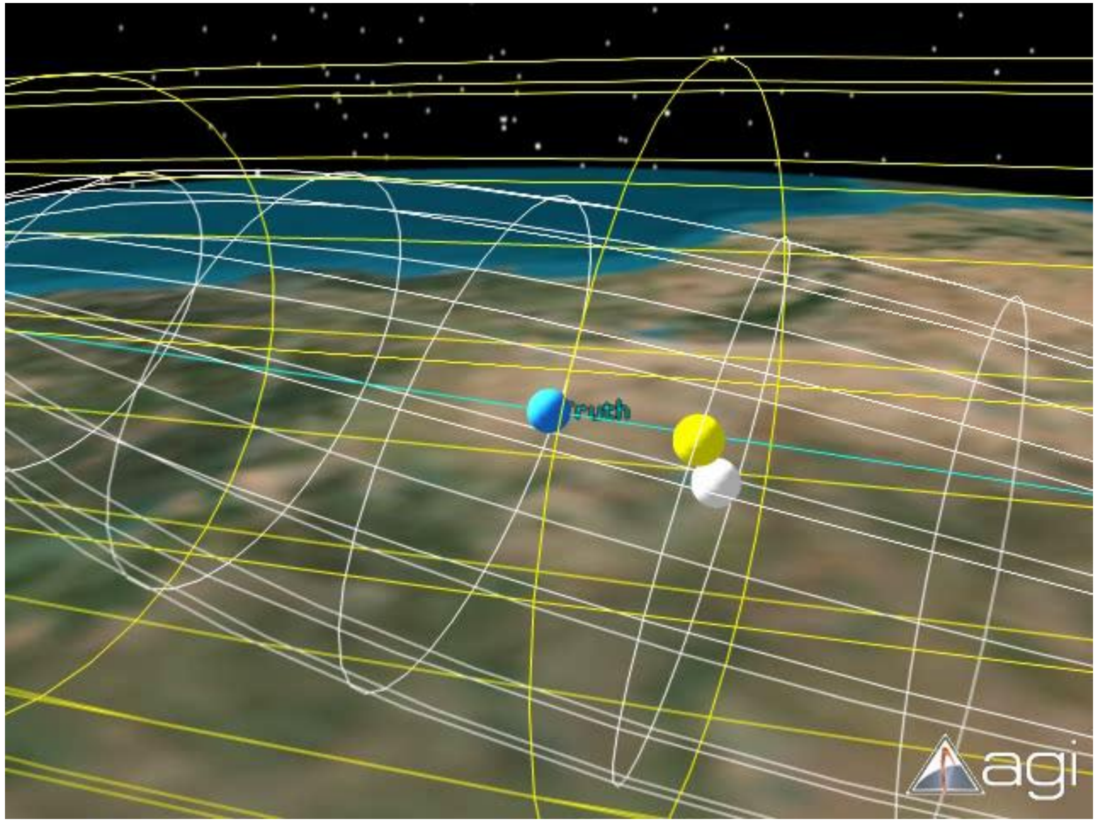
- TDRS
  - 4L range, 5L Doppler
  - 3L return-link Doppler
- Sat-to-sat
  - Range
  - RA /Dec
  - Delta RA/DEC
  - Az /El
  - Doppler
- Accelerometers
- Ephemeris (STK, ITC, CCSDS)

