Computation Errors in Look Angle and Range Due to Redefinition of UTC

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Colloquium on Decoupling Civil Timekeeping from Earth Rotation

6 October 2011

Outline

- Purpose
- Definition of Universal Time and Atomic Time
- Coordinated Universal Time and Leap Seconds
- Impact of Discontinuing Leap Seconds
- DUT1 Error Display Tools
- Display of Impacts
- Conclusions

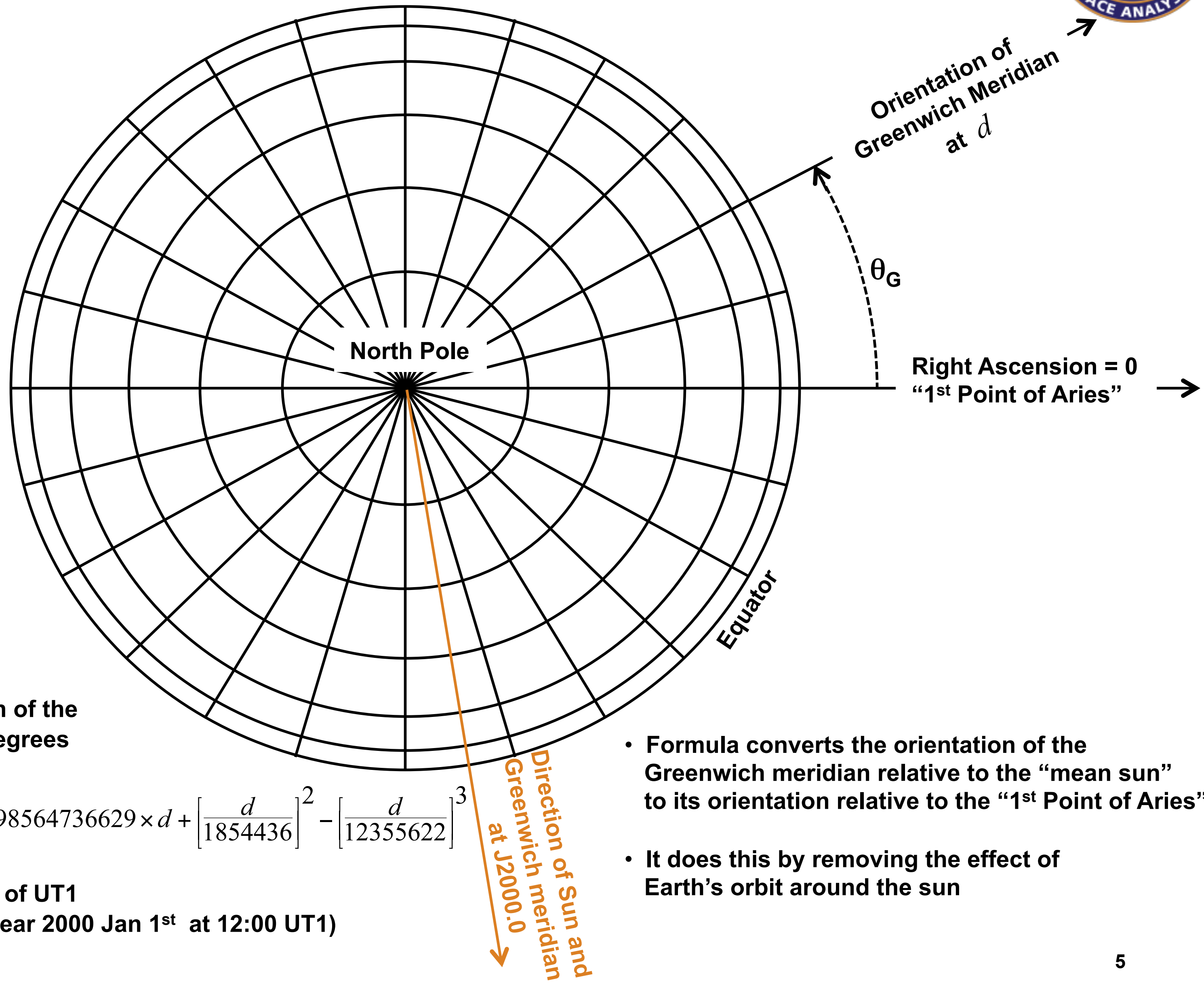
Purpose

- Explain the three major types of time scales:
  - Universal Time 1 (UT1)
  - Atomic Times (TT, TAI, GPS, etc.)
  - Coordinated Universal Time (UTC)
- Provide brief history of time scale development
- Discuss the impacts of eliminating leap seconds from UTC
  - Software that uses UT1 to compute Earth orientation
  - Software that uses UTC to approximate Earth orientation
- Discuss DUT1 Error Display Tools
  - DUT1 Sky Plot Tool
  - DUT1 Cardinal Direction Tool

Definition of Universal Time 1 (UT1)

- Universal Time 1 (UT1) is based on the orientation of Earth about its axis
  - Strictly speaking, UT1 is not a time, but an angle measured in hours
  - It's the orientation angle of the Greenwich meridian relative to the sun
  - In particular, it is measured from the point on the equator opposite the "mean sun" eastward to the Greenwich meridian
    - The "mean sun" is a concept whereby the variations due to Earth's axis inclination and Earth's orbital eccentricity are removed
- UT1 is also used as a time since Earth's rotation rate is nearly uniform
  - Earth's rotation rate is slowing down, thus increasing the length of the solar day by about 1.4 milliseconds per century
  - Superimposed are smaller irregular variations due to the changing mass distribution within Earth
  - Despite this variability, Universal Time has been used as the basis for civil time for centuries
- UT1 is principle argument for computing Earth Orientation needed for:
  - Computing position of space objects relative to positions on Earth
  - Computing position of Earth objects relative to positions in space

Computing Right Ascension of Greenwich Meridian from UT1



θ_G is the right ascension of the Greenwich meridian in degrees

$$\theta_G = 280.46061837 + 360.98564736629 \times d + \left[\frac{d}{1854436}\right]^2 - \left[\frac{d}{12355622}\right]^3$$

d is the number of days of UT1 elapsed since J2000.0 (year 2000 Jan 1st at 12:00 UT1)

- Formula converts the orientation of the Greenwich meridian relative to the "mean sun" to its orientation relative to the "1st Point of Aries"
- It does this by removing the effect of Earth's orbit around the sun

Definition of Atomic Time

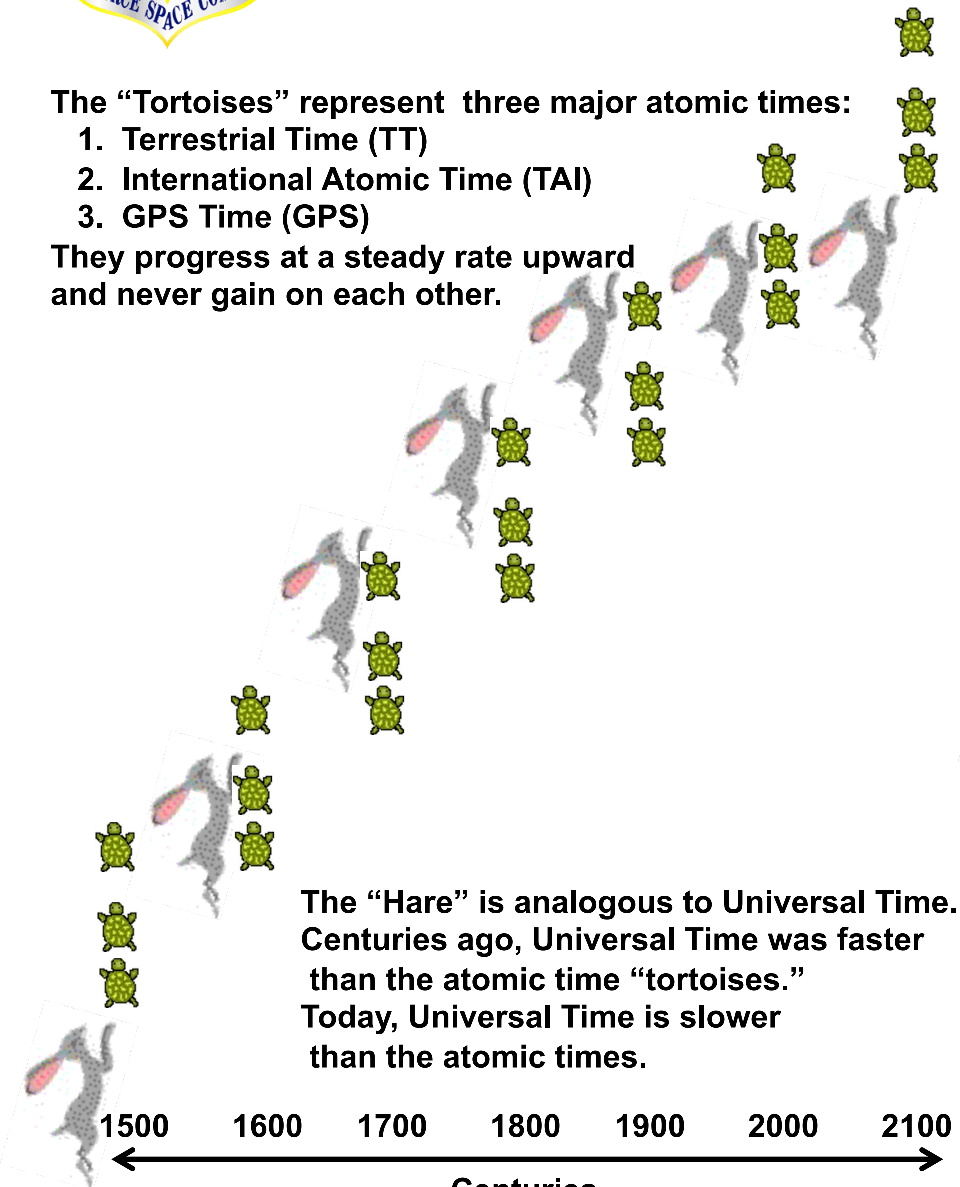
- Atomic time is a true time scale in the strictest sense
  - It does not vary with Earth's changing rotation rate
  - Based on a day with exactly 86,400 System International (SI) seconds
  - The SI second is defined as "the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyper-fine levels of the ground state of the cesium 133 atom"
  - This was chosen to be as close as possible to a second of Ephemeris Time (ET), now known as Terrestrial Time (TT)
    - The ET second was defined as 1/31,556,925.9747 of the length of the tropical year for the year 1900 January 0 (1899 Dec 31) at 12:00 ET
    - The TT second is now defined to be identical to the atomic (SI) second
- There are several atomic times (differing by a constant offset in seconds)
  - Terrestrial Time (TT)
  - International Atomic Time (TAI)
  - GPS Time
  - Discontinuing leap seconds from civil time would result in a time scale similar to an atomic time – "Civil Atomic Time?"

The "Tortoise" and the "Hare" Analogy

The "Tortoises" represent three major atomic times:

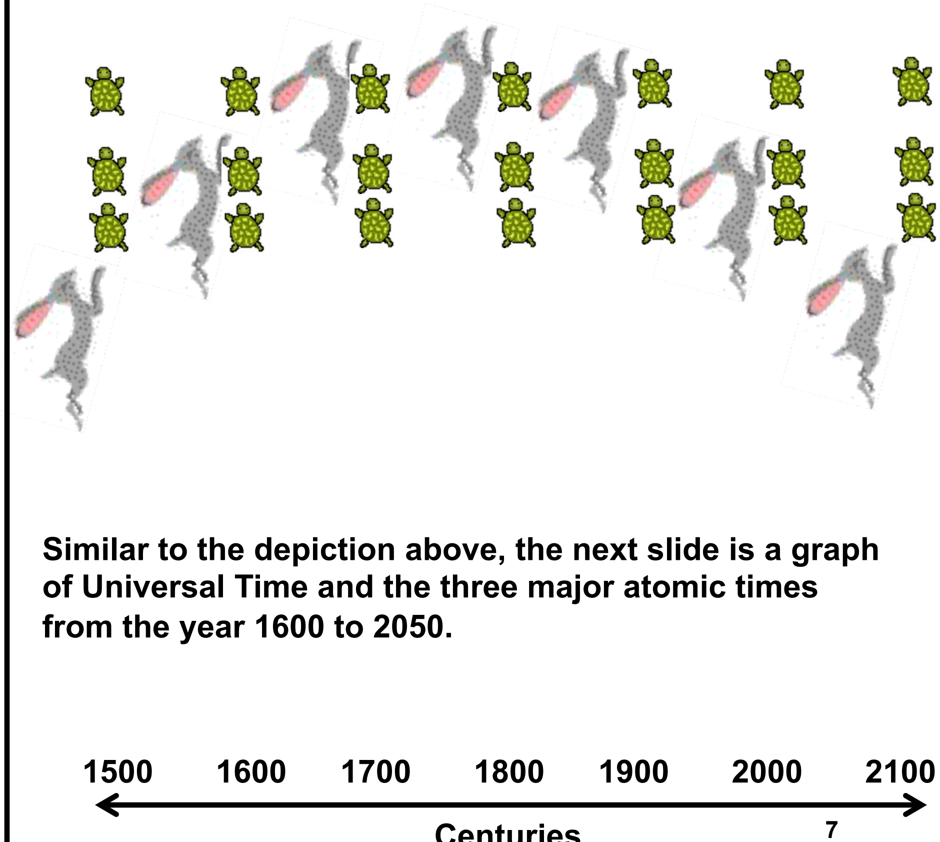
1. Terrestrial Time (TT)
2. International Atomic Time (TAI)
3. GPS Time (GPS)

They progress at a steady rate upward and never gain on each other.



