Assessment of TLE-based Orbit Determination and Prediction for Cubesats

Alexander Smith
Omitron, Inc.
NASA GSFC Flight Dynamics Facility

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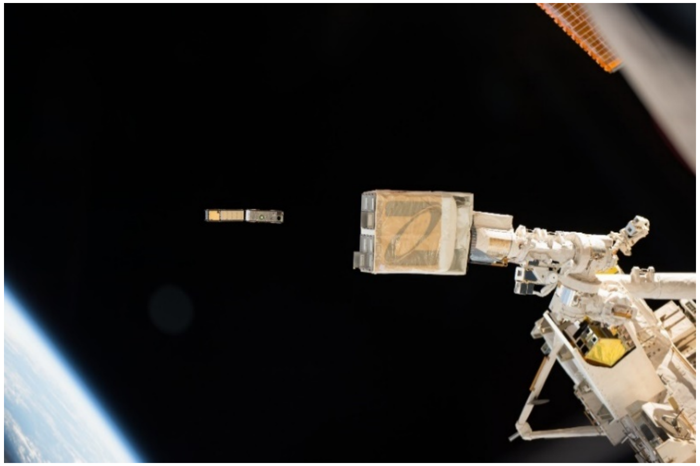
Ensure Mission Success

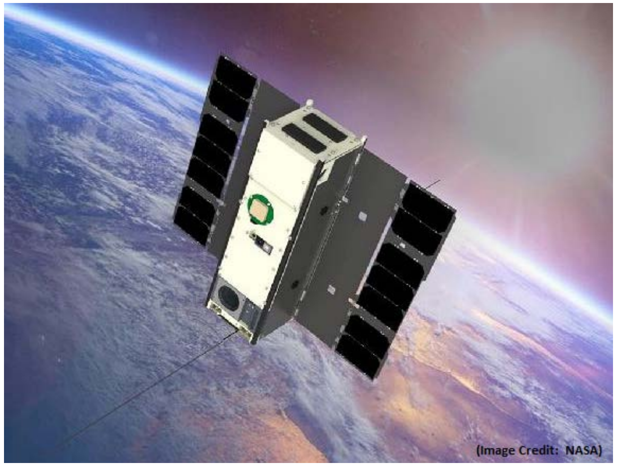
Outline

- ***Introduction***
  - IceCube deployment and acquisition troubles
- ***Preliminary Analysis***
  - Initial orbit state estimation
- ***Spacecraft Characterization/Propagation Analysis***
  - Simulate measurements from Two Line Element (TLE) states in extended Kalman Filter (EKF)
  - Demonstrate definitive/predictive accuracy of filtered solution
- ***Global Positioning Satellite (GPS) Measurement Calibration Analysis***
  - TLE EKF solution used to estimate GPS timing biases
  - Incorporation of calibrated GPS measurements into TLE EKF for covariance reduction
- ***Conclusions***

Introduction

- ***IceCube*[1][2]**
  - 3U cubesat deployed from International Space Station NanoRacks in May 2016
  - Technology demonstrator studying ice clouds and precipitation processes
  - Used TLEs for acquisition data and scheduling
    - Provided by United States Strategic Command (USSTRATCOM) via SpaceTrack website
  - Onboard GPS receiver downlinks GPS states for science data processing and orbit determination
  - Spin-stabilized attitude about sun-pointing line




(Image Credit: NASA)

Acquisition Troubles

- ***Following initial acquisition, IceCube MOC lost contact with the spacecraft for a period of 7 days***
  - TLEs were not received from USSTRATCOM during this time period, leaving mission to propagate stale states for acquisition data
- ***Numerous issues made locating spacecraft difficult***
  - Narrow 3° antenna beamwidth corresponds to 22-40 km required orbital accuracy
    - TLE propagation accuracy can degrade past this value within 2-3 days
  - Downlinked GPS states did not agree with concurrent TLEs and showed errors in excess of 300 km
  - Spacecraft attitude and thus drag area was unknown, therefore Low Earth Orbit (LEO) predominant drag forces could not be determined
    - Even in ideal mission attitude (spin-stabilized sun-pointing), drag area varies between 0.01 and 0.14 m^2 throughout orbit

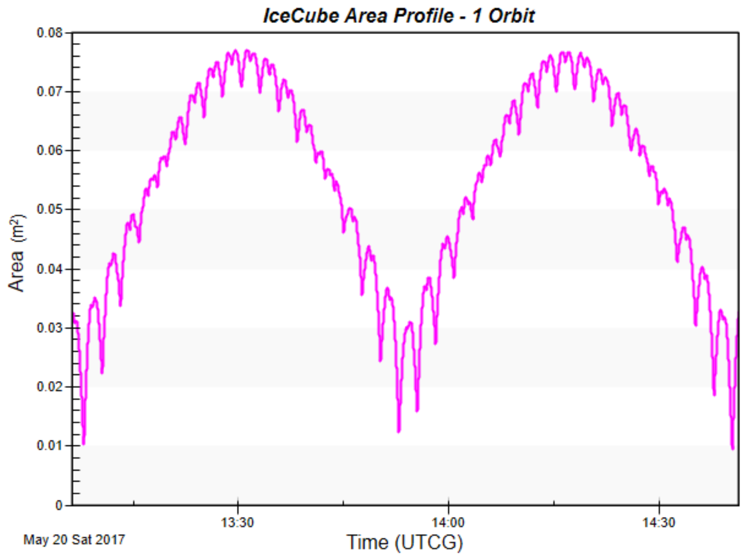
There was an operational need to provide accurate predictive states and acquisition data using the limited TLE and GPS data available.