Motivation

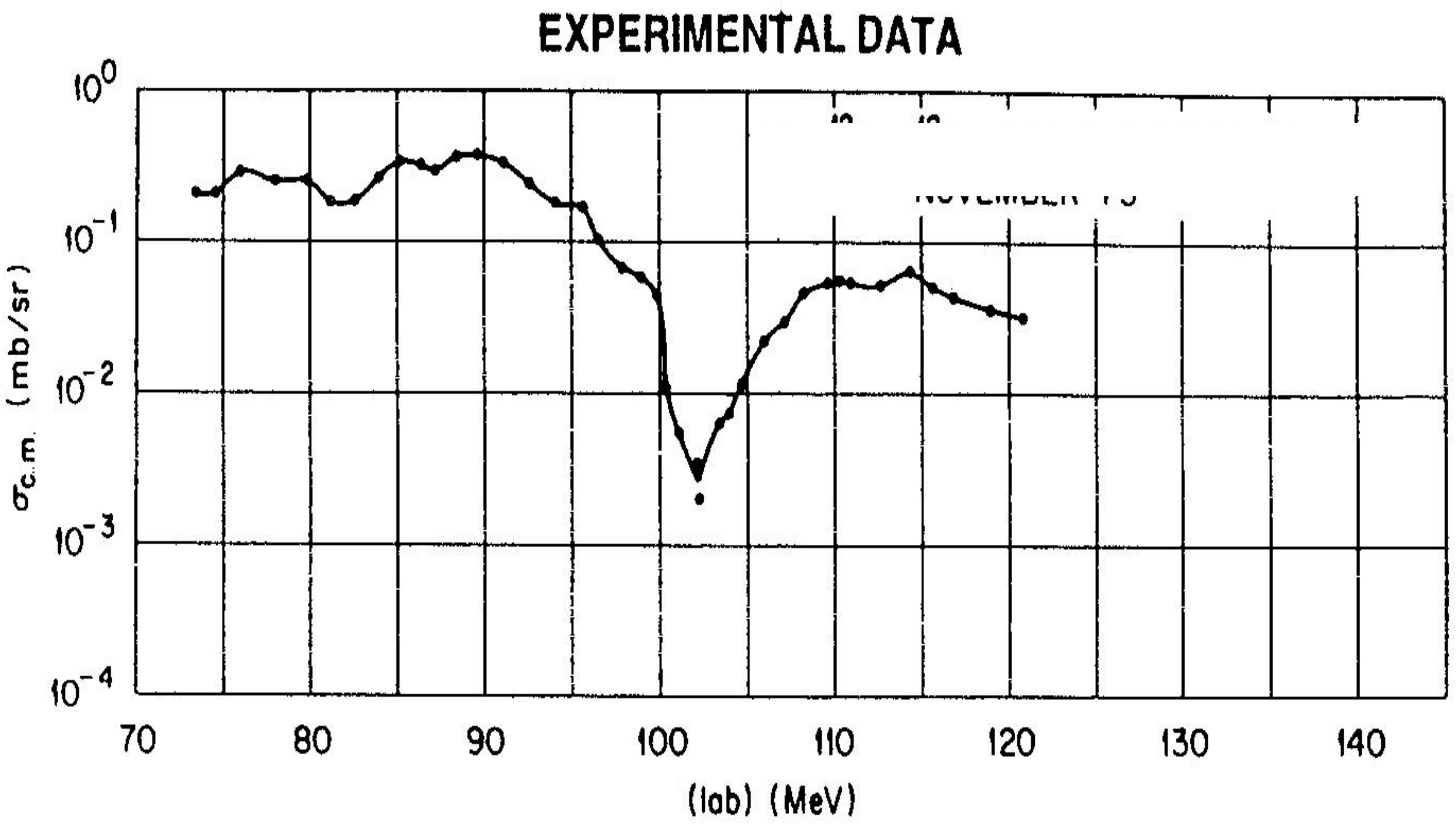
- We want to have:
  - Accurate definitive ephemeris
  - Accurate predicted ephemeris
  - Realistic covariance
- Meet mission requirements
- Support accurate conjunction risk assessment
- Reduce the amount of tracking needed
- Timely detection of maneuvers or anomalous behavior