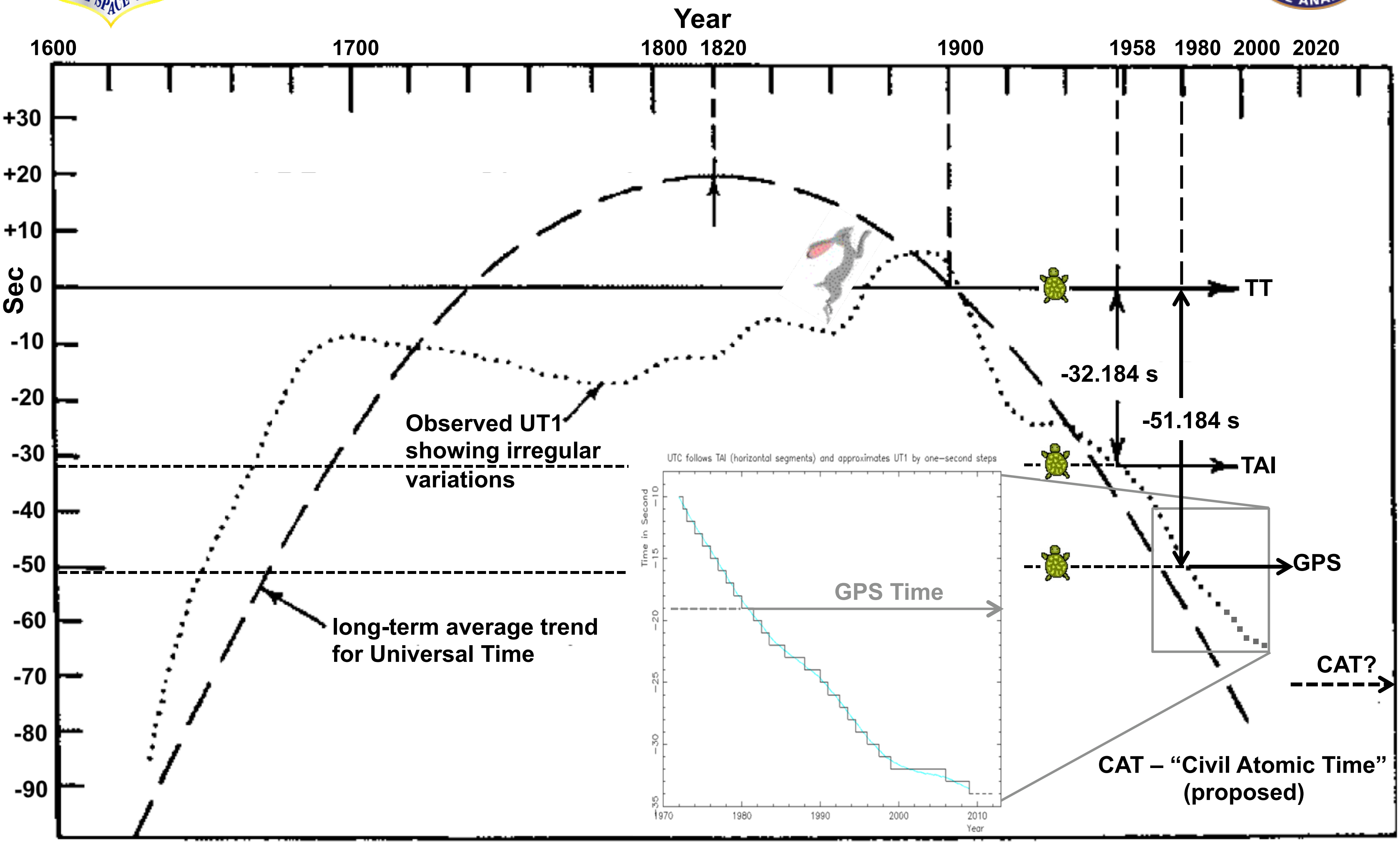
The "Hare" is analogous to Universal Time. Centuries ago, Universal Time was faster than the atomic time "tortoises." Today, Universal Time is slower than the atomic times.

When referenced to the progression of the atomic time "tortoises," the Universal Time "hare" catches up and surpasses the atomic times and then falls behind.



Similar to the depiction above, the next slide is a graph of Universal Time and the three major atomic times from the year 1600 to 2050.

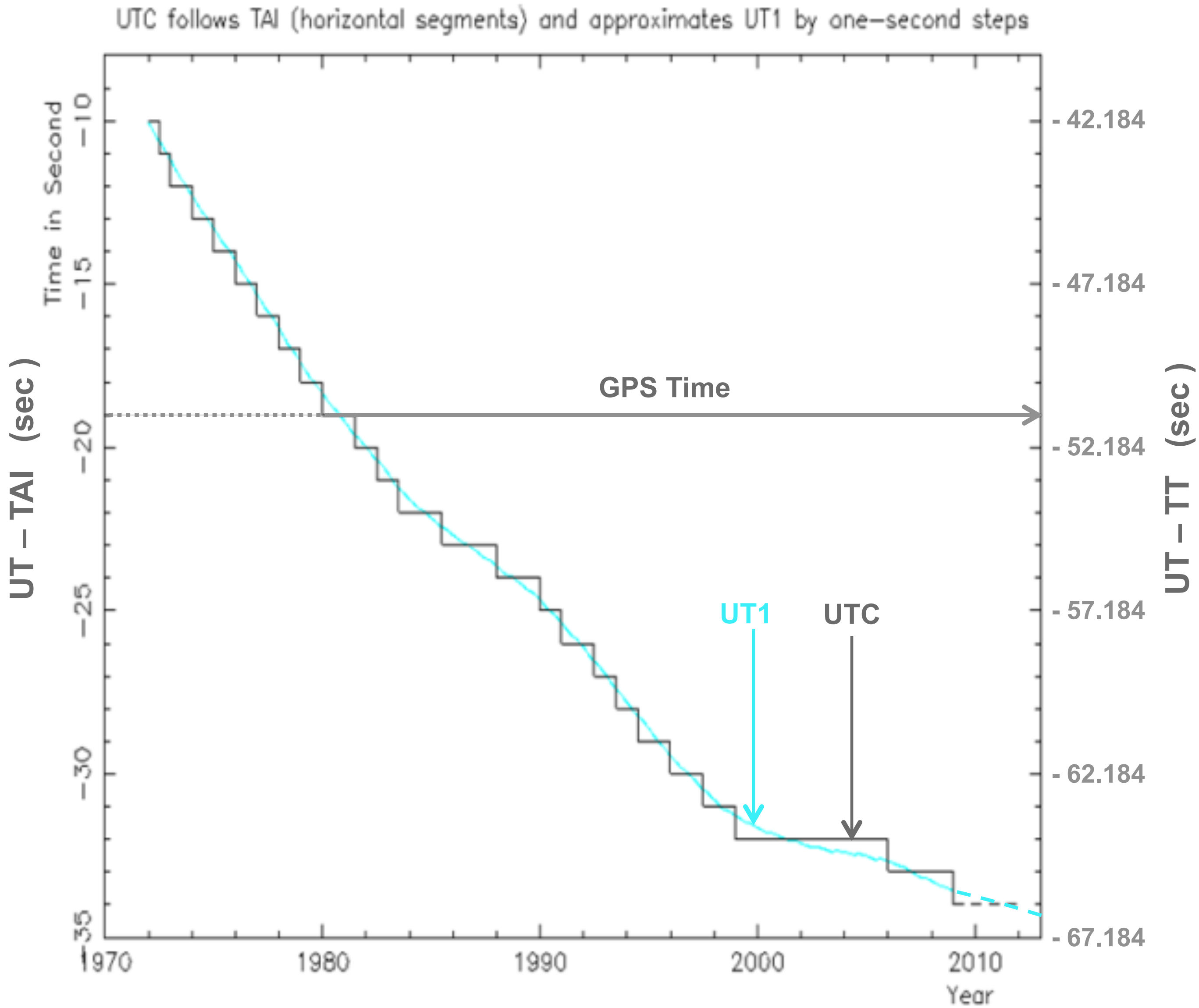
Universal Time (UT1) over last 4 Centuries



Coordinated Universal Time

- **Coordinated Universal Time (UTC) is a "hybrid" between UT1 and atomic time**
  - **Established January 1st 1972 as the new "civil time" replacing Greenwich Mean Time (GMT)**
  - **Kept within 0.9 second of UT1 through periodic leap second adjustments**
  - **Adjustments are typically made at the end of June or the end of December**
    - **Unless more than 2 leap seconds are needed in a year**
  - **In 1972, UTC was 10 seconds behind TAI – today it's 34 seconds behind TAI**
- **Since |UTC-UT1| < 0.9 second, UTC may be used to approximate UT1**
  - **UTC may be used to compute Earth orientation within ±13.5 arc seconds**
  - **Equivalent to ~418 meters of error on Earth's equator at the surface**
  - **Many tracking applications can tolerate these errors**

UT1 and Coordinated Universal Time (UTC) over last 4 Decades



Proposal to Discontinue Leap Seconds

- **International Telecommunications Union (ITU) is working to determine international consensus on whether or not to discontinue leap seconds**
  - **Several commercial systems have trouble with leap second adjustments**
  - **ITU-sponsored decision expected in Jan 2012**
  - **If 70% of delegates vote in favor of discontinuance, it will be implemented**
  - **If decided to discontinue, could go into effect as early as 1 Jan 2018**
- **ASD(NII) memo to DoS (29 Jun 09) supports leap second discontinuance**
  - **ASD requested discontinuance not go into effect before 1 Jan 2019**
  - **ASD considers this adequate time to make necessary system modifications**

Impact of Discontinuing Leap Seconds

- **UTC is used to compute UT1 or to approximate UT1**
  - **Discontinuing leap seconds will significantly change how UT1 is computed or approximated in operational software**
- **Two classes of software affected by discontinuing leap seconds**
  - **Software that computes UT1 exactly**
    - **Without leap seconds, DUT1 (= UT1 – UTC) needed to compute UT1 from UTC would grow indefinitely – eventually exceeding storage constraints and error thresholds**
    - **Software upgrades are needed requiring thorough integration and testing**
    - **This software must be upgraded *before* leap second discontinuance goes into effect**
  - **Software that uses UTC as an approximation to UT1**
    - **Without leap seconds, UTC would drift farther away from UT1 until it could no longer be used to compute look angles and ranges to (and from) space objects**
    - **Would take several decades to become an operational problem – but this software is pervasive in operational space systems**
    - **This software may be upgraded *after* leap second discontinuance goes into effect**

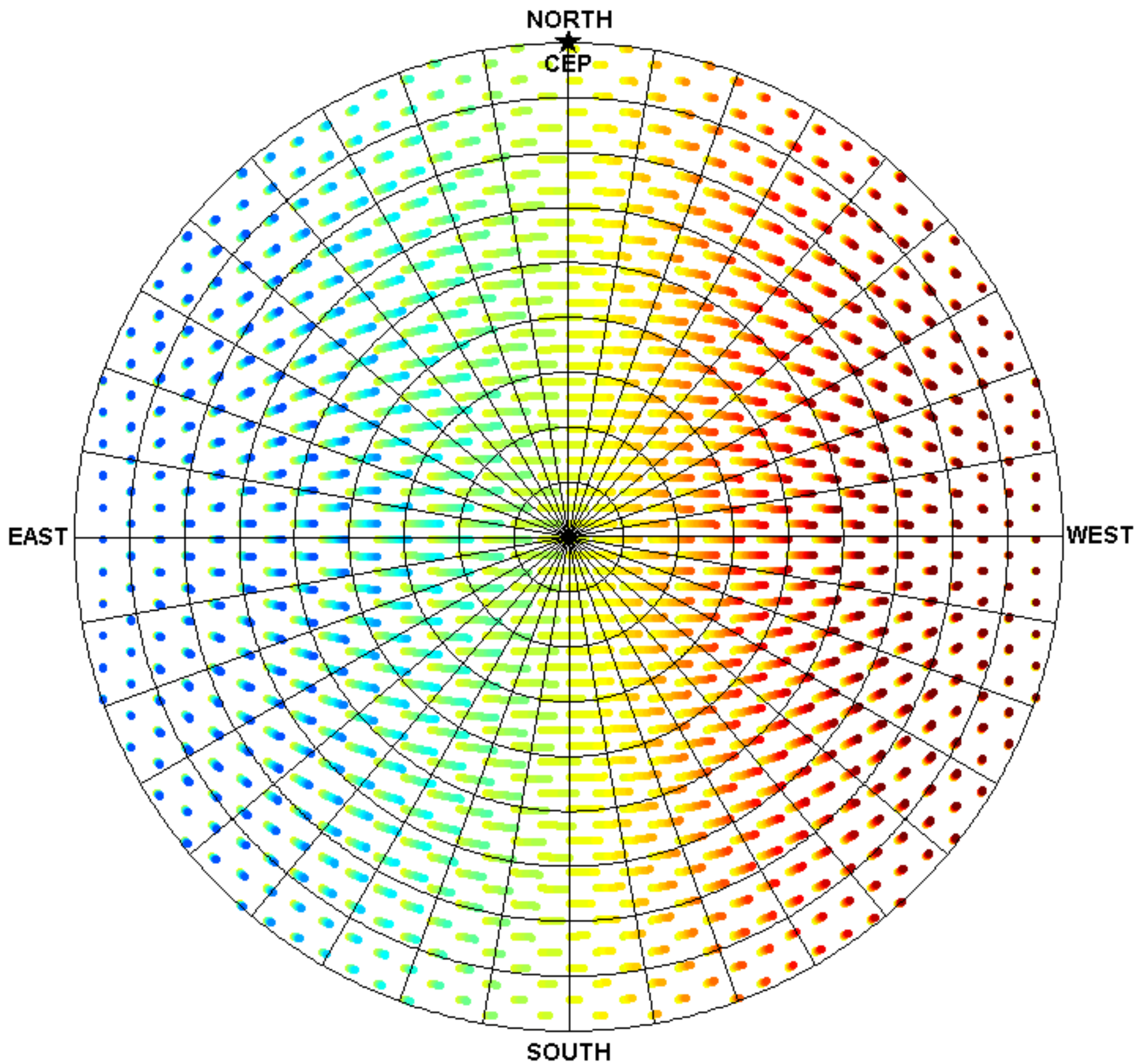
Sky Plot Error Tool to Study Impacts

- "DUT1-Skyplot" MATLAB tool was developed at HQ AFSPC/A9A
  - Tool needed to investigate the slow degradation in space tracking algorithms that use UTC as an approximation for UT1
  - Plots the error in elevation angle, azimuth, and range as a function of:
    - Direction in the sky
    - Latitude of the ground site in degrees
    - Altitude of the space object in km
    - Value for DUT1 in seconds (DUT1 = UT1- UTC)
  - The length of arc represents error in look angle (elevation and azimuth angles)
  - The color of the arc represents the range error
    - Deep red indicates computed ranges more than 10 km greater than truth
    - Deep blue indicates computed ranges more than 10 km less than truth
    - In between is a rainbow color scheme with yellow-green indicating a zero range error