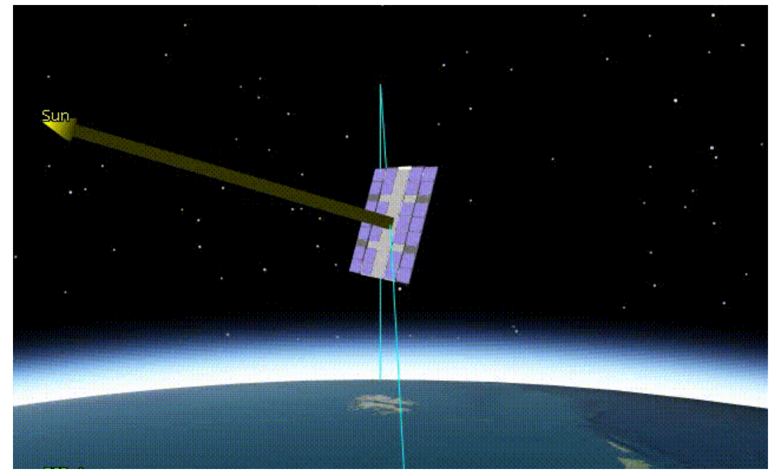
Preliminary Analysis

- ***Propagate TLEs to next TLE epoch to get rough estimate of accuracy***
  - TLEs are most accurate around their epoch due to both the Simplified General Perturbations 4 (SGP4) propagator, and propagation errors due to atmospheric drag in LEO
  - State differences grow rapidly between TLE epochs
    - IceCube TLEs were spaced approximately every 15-16 hours (~10 orbits)
- ***Examine GPS states and compare to nearest TLEs***
  - The two did not match and had differences of ~300 km, primarily in the in-track direction
- ***Determine averaged area for spin-stabilized sun-pointing attitude***
  - Used Satellite Tool Kit (STK) Area Tool assuming nominal attitude profile
    - Spin-stabilized and sun-pointing at 1.2 deg/sec (1 rev every 5 minutes)
    - Significant drag area variations per 5 minute rotation and per orbit
    - Additional seasonal variations throughout the year

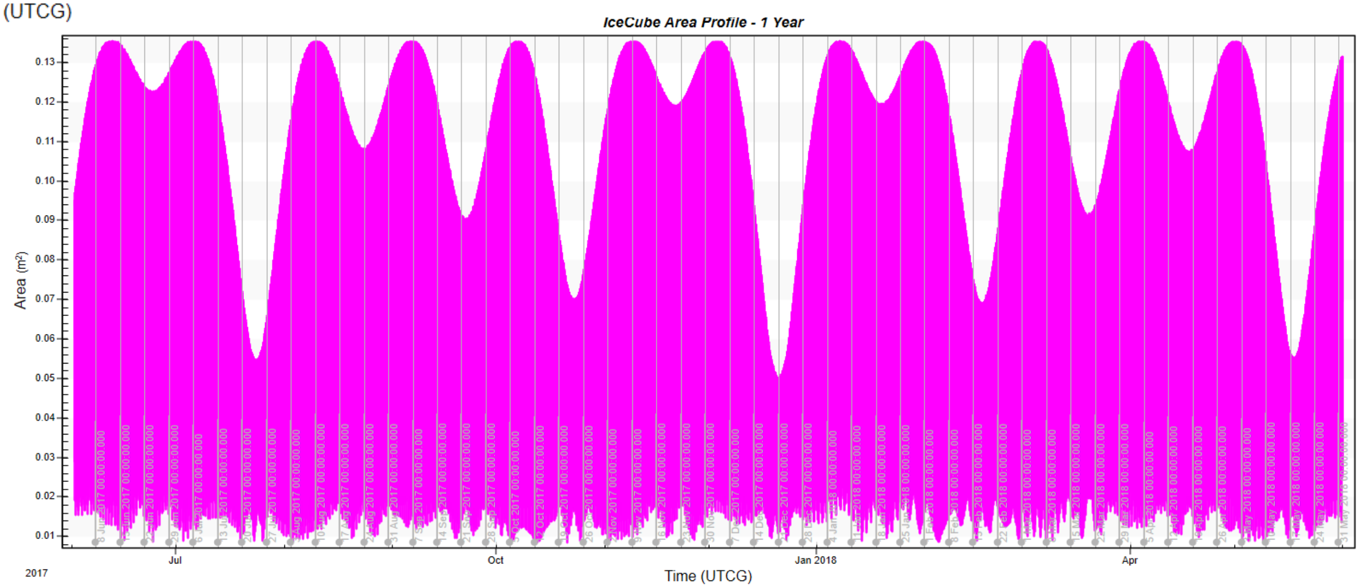
IceCube Area and Attitude

(m)