Covariance

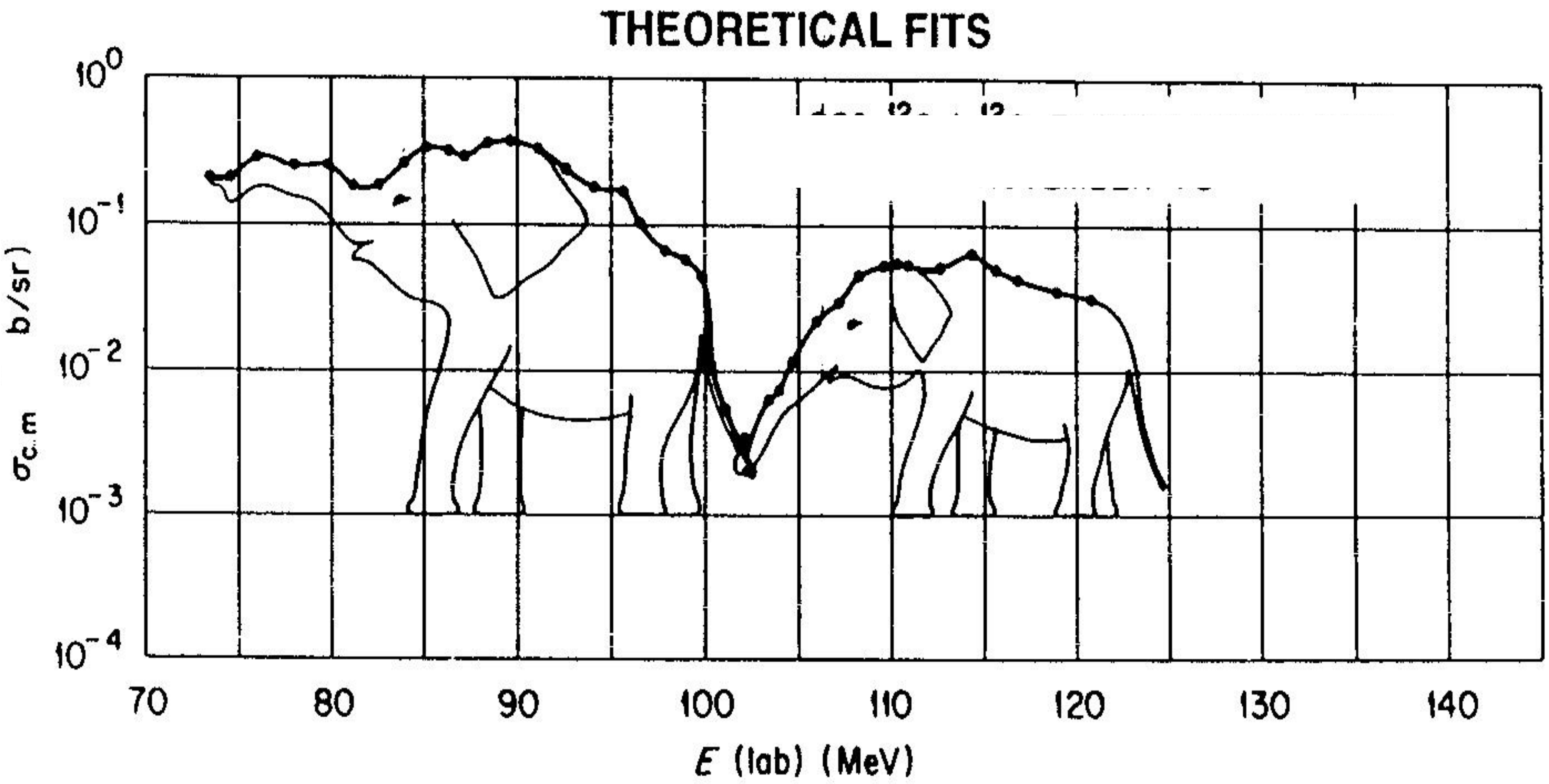
- Display position ellipsoids
  - Truth (blue)
  - Filter (yellow)
  - Smoother (white)
- Use ephemeris and covariance for analysis