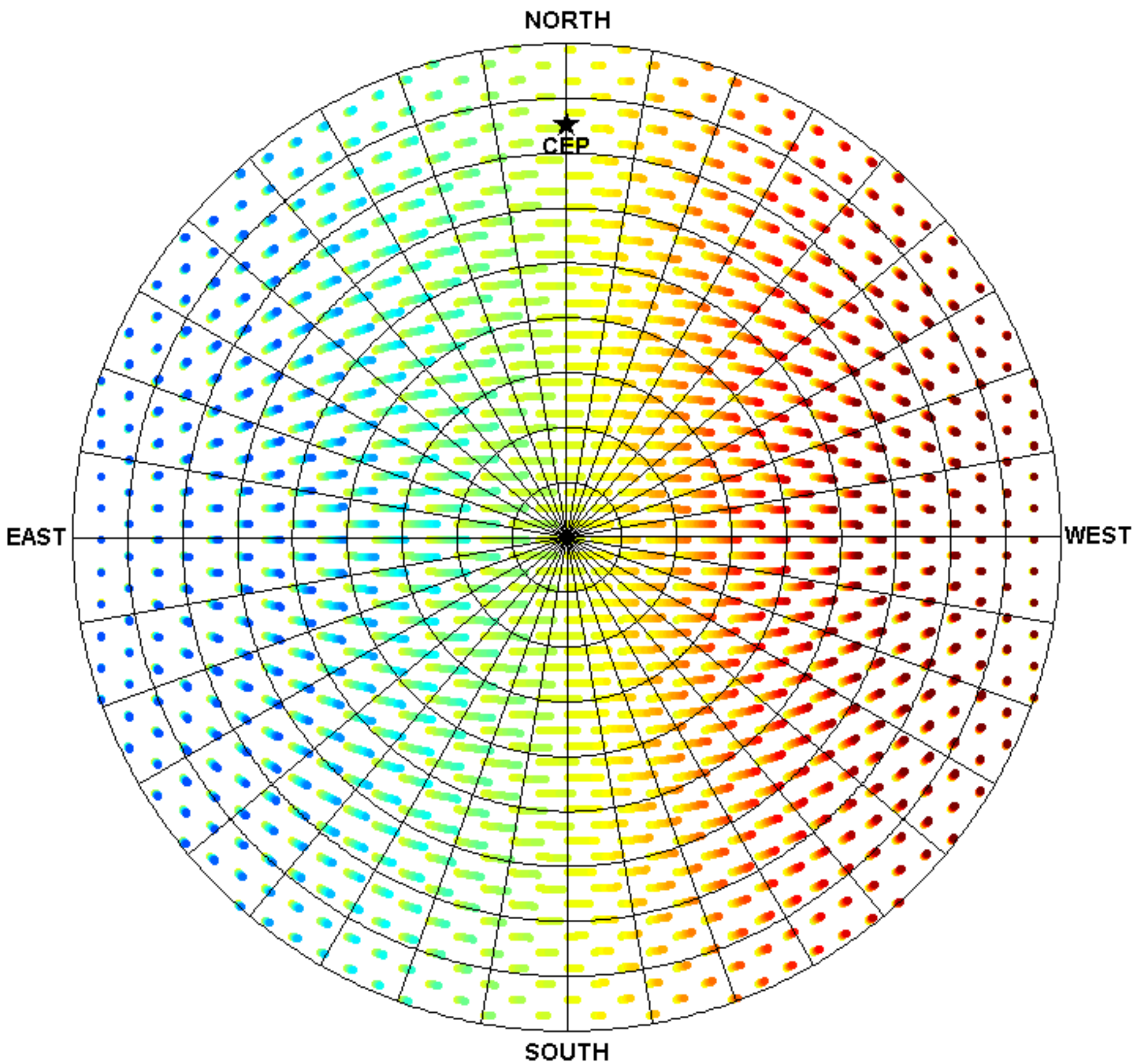
Look Angle Error - Variation with Latitude

- The next set of charts display the change in look angle error with latitude
  - Space object altitude is set to 100 km
  - DUT1 is set to 30 seconds
  - Errors are displayed for latitudes = 0°, 15°, 30°, 45°, 60°, 75° and 90° N
- The greatest errors occur at the equator
  - At zenith, look angle error is over 8° and decreases with cos(latitude)
    - Can expect this error 30 to 50 yrs after leap seconds discontinued
  - In all charts except latitude = 90° N, look angle arcs exhibit an east-west orientation
    - This is due to the proximity of space objects at 100 km altitude
    - Only at high altitudes do the space objects begin to spin around the celestial pole (like distant stars)

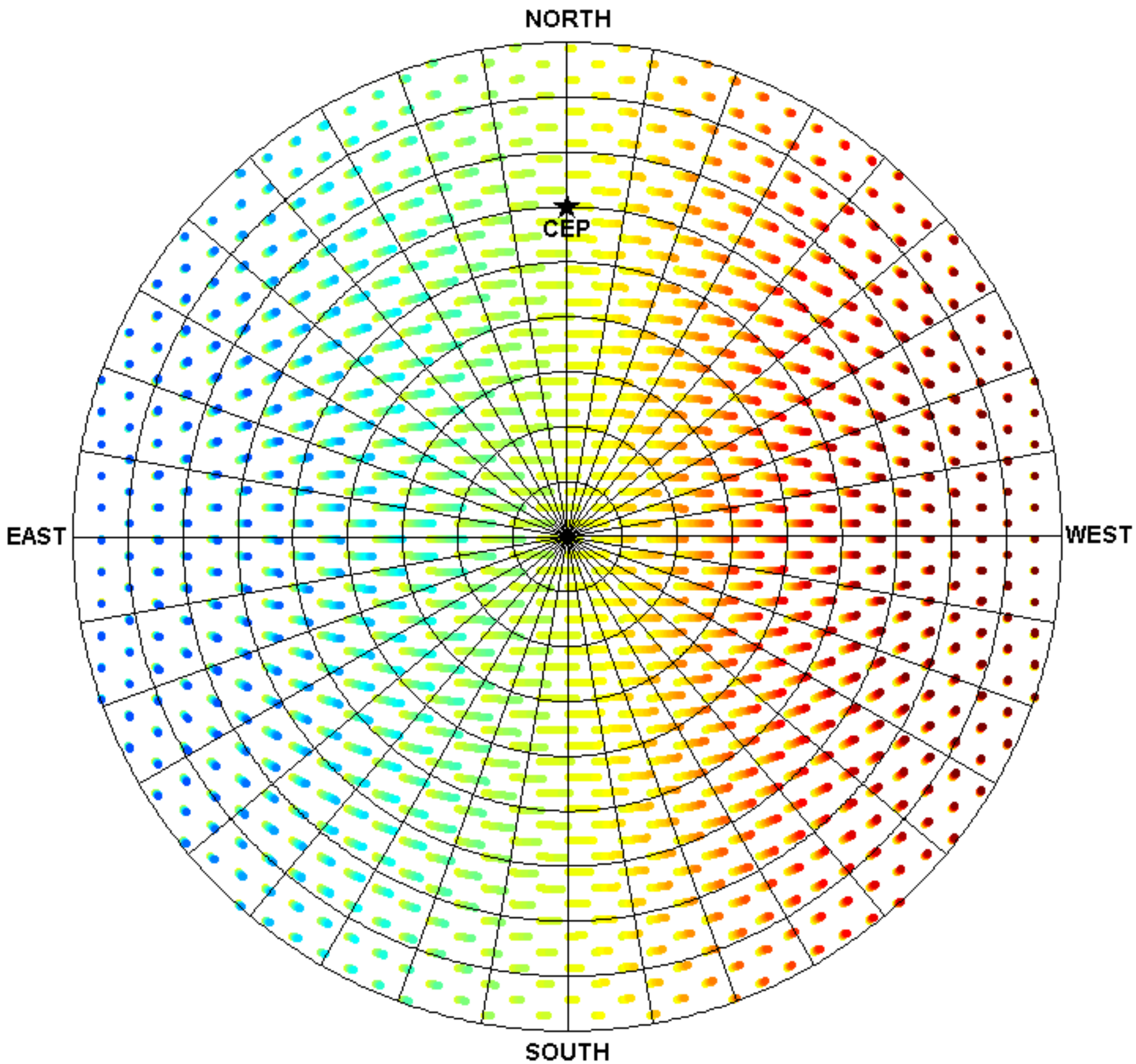
Sky Plot at 0° for Space Objects at 100 km altitude (DUT1 = 30 s)



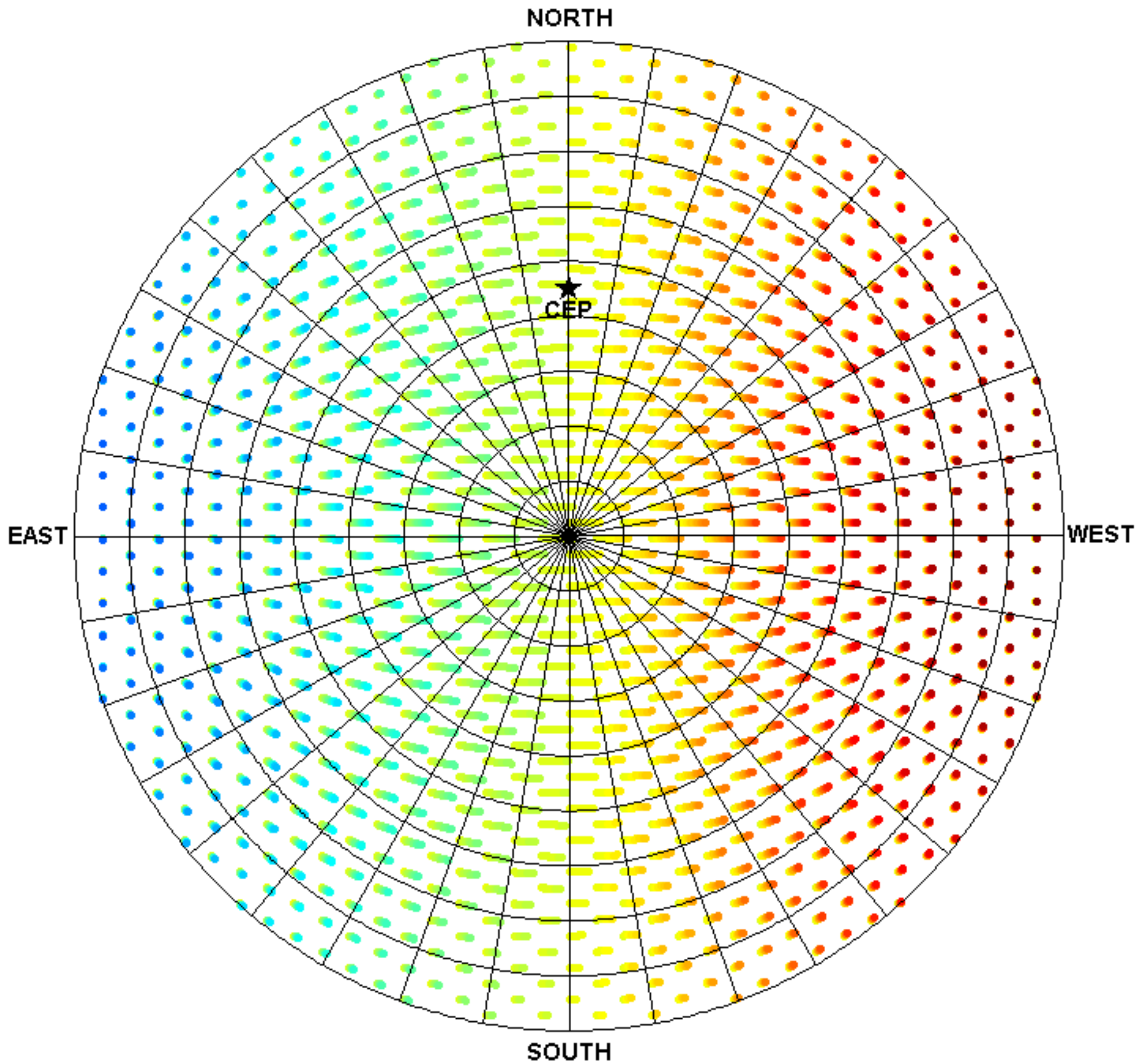
Sky Plot at 15° N for Space Objects at 100 km altitude (DUT1 = 30 s)



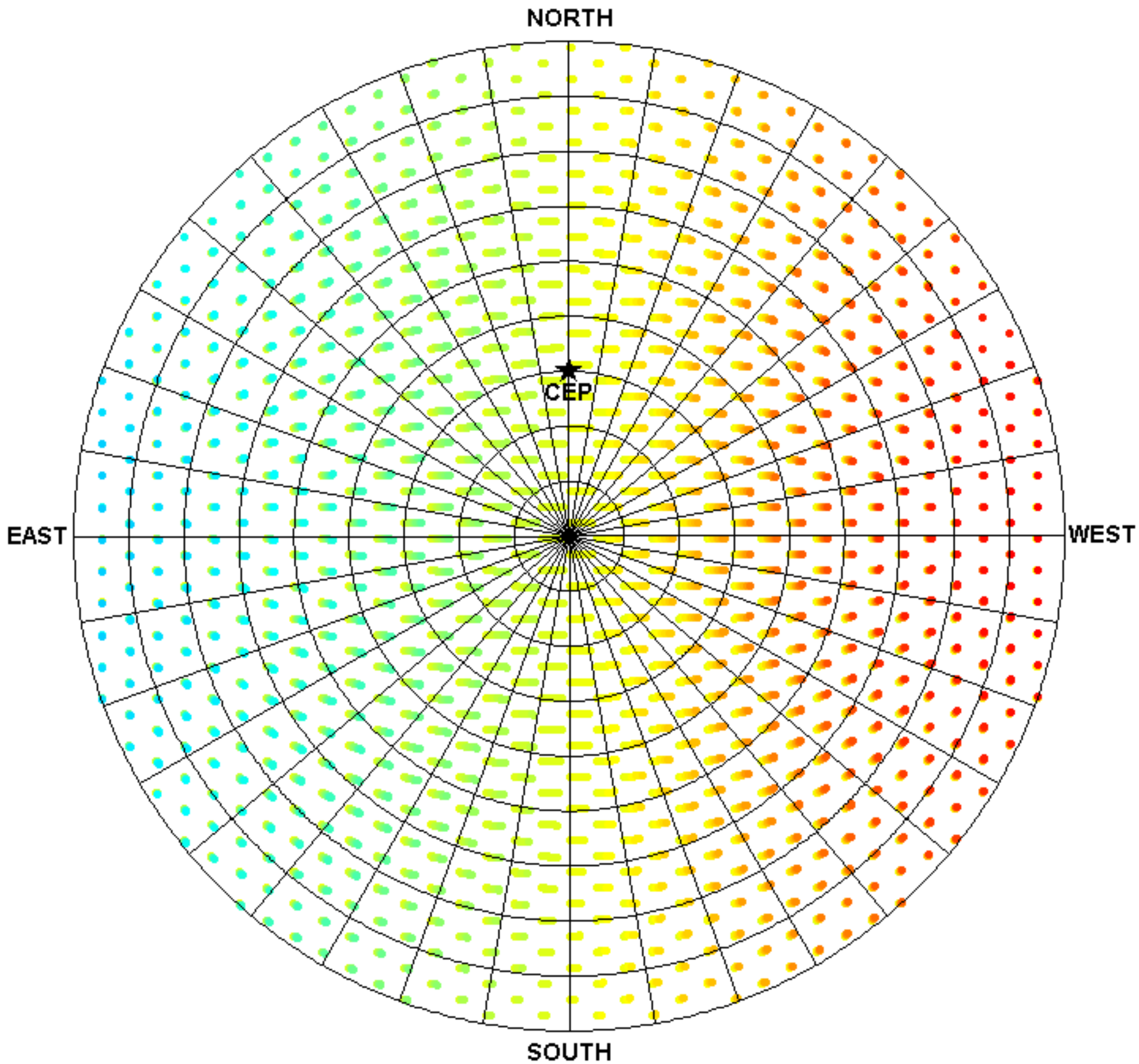
Sky Plot at 30° N for Space Objects at 100 km altitude (DUT1 = 30 s)