- Large area variations indicate that drag values from individual TLEs are not be suitable for long-term propagation

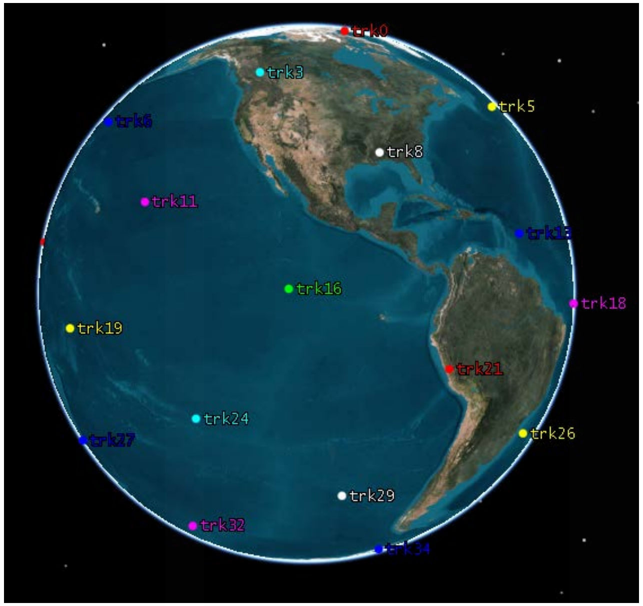


Spacecraft Characterization/Propagation Analysis

- ***The available TLEs are used as seeds to generate spans of simulated ground antenna ranging measurements***
- ***TLE-simulated measurements run through an extended Kalman Filter***
  - Orbit Determination Tool Kit (ODTK) EKF allows continuous estimation of states as solution moves away from each TLE epoch
    - Atmospheric drag states are estimated as solution accepts TLE-simulated measurements
  - Subsequent use of the ODTK Smoother “fills in” gaps where propagated TLE accuracy is degraded
    - Covariance for entire solution will be closer to TLE accuracy around epoch
  - TLE solution run through EKF can be propagated with lower covariance and used to generate acquisition data with higher confidence

Methodology

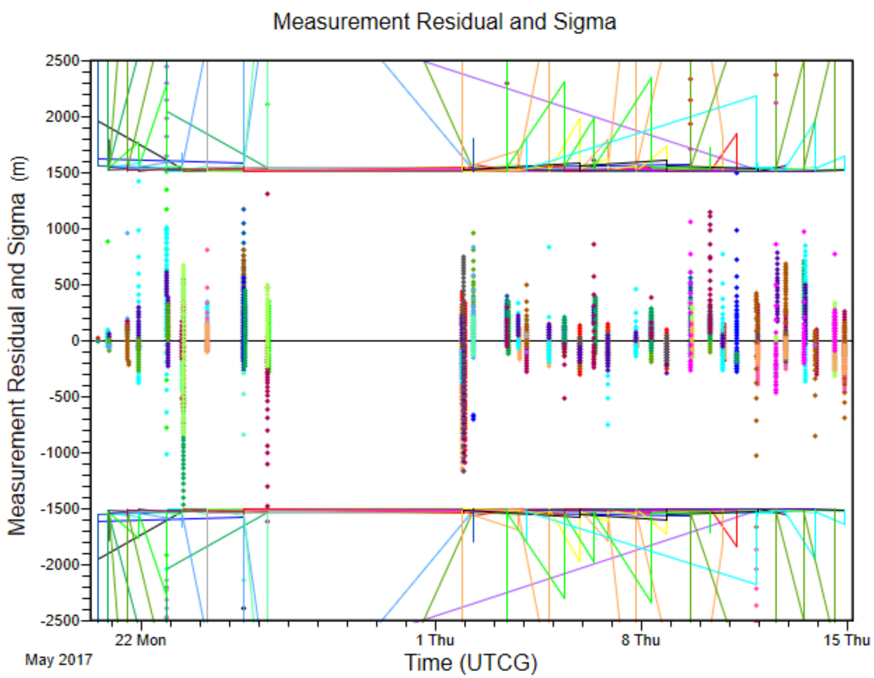
- ***TLEs are ingested into STK and propagated using SGP4***
  - The propagated span the 40 minutes before TLE epoch
    - 40 minutes is approximately ½ orbit, a span where definitive TLE accuracy is most trusted
- ***ODTK scenario setup with representative tracking stations for simulation***
  - Satellite state is set to follow the propagated TLE and simulate range measurements
  - Representative ground stations are created at equidistant spacing around Earth
    - Allows for continuous view around TLE epochs
  - Process is repeated for each available TLE