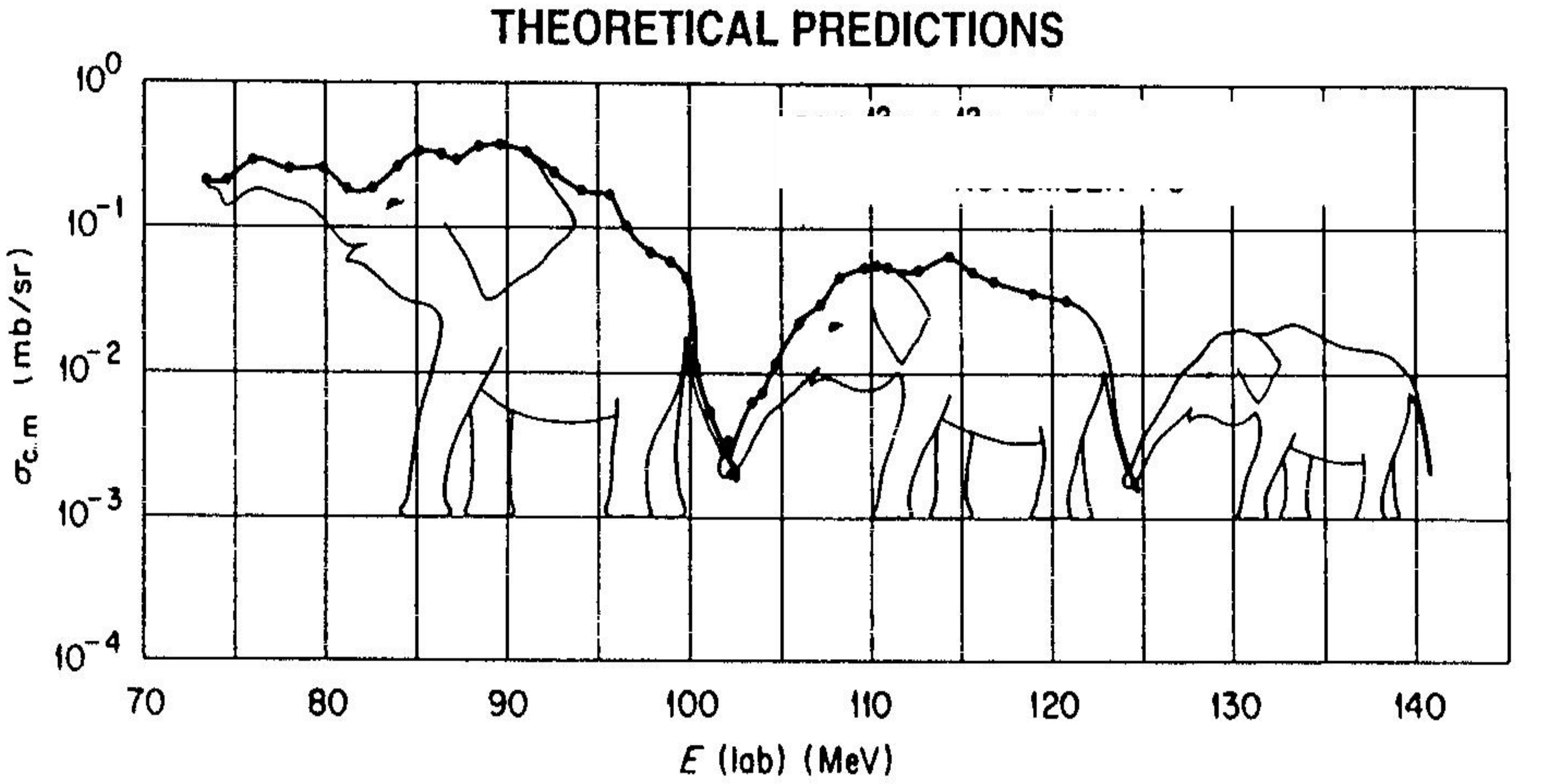
OD is “curve fitting”



The right model improves the fit



and improves the prediction



Forces

- Gravity
  - Earth
  - Moon
  - Sun
- Drag
  - Atmospheric density
  - Shape
  - Attitude
- Solar radiation pressure
  - Distance from the Sun
  - Shape
  - Attitude
- Radiation pressure
- Maneuvers
  - Why?
    - Stationkeeping
    - Relocation
    - Momentum management
  - How?
    - Chemical
    - Electric
  - Signature
    - Impulsive
    - Finite

But our models are not perfect

- Measurement modeling errors
  - Noise (white) and measurement biases
  - Satellite transponder bias
  - Troposphere
  - Ionosphere
  - Clock phase & frequency
  - Antenna phase center
  - Tracker location
- Force modeling errors
  - Earth gravity
  - Solar pressure (dynamic area)
  - Drag (dynamic area and atmospheric density)
  - Thrust magnitude and direction
  - Spacecraft area & surface properties
  - Earth radiation
  - Spacecraft radiation

How to minimize impact of errors?

- Improve force models
  - But there are practical limits
  - And things that go “bump in the night”
    - e.g. solar flares, unscheduled outgassing, “safe mode”, etc
- Improve measurement models
  - But tracking hardware has its own limits
- Segment the fit
  - A simple model can approximate a complex one locally

Calibration Reference Orbits

- GNSS derived
  - IGS MGEX SP3 solutions for GPS, Galileo, Glonass, Beidou, QZSS
  - QZSS and Beidou also have GEO targets
  - On-board GNSS receivers – Jason-3, ICESAT, etc. Hard to get definitive solutions.
  - GPS is near real-time, other solutions have production lags
- SLR derived
  - ILRS predicts (CPF)
  - ILRS actuals (SP3) – publish more of these!
  - Must be cautious about maneuvering satellites (Cryosat, Swarm, etc.)
- Operator ephemeris
  - Suspect unless GNSS derived
  - Often confuse consistency with accuracy …
- Self-calibration
- TLEs and VCMs are "suggestions …"
- Observability issues
  - Not all sensors can reach MEO or even high LEO …