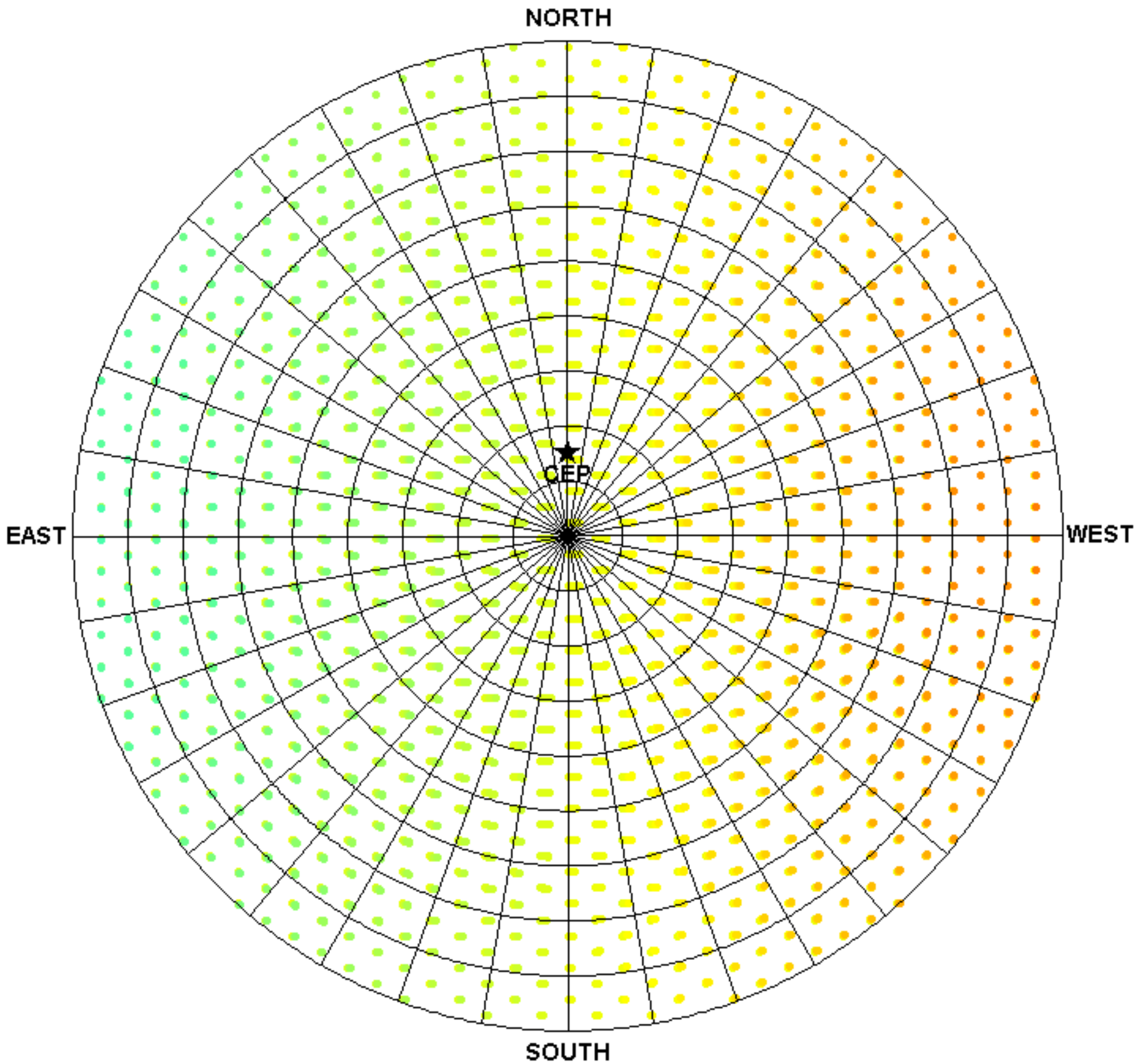
Sky Plot at 45° N for Space Objects at 100 km altitude (DUT1 = 30 s)



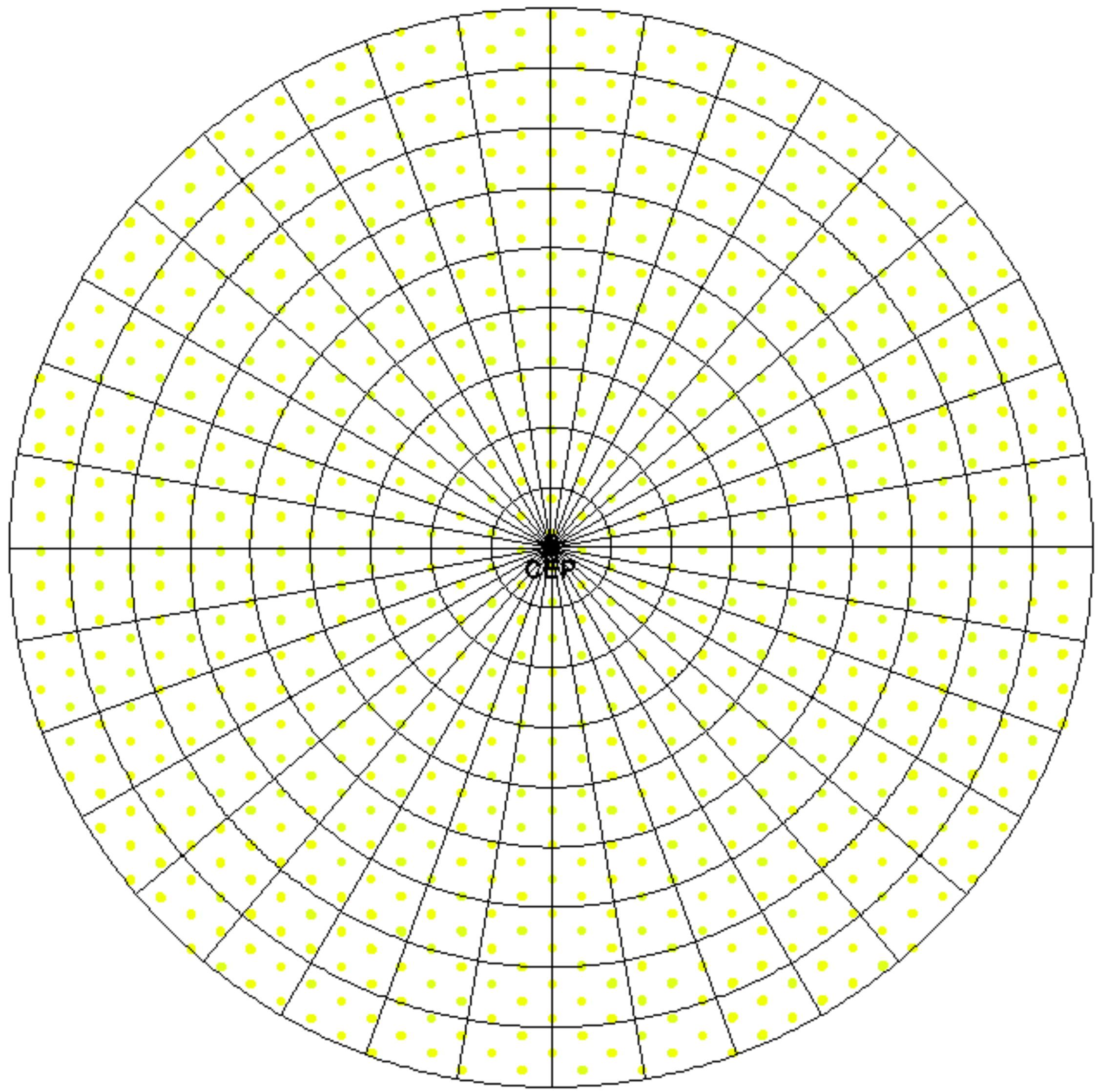
Sky Plot at 60° N for Space Objects at 100 km altitude (DUT1 = 30 s)



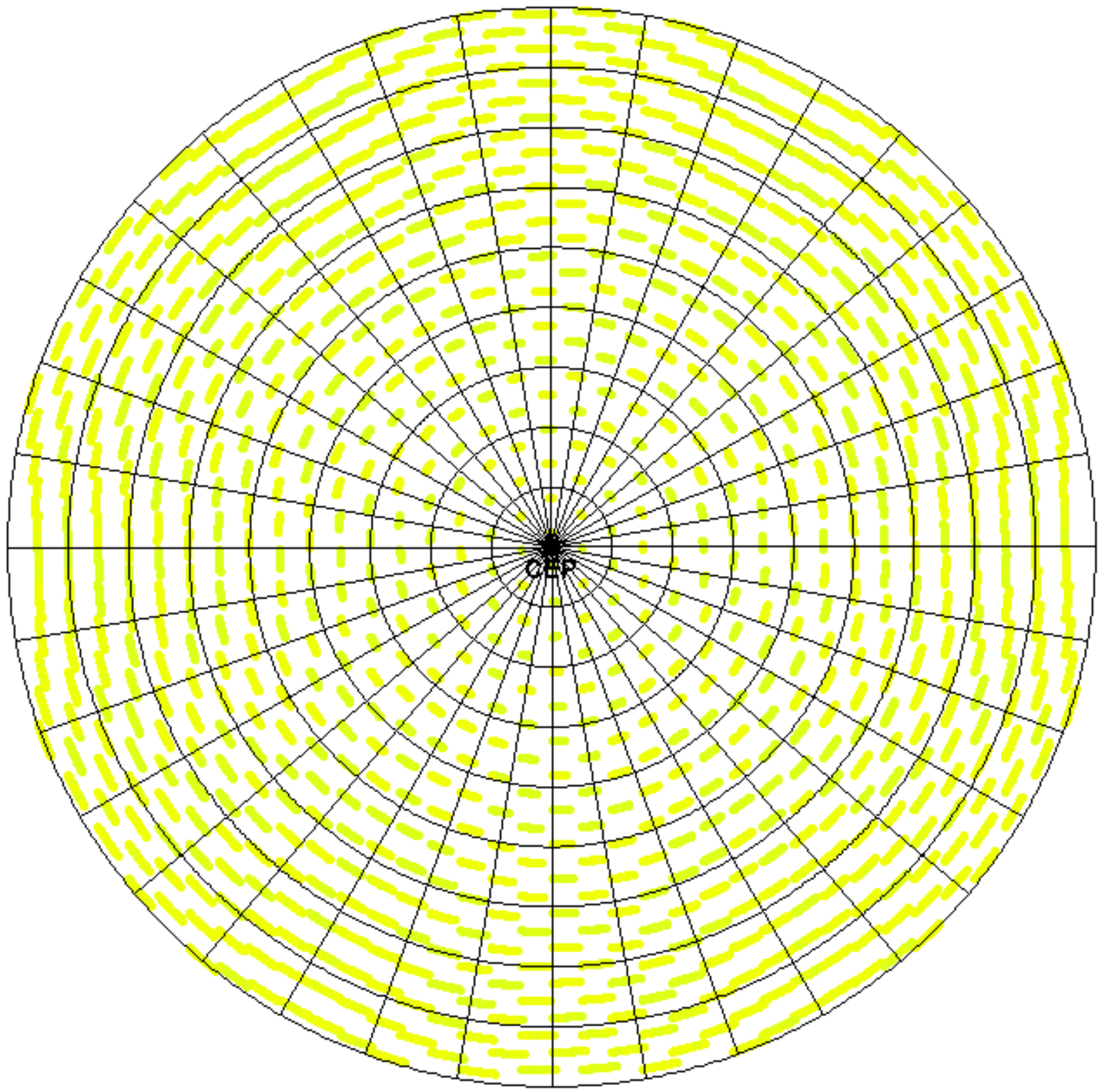
Sky Plot at 75° N for Space Objects at 100 km altitude (DUT1 = 30 s)



Sky Plot at 90° N for Space Objects at 100 km altitude (DUT1 = 30 s)



Sky Plot at 90° N for Space Objects at 100 km altitude (DUT1 = 900 s)