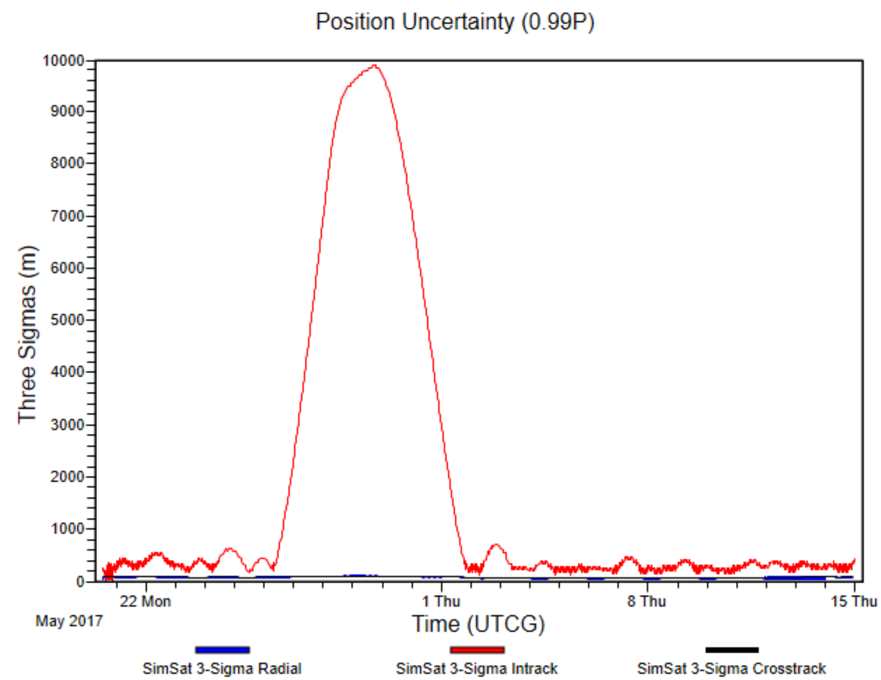


- ***Simulated measurements processed in EKF***
  - Initial state seeded from first available TLE
- ***Converged solution is representative of combined TLE states***
- ***Solution smoothed to provide accurate definitive states***
  - Reduces overall definitive covariance between TLE updates
- ***Solution then propagated forward to create acquisition data***

TLE EKF Solution

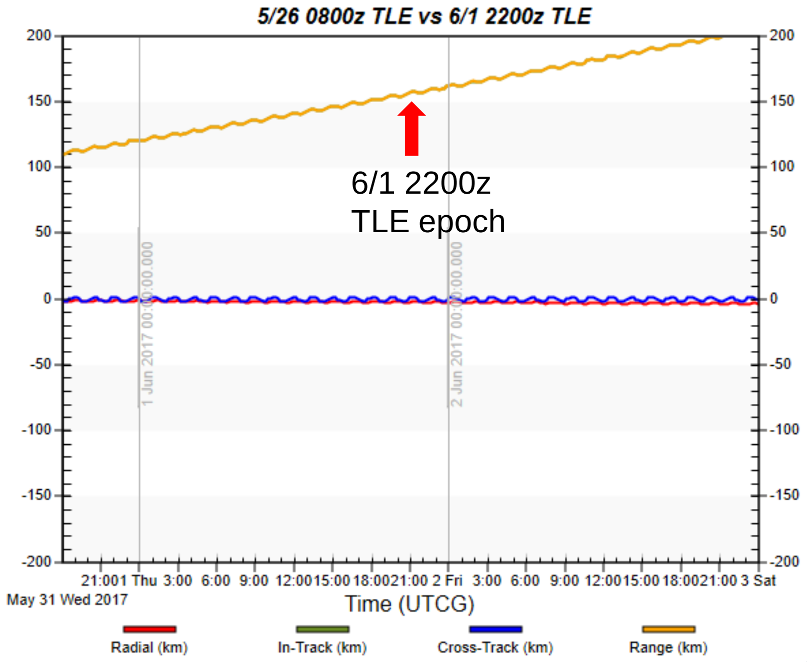
- ***EKF converges on TLE-simulated range measurements***
  - Simulated measurements fit well within typical TLE accuracy
  - Solution robust enough to converge again following 7 day data gap
- ***Definitive position covariance (when measurements present) less than 600m, expected largest error in the in-track direction***