Simultaneous OD

- Estimate multiple RSOs at the same time
  - Reduces chances of sensor biases aliasing into the force models
- Produce solutions using all combinations of measurements
  - Optical only
  - Optical + radar
  - Radar only
  - Range only
  - Doppler only
  - Etc.
- Evaluate definitive accuracy, prediction accuracy, covariance realism

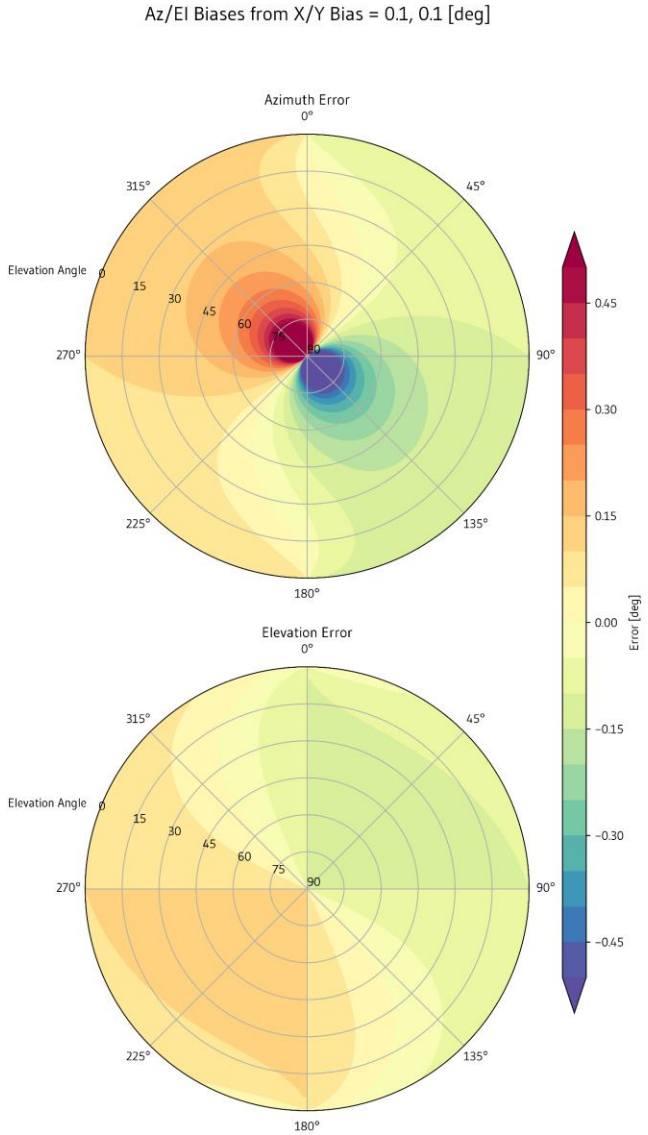
Timing Issues

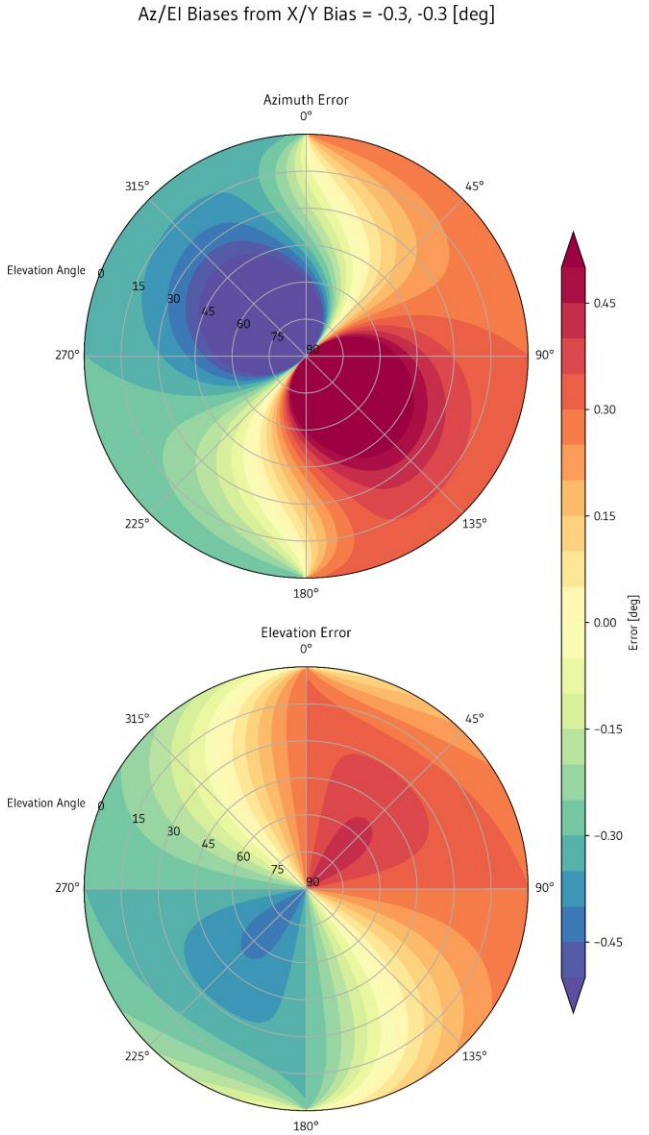
- What is the source clock?
  - Must be GNSS based. Not NNTP to your grandmother's time server …
  - Stability
  - Timing bias
- What does the time tag represent?
  - Time of tracker transmit, satellite receive, satellite transmit, tracker receive
  - Is it the leading edge of a pulse, middle, or trailing?
- Many measurements are integrated
  - What is the integration time?
  - Is the time tag at the middle of the integration or the end?

Measurement "Corrections"

- Report the raw measurements
  - No corrections!
    - Particularly for ionosphere, troposphere, light time delay
    - No aberration
    - No biases
  - Ok to correct time biases (if you can do it well …)
  - No averaging.
- Don't transform the measurements
  - If the raw measurements are U, V, report that.
  - Don't map into some other measurement space.
  - Transformations are non-linear.
- Tell us the reference frame!

Az/El Errors due to X/Y biases





What does an analyst need to know?

- Know your tracking problem
  - Performance of trackers / sensors
    - Bias uncertainty & variability
    - Noise characteristics
    - Real-time responsiveness
    - Sensitivity
  - Limitations of force models
    - Agility of the target