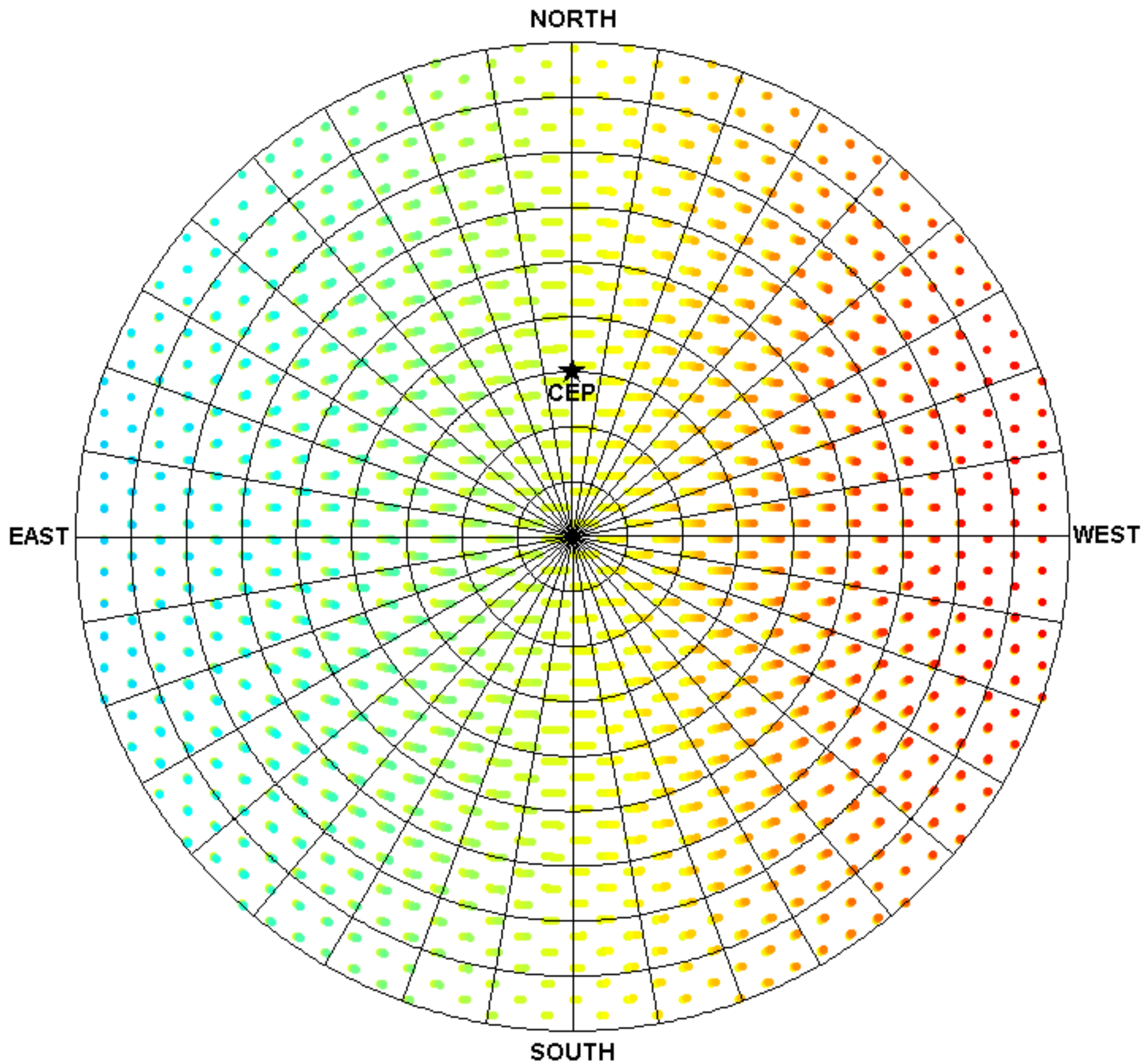


Look Angle Error - Variation with Altitude

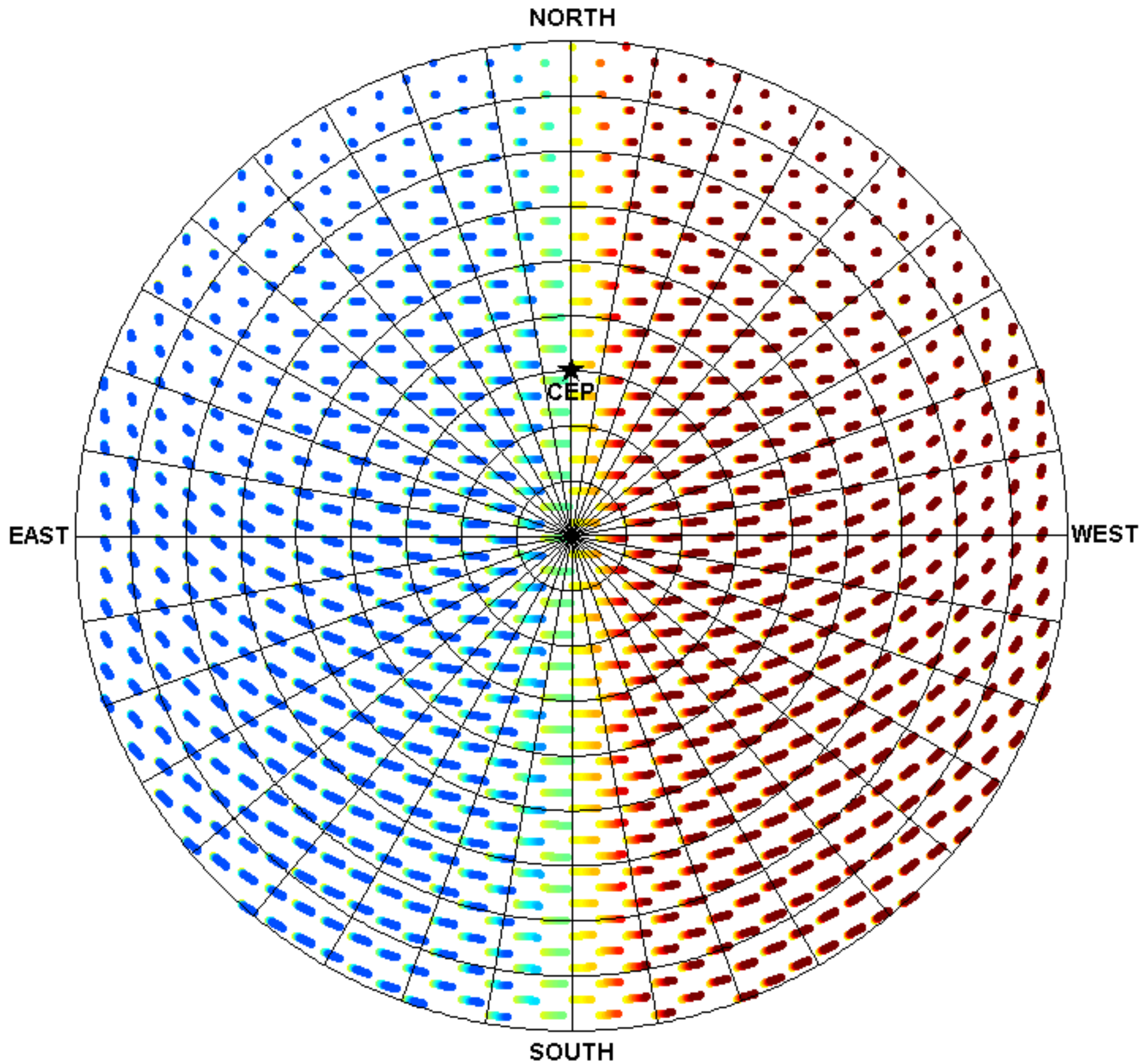
- The next set of charts display the change in look angle error with altitude
  - Latitude of the ground observer is set to a fixed value of 60° N
  - Errors are displayed for the following altitudes:
    - 100 km with DUT1 = 30 seconds
    - 1000 km with DUT1 = 300 seconds
    - 10,000 km with DUT1 = 600 seconds
    - 1,000,000 km with DUT1 = 900 seconds

    (DUT1 is increased with altitude for display purposes)
- Charts reveal how error arcs transition from an east-west orientation to an orientation around the celestial ephemeris pole (CEP)
  - Transition occurs as the space object altitude increases
  - Error arcs appear to rotate about a "false" celestial pole
    - At 60° N, the false pole appears on the horizon at the north point for an altitude 1000 km
    - At higher altitudes, the false pole rises until it occupies the position of the CEP

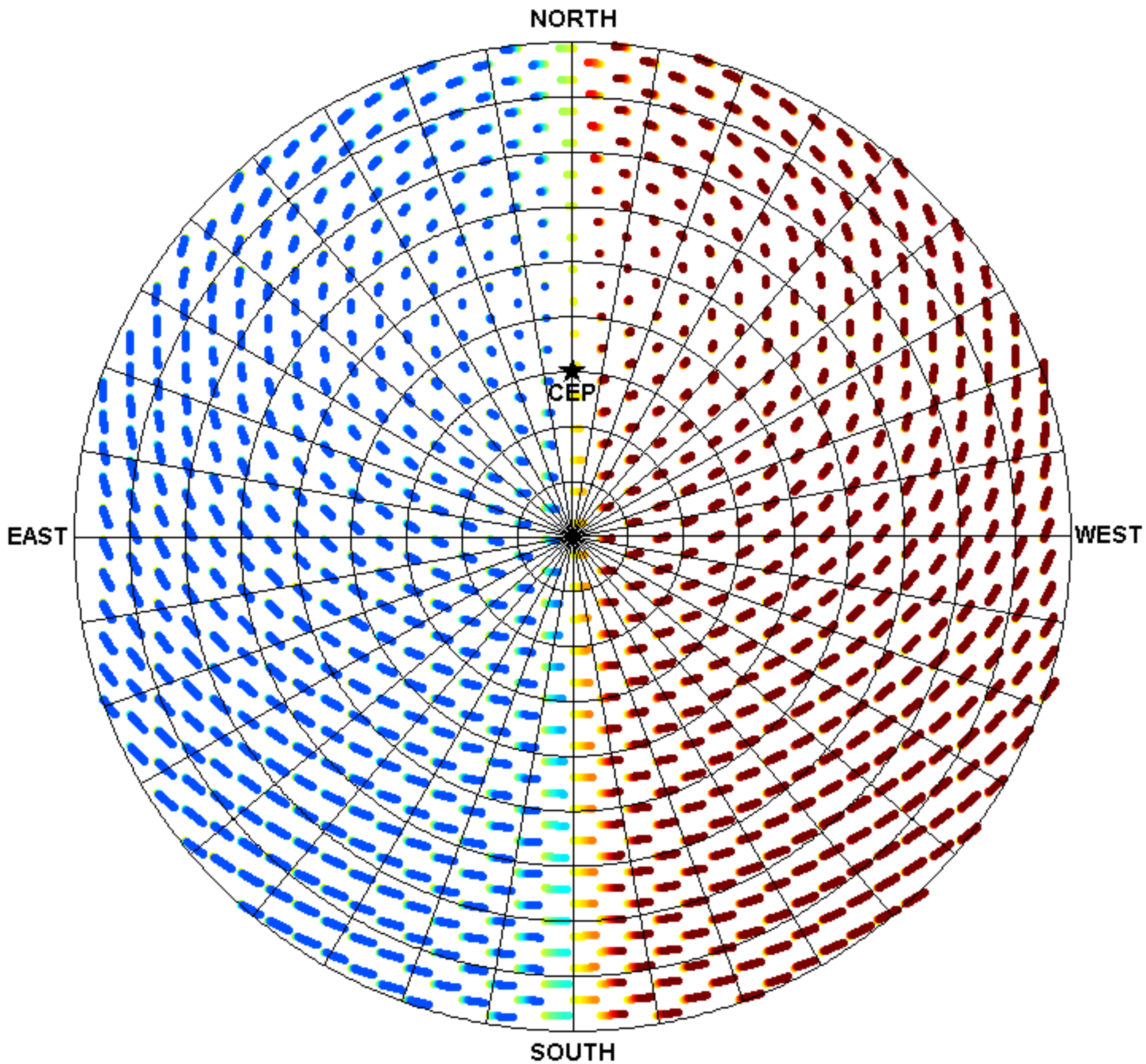
Sky Plot at 60° for Space Objects at 100 km altitude (DUT1 = 30 s)



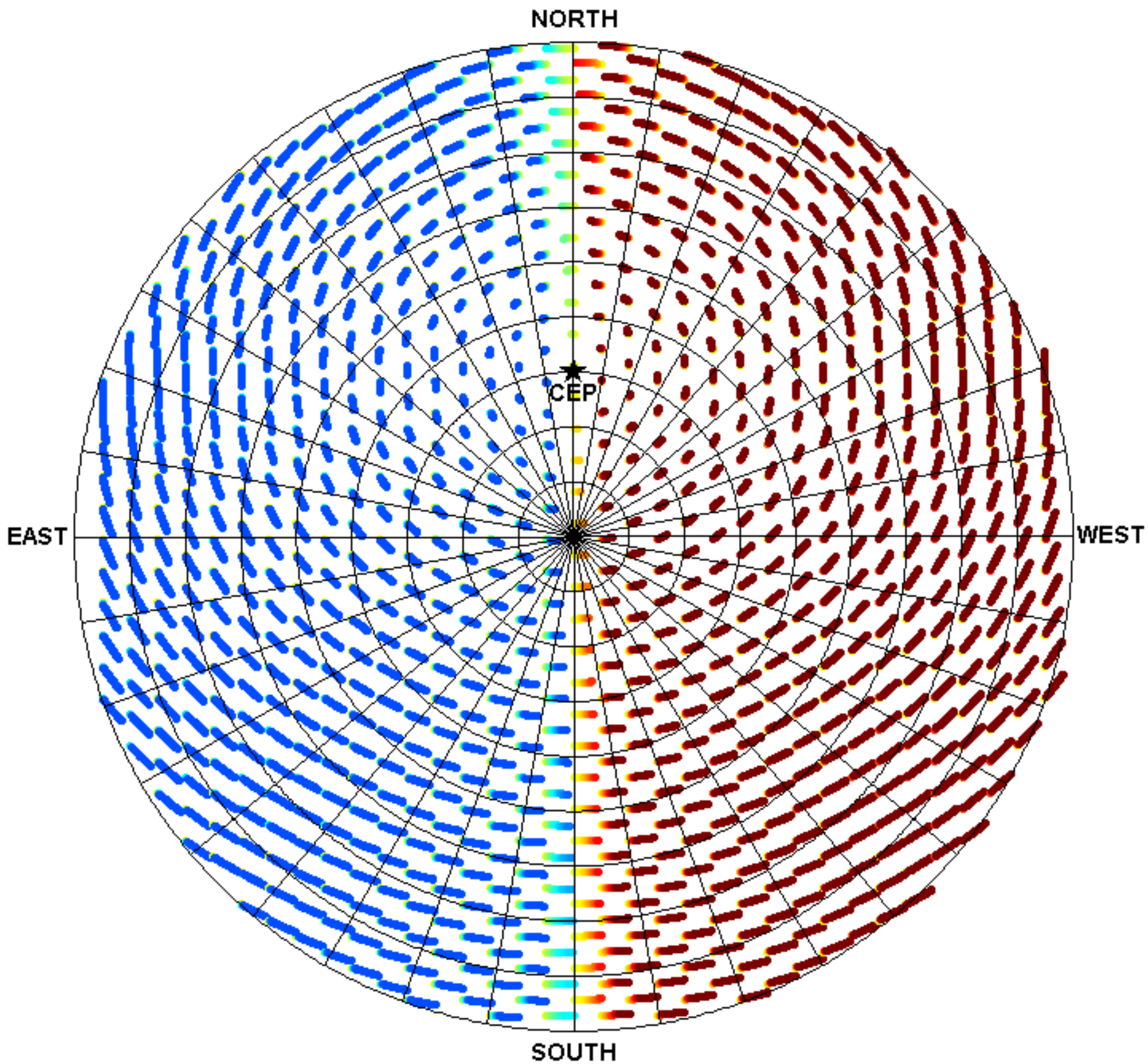
Sky Plot at 60° for Space Objects at 1000 km altitude (DUT1 = 300 s)



Sky Plot at 60° for Space Objects at 10,000 km altitude (DUT1 = 600 s)



Sky Plot at 60° for Space Objects at 1,000,000 km altitude (DUT1 = 900 s)