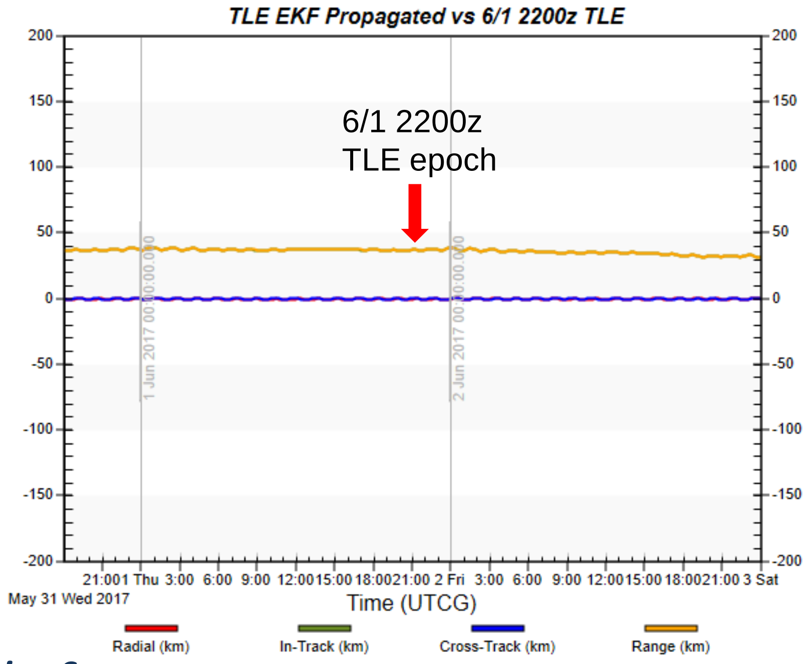




TLE EKF Propagation Accuracy

- ***Last TLE prior to data gap: epoch 5/26 0800z, next TLE after data gap: epoch 6/1 2200z***
- ***5/26 TLE propagated has >100 km difference at 6/1 TLE epoch***
  - Expected accuracy from long TLE propagation
- ***TLE EKF propagated has <40 km difference at 6/1 TLE epoch!***





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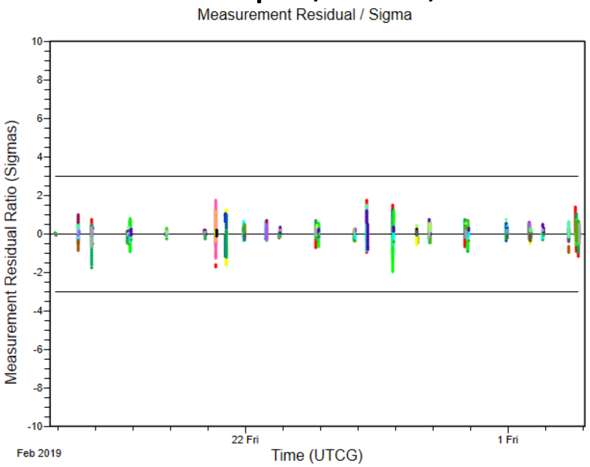
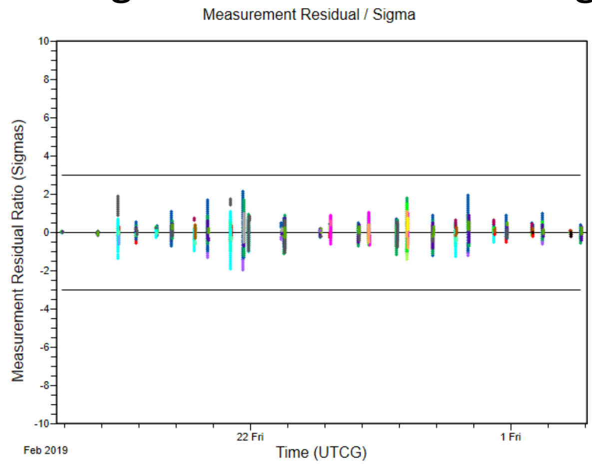
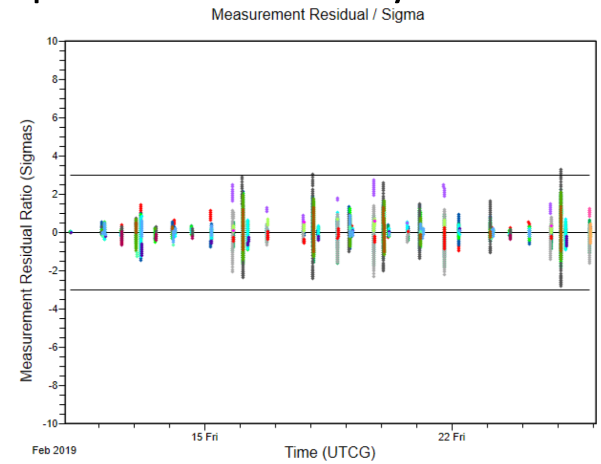
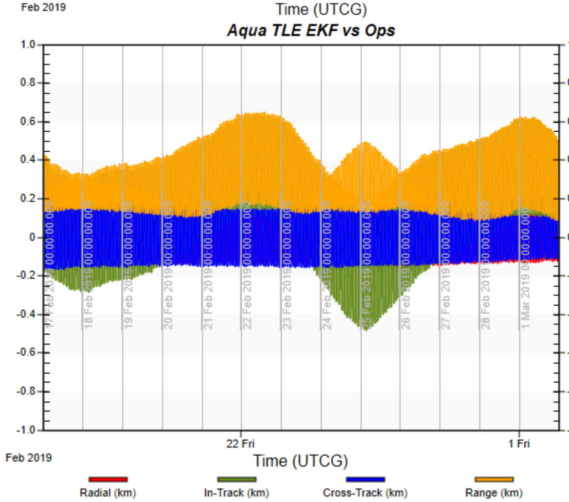
TLE EKF Solution Accuracy Check