    - Variability of cross-section
    - Maneuverability
- Recognize a “good” or “bad” solution

Integrating Data from Multiple Networks

Challenge

- Different networks/sources will
  - Have different identifiers for the same satellite
  - Have different identifiers for the same ground station
  - Use different tracking data formats
- Often seen during launches or anomalies when you get data from multiple sources
- Each source tends to use its own ID convention for identifying satellites and trackers – which leads to trouble when you want to use all the data in your solution
  - Want to avoid duplicating trackers and satellites
- Commercial SSA sources generally use the "NORAD" number or COSPAR ID
  - Not everything has a COSPAR ID – e.g. analyst sats from the 18th SPCS

Example Mappings

	TDRS-3 Satellite	DSN DSS-46 Tracker ID	SSC Kiruna-2 Tracker ID	AFSCN GUAM-B Tracker ID	SSN EGLIN FPS-85 Tracker ID
NASA UTDF Support Identification Code (SIC)	?	1546	1905	1375	4345
NASA DSN TRK-2-34	?	46			
US Air Force Satellite Control Network (AFSCN)	IRON ?			GTSB	
US Space Surveillance Network (SSN) B3	19548				399 (398 deep space mode)
CCSDS Tracking Data Message (TDM)	TDRS-3	DSS-46	KIR-2		
COMSPOC and other commercial SSA providers	19548	TBD			399
COSPAR	1988-091B				

Measurement Formats

Concept

- Don’t confuse measurement format with measurement model
- Model
  - Mathematical expression to calculate a measurement from the state
  - $Range = \sqrt{(x - x_s)^2 + (y - y_s)^2 + (z - z_s)^2}$ where “s” is the sensor location.
- Format
  - The way the measurements are provided in a data file
  - Text or binary
  - Fixed format, comma separated, JSON, XML, etc.