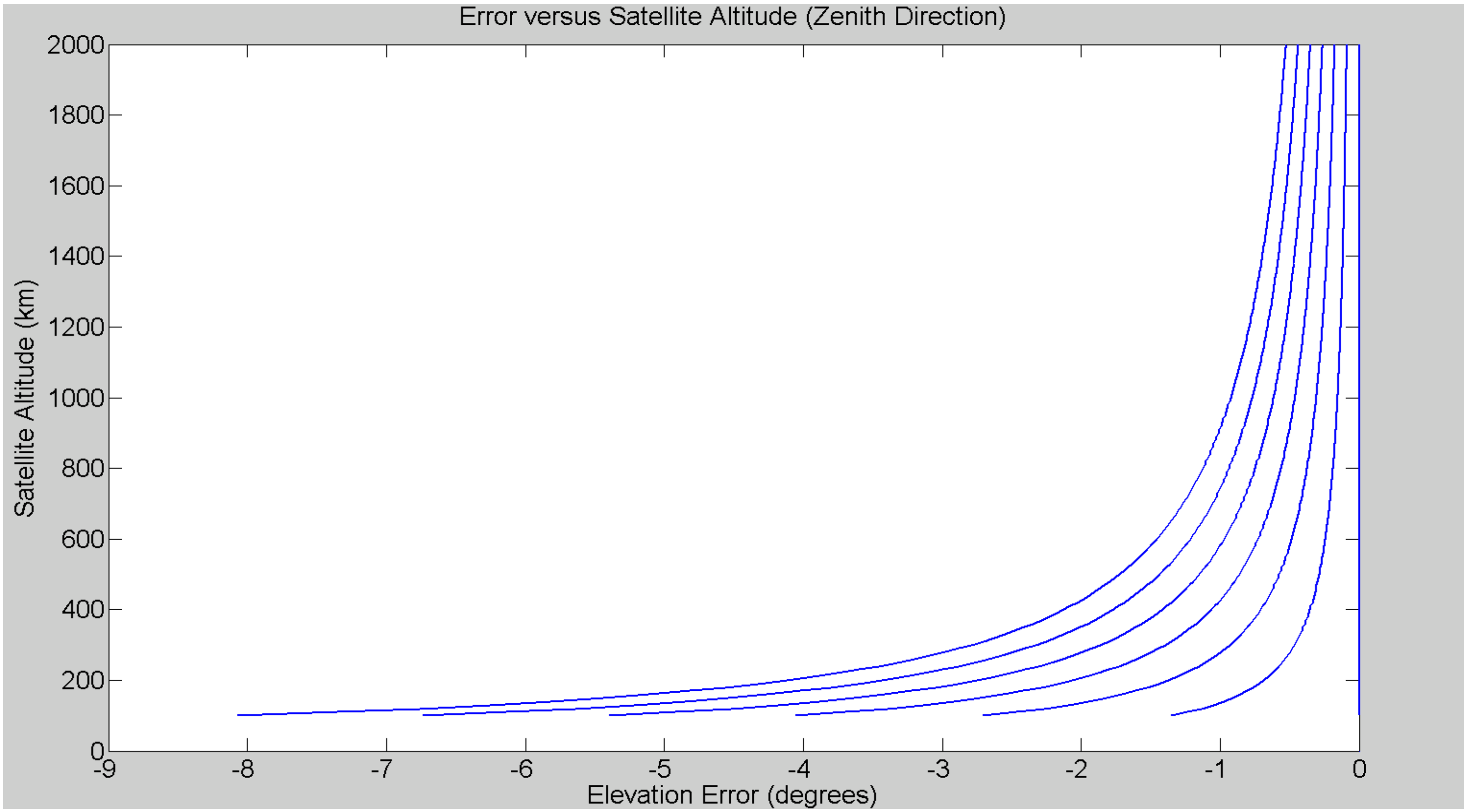
Cardinal Direction Error Tool

- **"DUT1-Cardinal" MATLAB Tool was developed at HQ AFSPC/A9A**
  - **Tool needed to investigate the degradation in accuracy of space tracking algorithms that use UTC as an approximation for UT1**
  - **Plots the error in elevation angle, azimuth and range as a function of:**
    - **Satellite altitude (km)**
    - **Value of DUT1 in seconds (DUT1 = UT1- UTC)**
  - **The following plots display the error in the 5 cardinal directions:**
    - **Zenith Direction (primarily an elevation angle error)**
      - **Elevation angle error increases dramatically for low altitude satellites**
      - **The zenith direction produces the largest angular error**
        - **Value of -8° for a satellite altitude of 100km with DUT1 = 30 sec**
    - **North and South Directions (primarily an azimuth angle error)**
      - **Error increases for low altitude satellites**
    - **East and West Directions (primarily a range error)**
      - **Range error is nearly constant with satellite altitude**
    - **All errors generally decrease with latitude according to cos(latitude)**

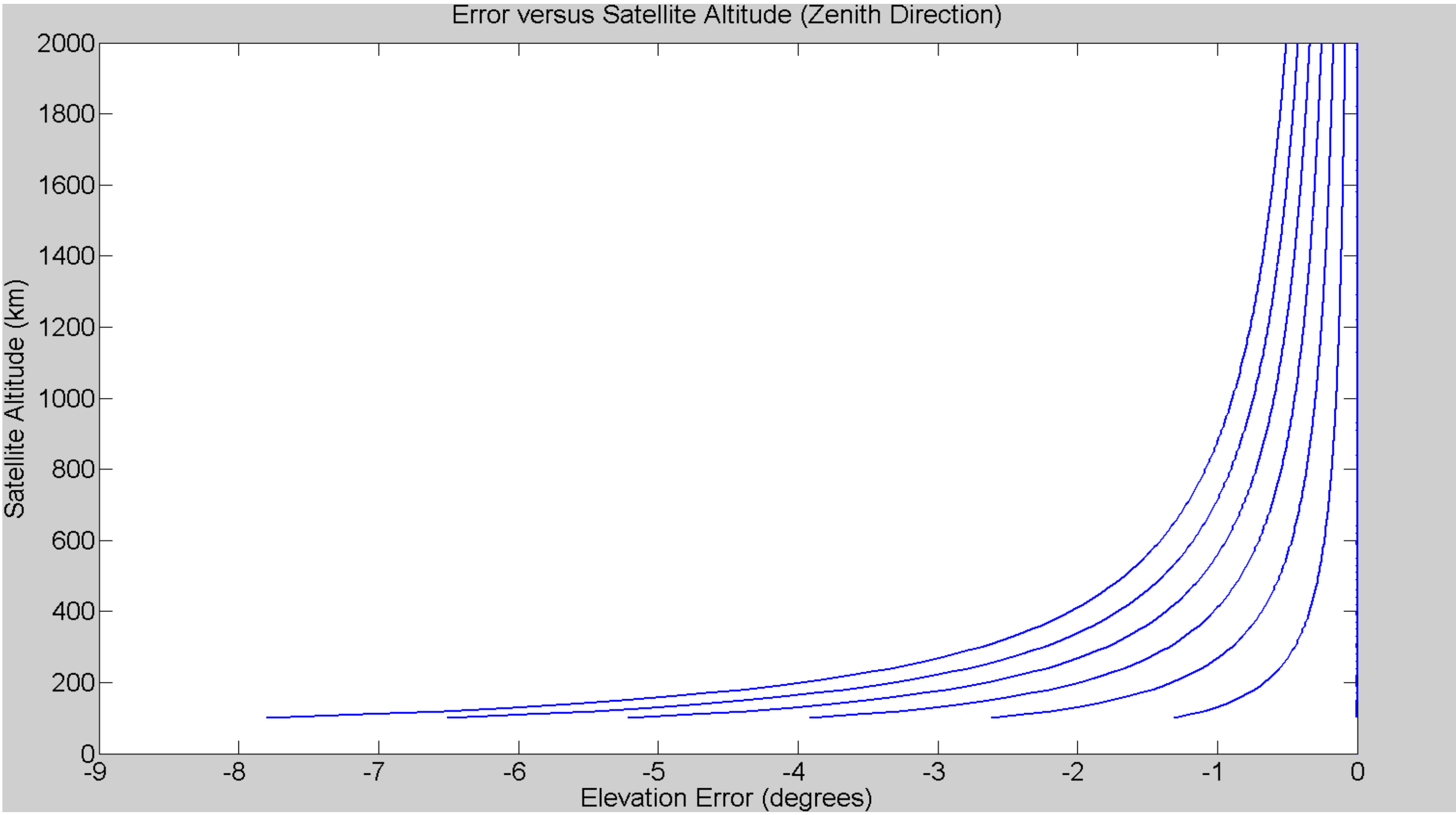
Look Angle Error - Variation with Altitude

- The next set of charts plot the errors in the 5 cardinal directions
  - Errors are displayed for latitudes = 0°, 15°, 30°, 45°, 60°and 75°N
  - The space object altitudes range from 100 km to 2000 km
  - Plots are produced for the following values for DUT1:
    0, 5, 10, 15, 20, 25 and 30 seconds
- Charts reveal how errors in cardinal directions vary with latitude
  - Charts reveal symmetry in errors in the east/west directions
  - Charts reveal asymmetry in errors in the north/south directions

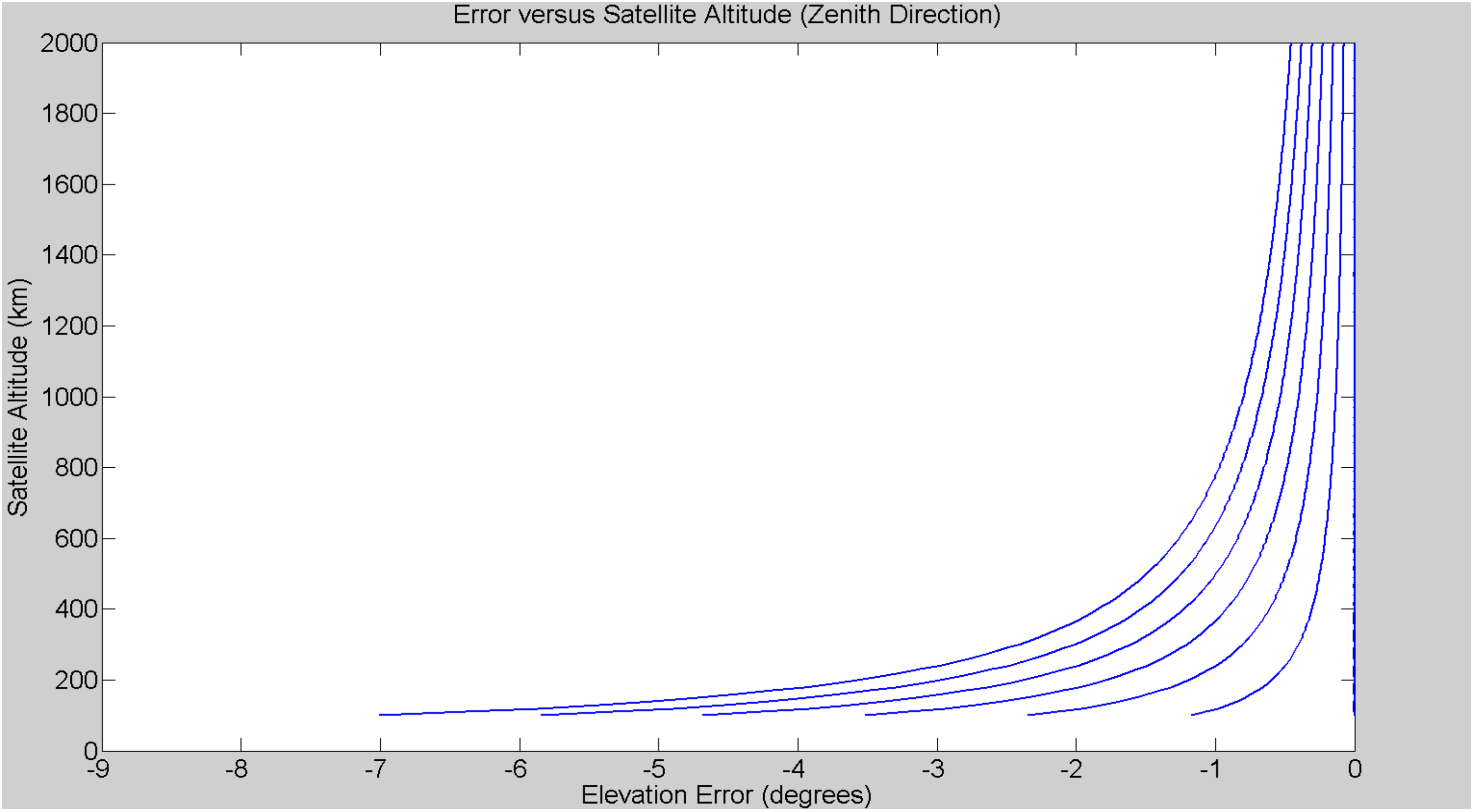
Zenith Direction Viewed from Equator
DUT1 = 0, 5, 10, 15, 20, 25, 30 sec



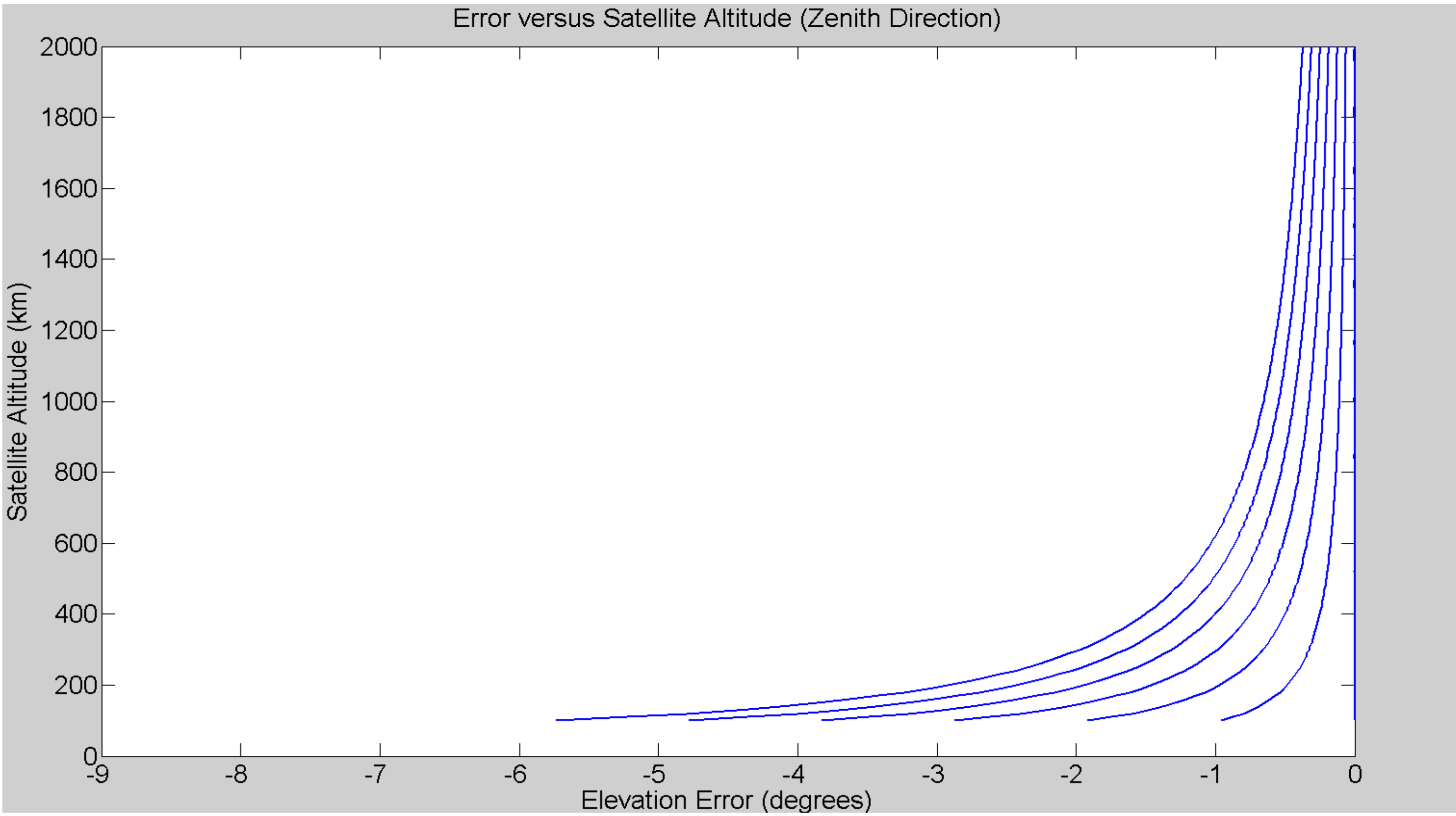
Zenith Direction Viewed from 15° N latitude DUT1 = 0, 5, 10, 15, 20, 25, 30 sec