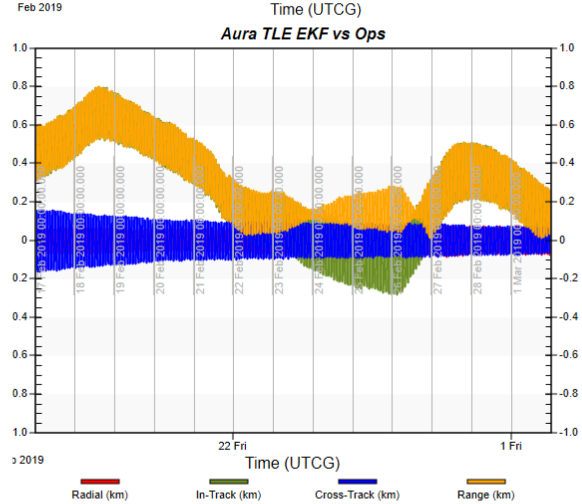
- ***Run TLE EKF process for satellites with well known definitive states***
  - Aqua, Aura, and Terra are good candidates with high operational accuracy

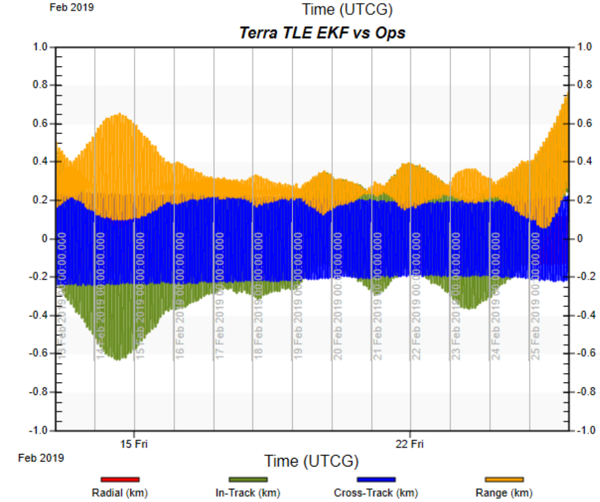










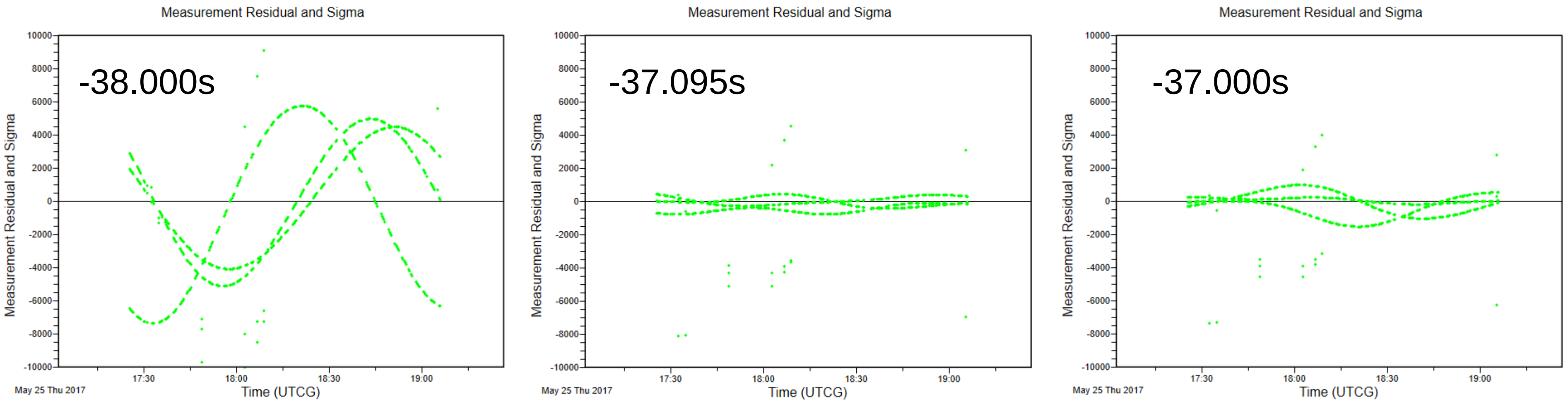


GPS Measurement Calibration Analysis

- ***Initial processing of GPS measurement states indicated possible timing bias present in data***
  - GPS Navigation Solution states received in Earth Centered-Earth Fixed (ECEF) coordinates
    - GPS states were received for 1 hour on 5/25, just prior to 5/26-6/1 TLE data gap
    - Second set of GPS states received for 1 hour on 6/12
  - Compared to TLEs of similar epochs, primary difference in the in-track direction
    - ~300 km in-track difference suspiciously close to TAI-UTC (37 leap seconds) at IceCube orbital velocity
    - Incorrectly applied measurement times were the likely culprit
- ***37 second timing bias applied to GPS states and compared to TLEs of similar epoch and to the TLE EKF definitive solution***
  - States within 10 km of closest TLE, however not quite within TLE EKF covariance
  - Propagated GPS states did not agree when compared to subsequent TLEs or TLE EKF

Use of TLE EKF Solution to Calibrate GPS

- ***TLE EKF solution can be used to compare and calibrate GPS states***
  - EKF solution will have lower covariance than single TLE due to its combining TLE states and estimation of atmospheric drag
- ***Compare GPS states residuals to TLE EKF residuals and adjust timing biases until they agree well***
  - TLE EKF run with GPS states force-rejected from state update calculations
    - This allows visualization of when the GPS state residuals begin to fall within the solution covariance of the converged TLE EKF