File Contents

- Meta data - all the non-measurement values
  - Sensor ID, RSO ID, coordinate frames, measurement correction flags, etc.
- Measurements
  - Time tagged observations or observation sets.
  - May also include observations of the visual magnitude or radar cross section. Known as “non-metric” observations.
- May contain multiple tracks in one file
- Not all formats have a concept of a “track”

Common Formats

- There is no "universal format"
- GEOSC – Fixed format text file originally created by NASA Goddard to support the GEOS-C satellite mission in the mid 70's
- UTDF – "Universal" Tracking Data Format – binary format used by NASA Goddard for near Earth Missions
- TRK 2-34 – binary format used by NASA JPL for deep space missions.
- RINEX – GNSS observations
- MPC – Minor planet center optical observations
- CRD – ILRS ranging data (full rate and normal point)

B3

- Fixed format text file created by USAF/USSF. See https://help.agi.com/odtk/#od/ODObjectsB3OBSType.htm
- Data source: USSF
- Usually has file extension ".obs".
- Transmit variant – used to send data from the sensors to the 18 SDS.
  - Easily recognized due to it's use of "))" at the beginning of a line and "$$" at the end.
  - Does not include the year, must be "known".
  - Observation set may span two lines.
- Archive variant – used to archive the data at the 18 SDS.
  - Adds the year.
  - Negative numbers use "overpunch" notation, represented by characters "J"-"R".
  - Observation set is on one line.
- Measurements:
  - Azimuth, elevation, range, doppler
  - Right ascension, declination
  - Space based azimuth, elevation, right ascension, declination and position of sensor.
  - Position and/or velocity
- No concept of a track.
- May contain multiple sensors and RSOs in a file.
- No visual magnitude or RCS observations.

B3 Archive Example

Tracker ID
Time HH:MM:SS.SSS
RSO ID
2 digit year
Day of year
Elevation DD.DDDD
Azimuth DDD.DDD
Range RR.RRRRR
Range Exponent 10^N
Observation Type

- U2355838996001015209431178016 3422654 10430002 -475850 01320 02956 00000 4 3
- U2355838996001015219367190901 3453475 99708801 -447859 01326 03270 00000 4 4
- U2355838996001015230167205012 3491035 95058881 -412303 01323 03666 00000 4 4
- U2355838996001015240642218755 3531913 90937061 -373284 01301 04090 00000 4 4
- U2355838996001015251334232579 3578034 87183161 -327837 01244 04536 00000 4 5
- U2355874596001015820133696952 2716046 41368121 2 1
- U2355839996001020136970216895 2140947 90784571 2 3
- U2355839996001020212371185576 1989882 10066542 2 4

CCSDS TDM "Tracking Data Message"

- Originally designed to exchange tracking data for deep space missions, and has been extended to accommodate more missions, including SSA.
- Data source: Anyone
- Text or XML format.
- Usual file extension is "*.tdm", "*.xml", "*.txt"
- Has a track concept.
- One sensor and RSO per TDM.
- Supports one track per TDM (unless using XML variant and combining multiple TDMs into a NDM "Navigation Data Message").
- Can contain visual magnitude or RCS observations.

TDM Example

```
CCSDS_TDM_VERS = 2.0

CREATION_DATE = 2023-05-26T08:10:32.697939
ORIGINATOR = SPACEFLUX

META_START
TIME_SYSTEM = UTC
PARTICIPANT_1 = aus-wa-1
PARTICIPANT_2 = 42917
MODE = SEQUENTIAL
PATH = 2, 1
TIMETAG_REF = RECEIVE
ANGLE_TYPE = RADEC
REFERENCE_FRAME = EME2000
META_STOP

DATA_START
ANGLE_1 = 2023-05-24T11:29:37.260      182.122507
ANGLE_2 = 2023-05-24T11:29:37.260        5.548885
MAG     = 2023-05-24T11:29:37.260       15.559292
ANGLE_1 = 2023-05-24T11:29:39.261      182.131630
ANGLE_2 = 2023-05-24T11:29:39.261        5.548979
MAG     = 2023-05-24T11:29:39.261       15.426511
ANGLE_1 = 2023-05-24T11:29:43.262      182.149040
ANGLE_2 = 2023-05-24T11:29:43.262        5.549493
MAG     = 2023-05-24T11:29:43.262       14.744301
DATA_STOP
```