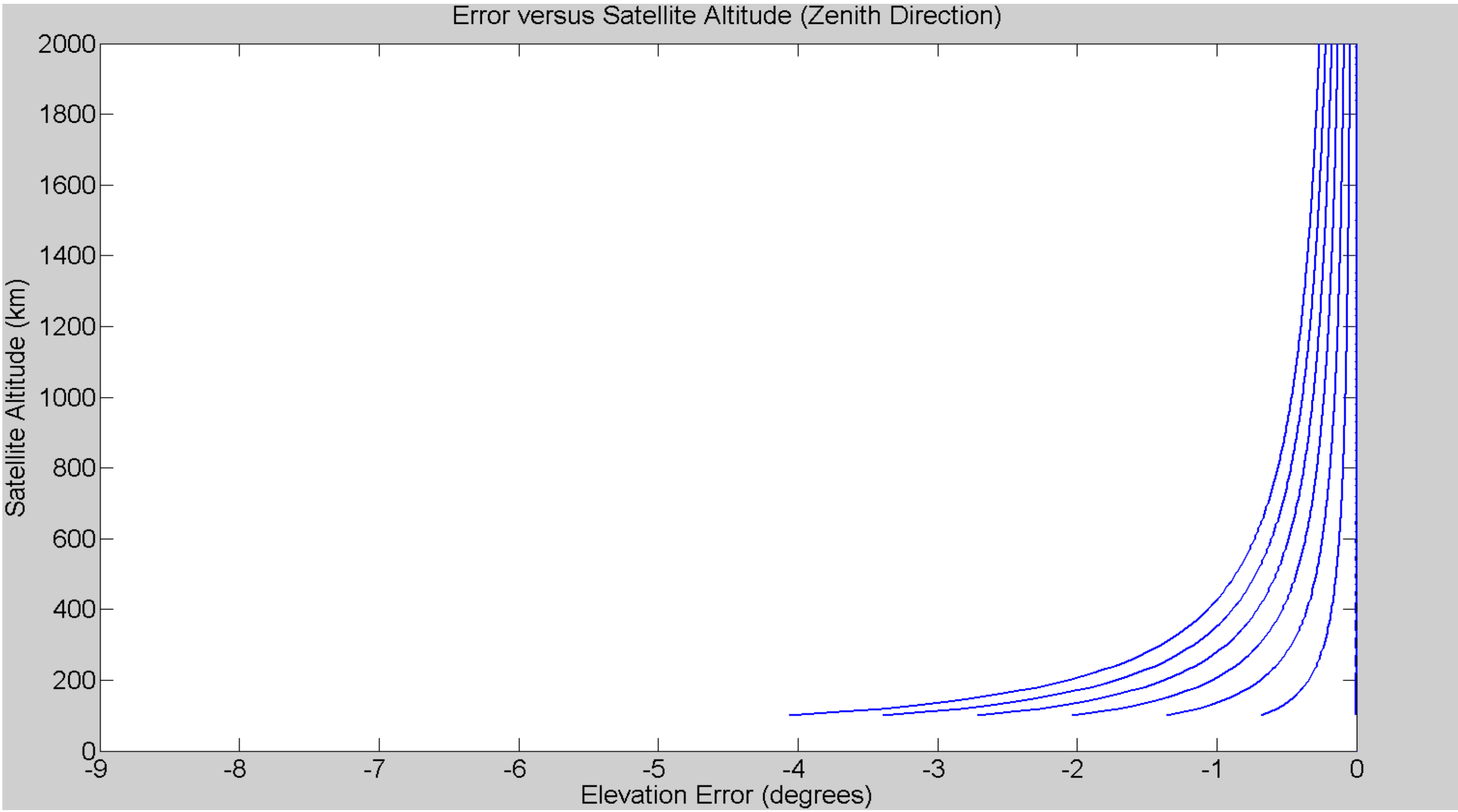
Zenith Direction Viewed from 30° N latitude DUT1 = 0, 5, 10, 15, 20, 25, 30 sec



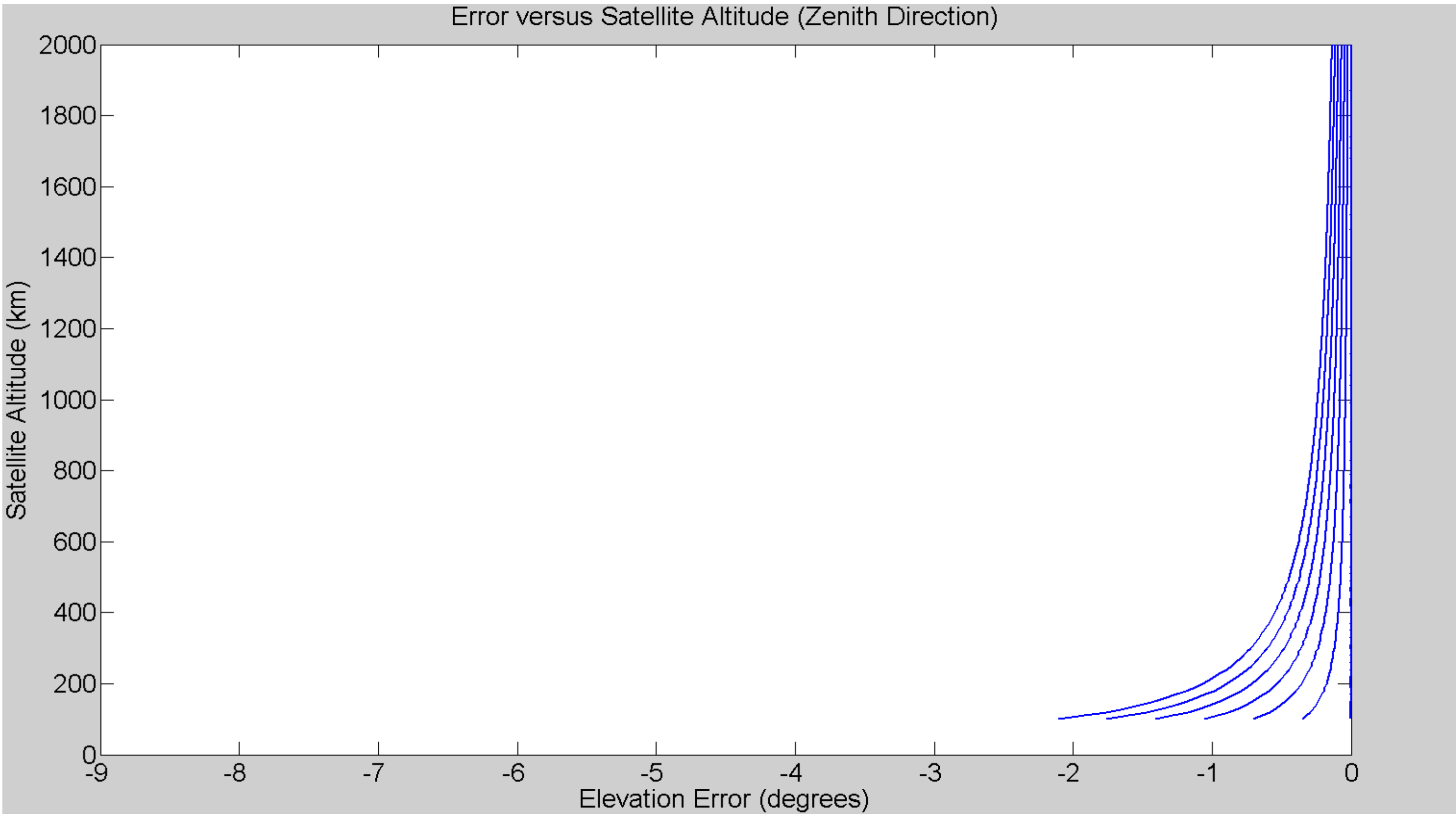
Zenith Direction Viewed from 45° N latitude DUT1 = 0, 5, 10, 15, 20, 25, 30 sec



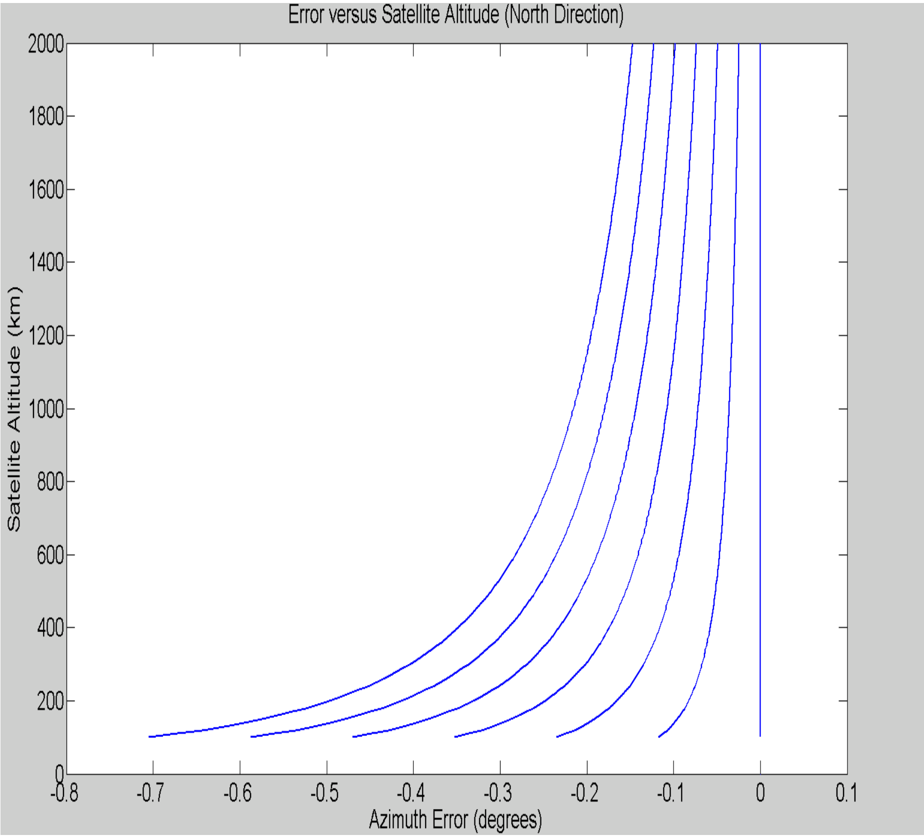
Zenith Direction Viewed from 60° N latitude
DUT1 = 0, 5, 10, 15, 20, 25, 30 sec