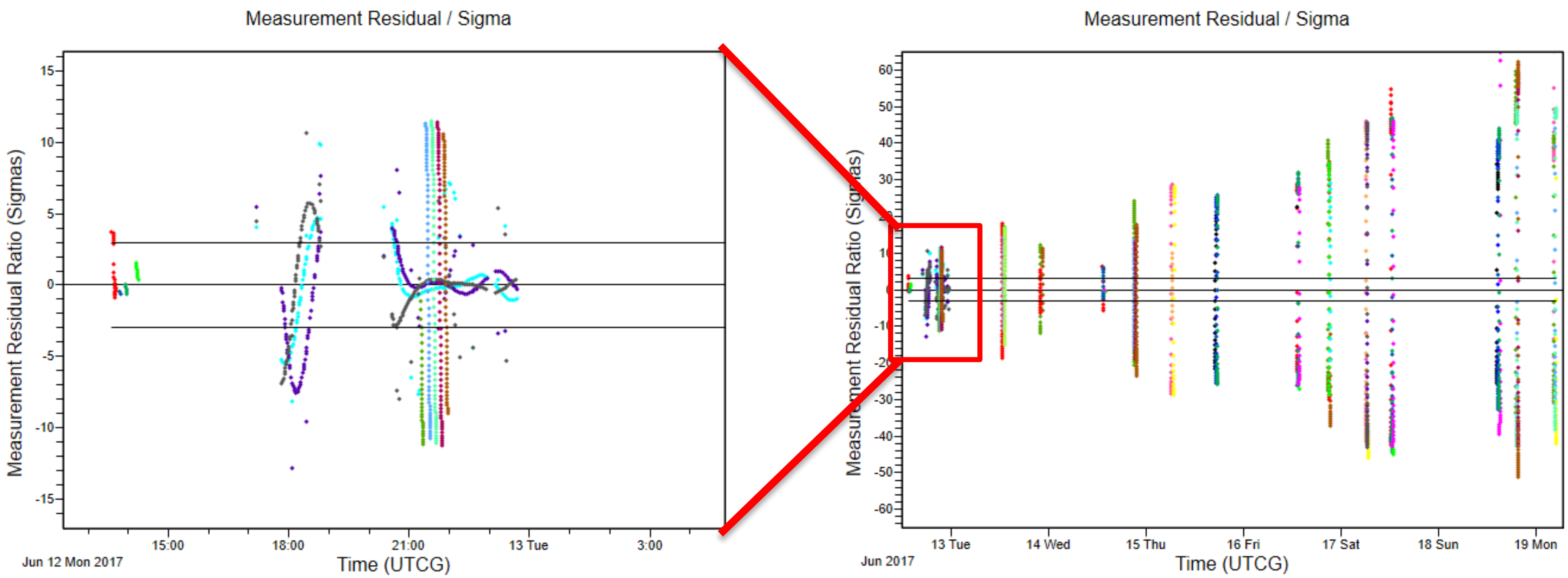


Combined GPS and TLE Solution

- ***Next, calibrated GPS states processed simultaneously in the TLE EKF***
  - In EKF, TLE-simulated measurements have ~1.5 km covariance (measurement white noise at 1.5 km) – GPS measurements within this threshold will be accepted into the solution
  - GPS states are inherently more accurate (measurement white noise less than 10m) and have higher measurement density
    - EKF will highly weight GPS states and resulting solution covariance will collapse to within GPS states white noise
  - If subsequent TLE-simulated measurements begin to diverge after processing GPS states, then timing bias needs further refinement
    - TLE-only EKF solution can be tuned to have a high sensitivity to incorrect GPS state timing biases
- ***Converged TLE/Calibrated-GPS EKF will have much lower covariance and therefore should provide more accurate orbit prediction***

Further Refinement of Timing Bias

- ***EKF highly weights GPS measurements and incorrect bias will cause subsequent TLE-simulated range measurements to diverge***
  - GPS measurement residuals (grey/cyan/purple) accepted into solution, but do not agree with simultaneous TLE-simulated range measurements
- ***GPS timing bias adjusted until agreement is obtained***



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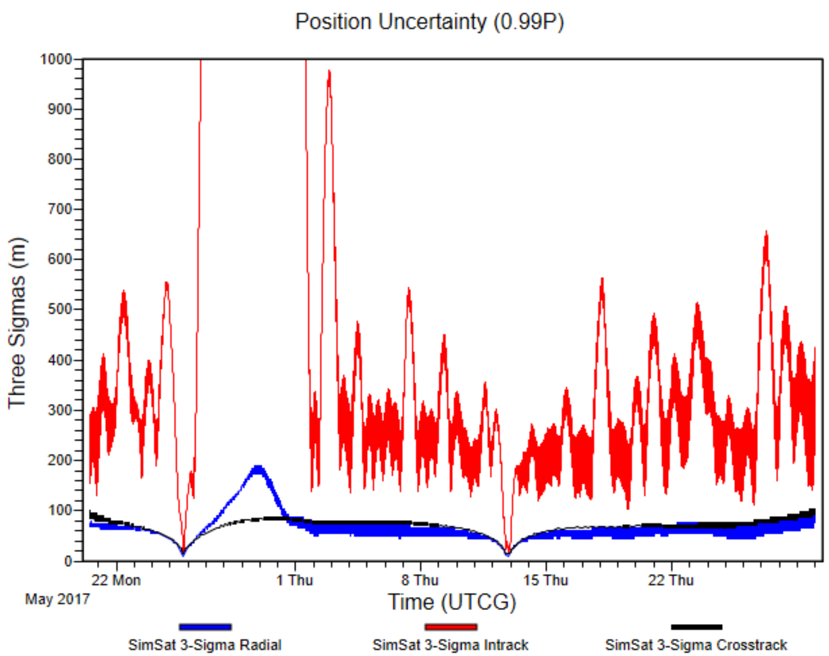
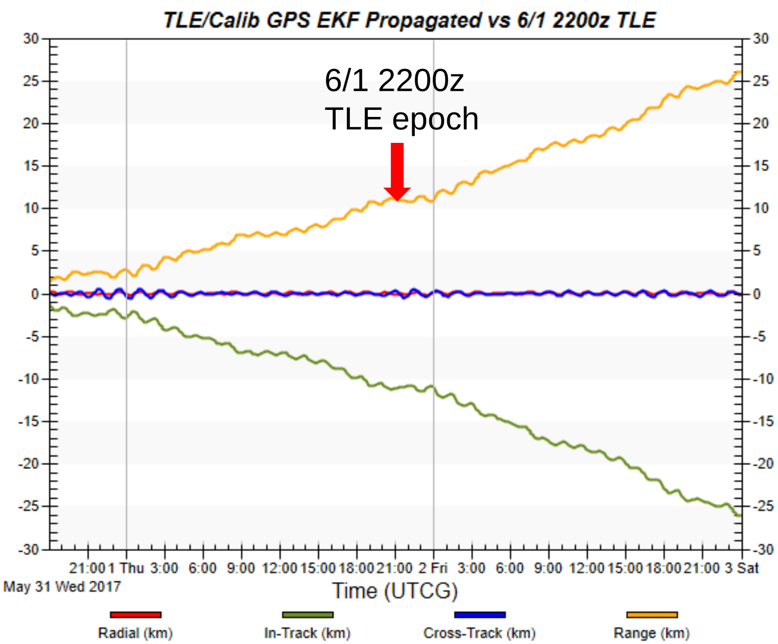
Combined TLE and Calibrated GPS in EKF

- ***Increase in solution accuracy due to inclusion of calibrated GPS in EKF***
  - Solution covariance collapses to within GPS noise during GPS passes
  - In-track covariance is highly reduced and grows slower following GPS passes
  - A more accurate definitive solution with slower covariance growth will give better propagation accuracy as well





Conclusions

- ***Simulating TLE-seeded range measurements and processing with an EKF can yield greater definitive/predictive solution accuracy***
  - "Fills-in" gaps between TLE states for better definitive accuracy
  - Allows significantly more accurate state prediction than older TLE
  - Proven accuracy when compared to high fidelity operational ephemerides
- ***TLE EKF solution can be used to calibrate onboard GPS***
  - Will be very useful for on-orbit GPS validation of future cubesat missions
  - TLE/Calibrated GPS EKF provides even better definitive and predictive accuracy
- ***TLE EKF can be used to obtain consistent and accurate states for satellites which do not have active tracking***
  - Robust tool for both low-cost orbit determination on cubesats, and for satellite emergencies where other tracking is limited or unavailable

Operation Use and Successes

- ***IceCube with 7 day TLE gap and biased GPS - May/June 2017***
  - Predictive solutions from both TLE EKF and TLE/GPS EKF would have allowed satellite acquisition despite the long TLE gap
- ***TDRS-3 telemetry only (no tracking) prior to maneuver – Feb 2018***
  - TLE EKF used to estimate orbit and provide accurate seed for operational orbit determination processes
  - Orbit determination and verification during long period of no active tracking
- ***IceCube prediction and acquisition prior to reentry – Sep/Oct 2018***
  - Delivered predictive acquisition data based off TLE/GPS EKF solutions
  - Allowed project to receive science data up until just before destructive reentry

Questions or Comments?

References

- 1) D. L. Wu, J. Esper, N. Ehsan, T. E. Johnson, W. R. Mast, J. R. Piepmeier, P. E. Racette, "IceCube: Spaceflight Validation of an 874 GHz Submillimeter Wave Radiometer for Cloud Ice Remote Sensing," ESTF 2014 (Earth Science Technology Forum), Leesburg, VA, USA, Oct. 28-30, 2014, URL: http://esto.nasa.gov/forum/estf2014/presentations/B1P5_Wu.pdf
- 2) Herbert Kramer, "IceCube — 874 GHz submillimeter wave radiometer mission on a 3U CubeSat" NASA, 2018, URL: https://directory.eoportal.org/web/eoportal/satellite-missions/i/icecube#footback1%29