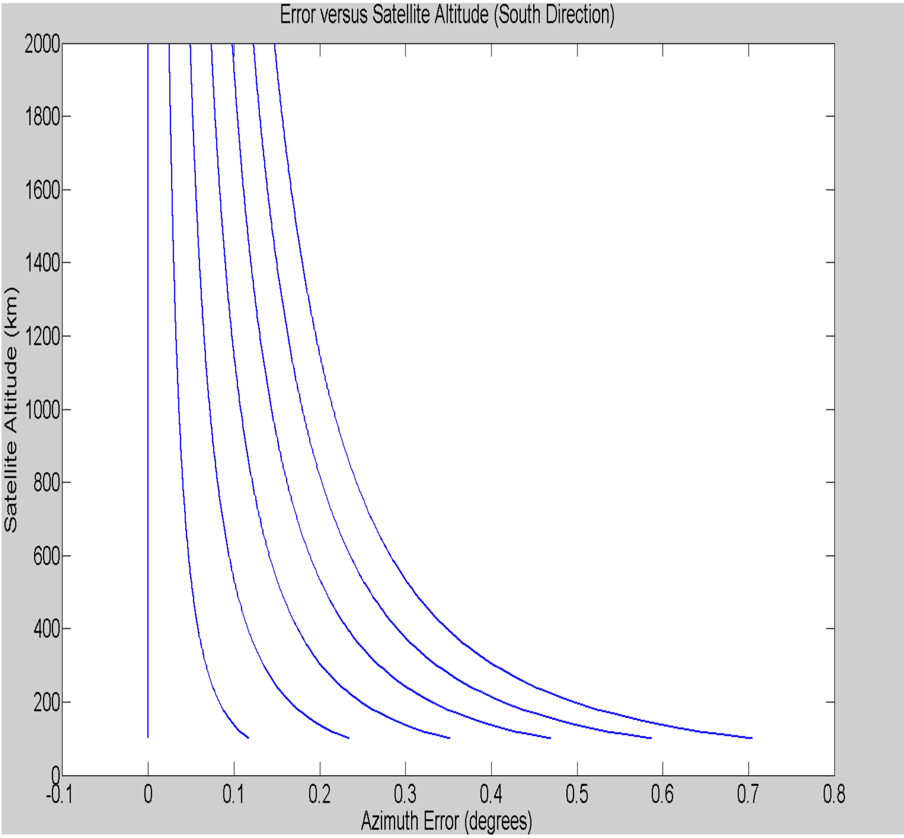


Zenith Direction Viewed from 75° N latitude
DUT1 = 0, 5, 10, 15, 20, 25, 30 sec

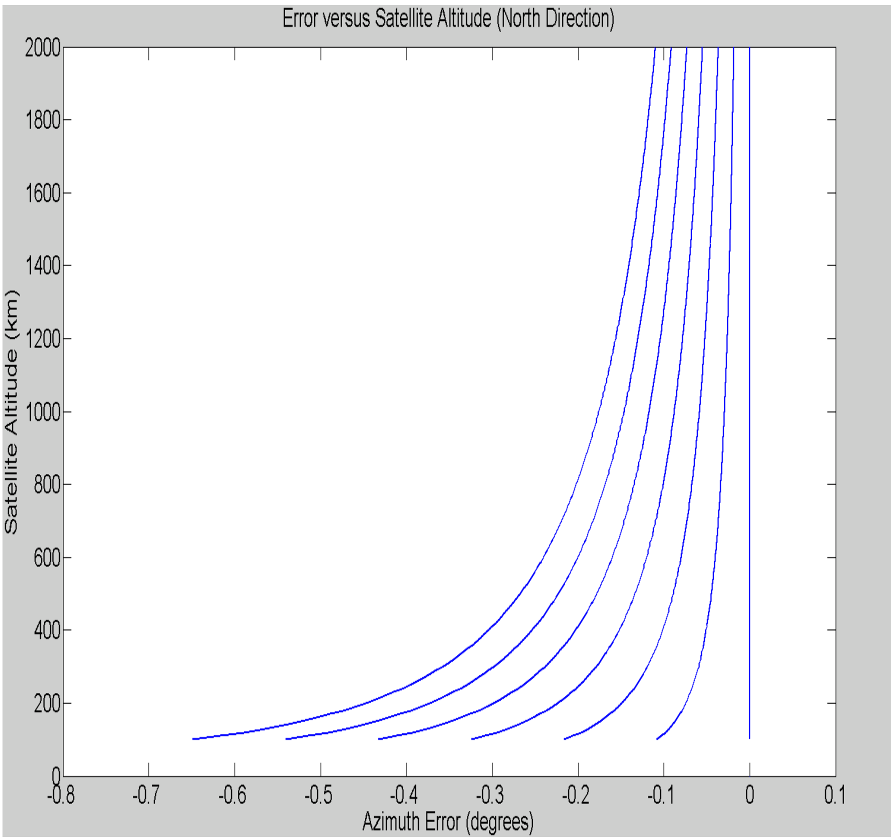


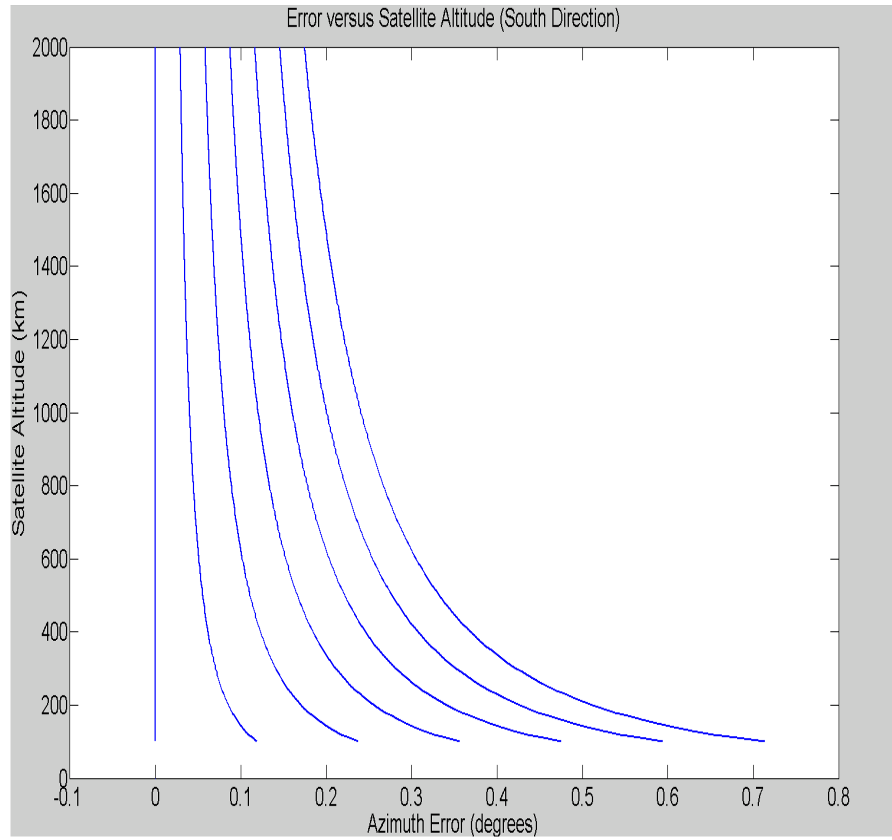
North/South Directions Viewed from Equator
DUT1 = 0, 5, 10, 15, 20, 25, 30 sec



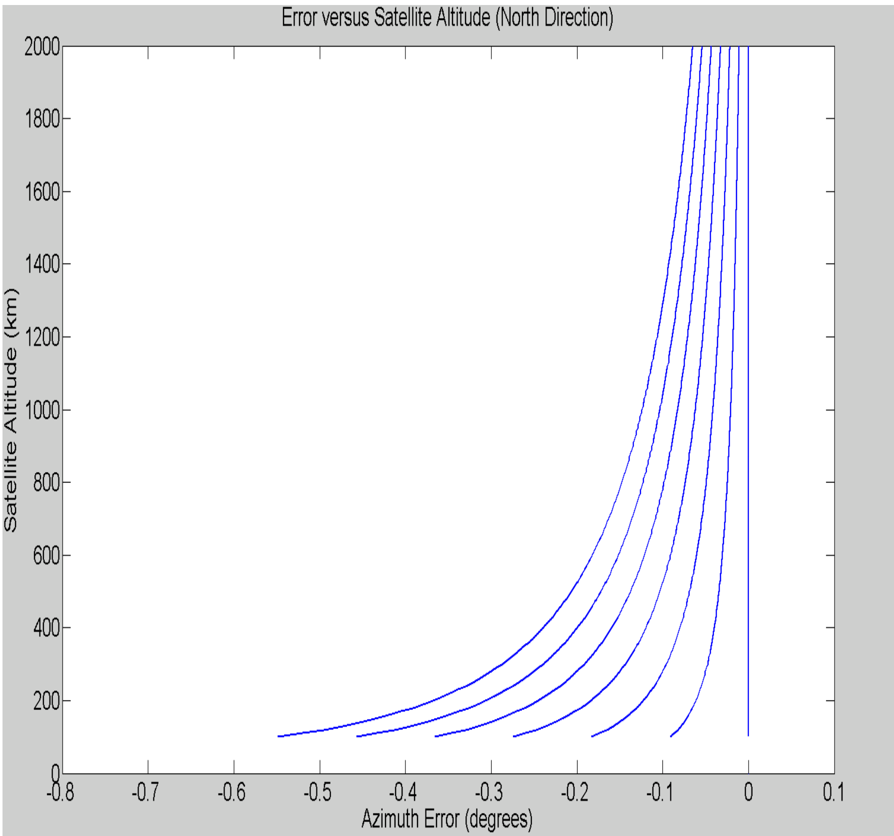


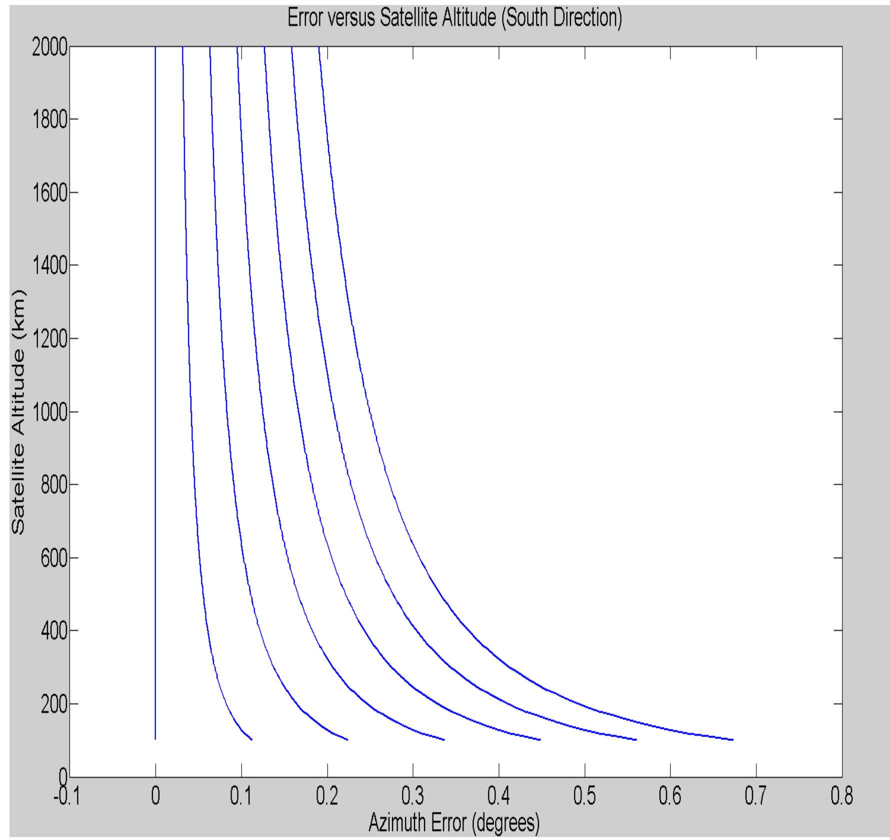
North/South Directions Viewed from 15° N
DUT1 = 0, 5, 10, 15, 20, 25, 30 sec



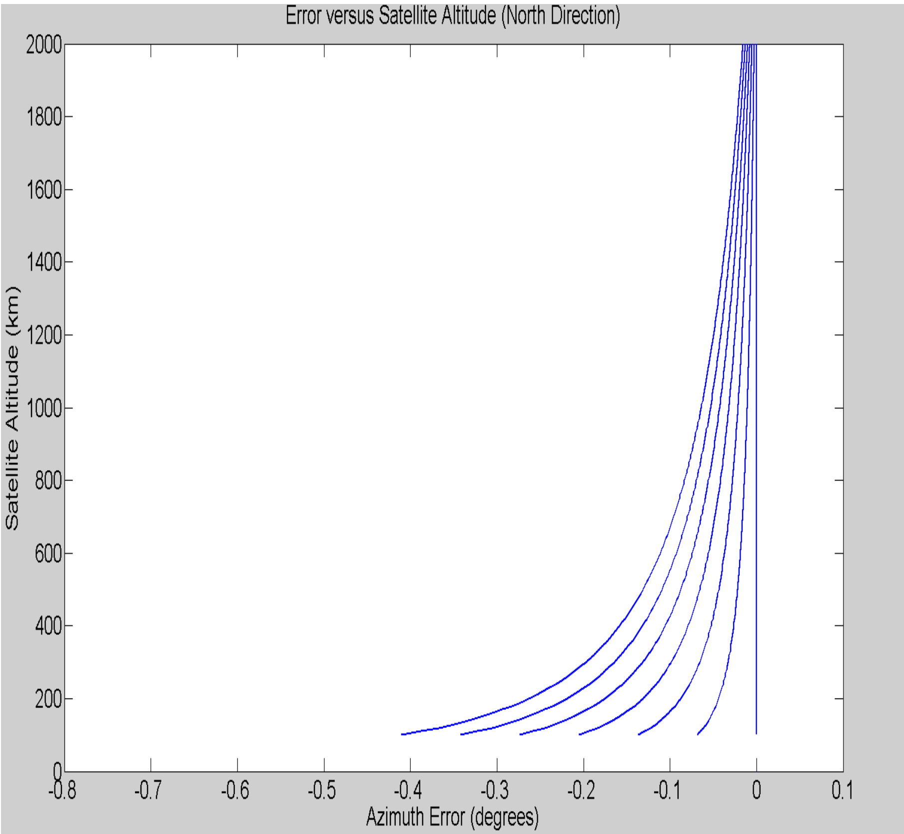


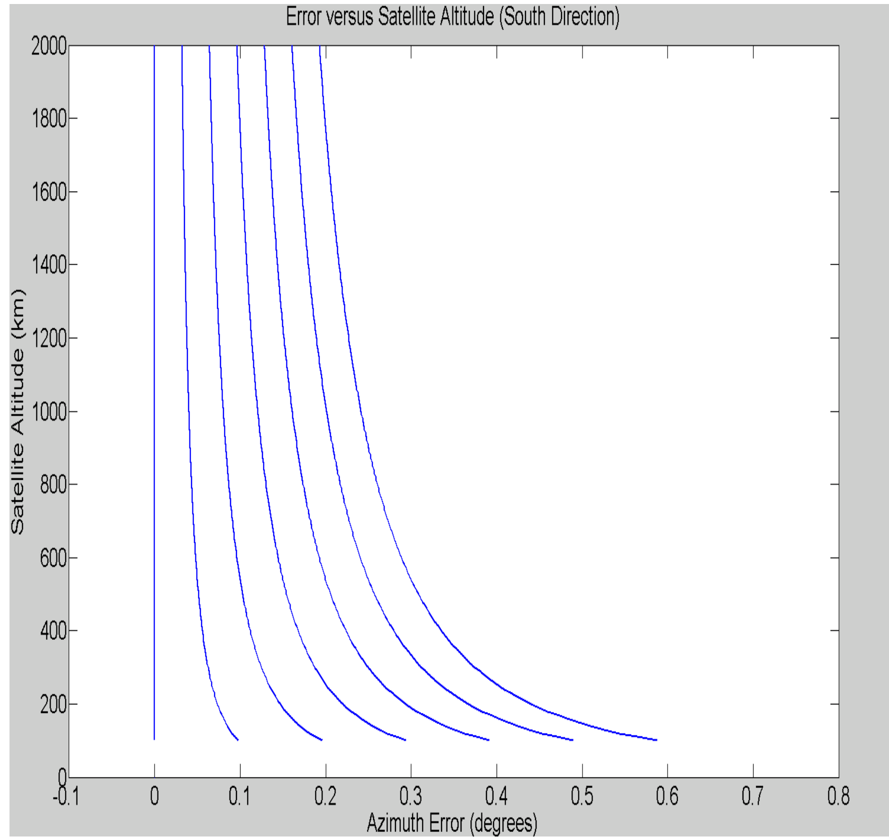
North/South Directions Viewed from 30° N
DUT1 = 0, 5, 10, 15, 20, 25, 30 sec



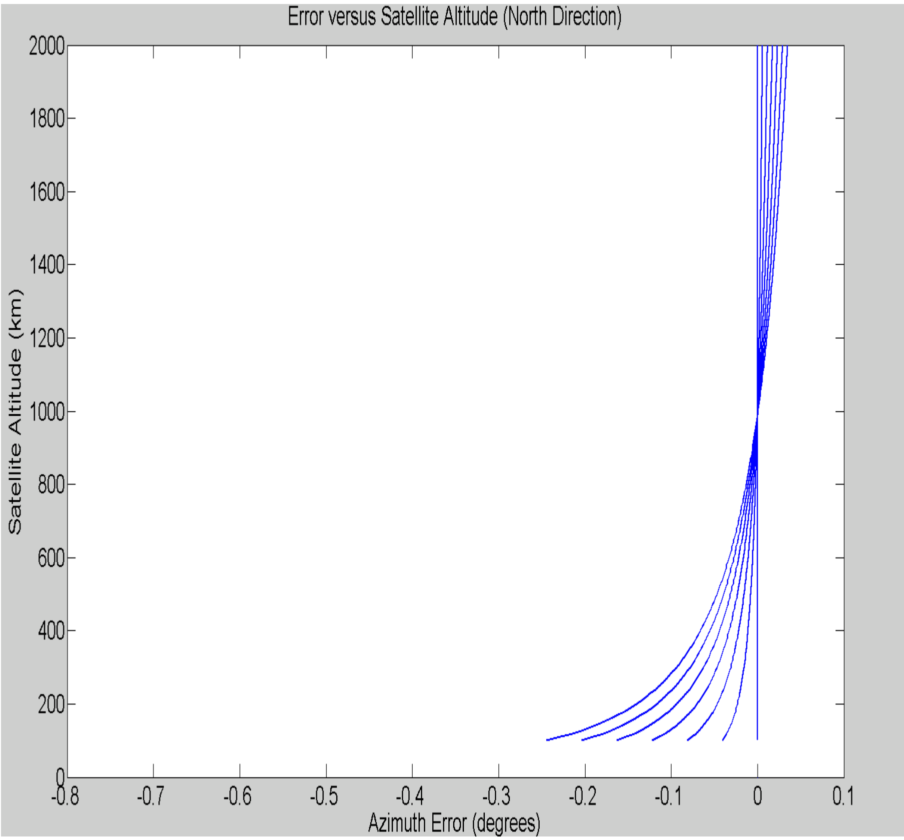


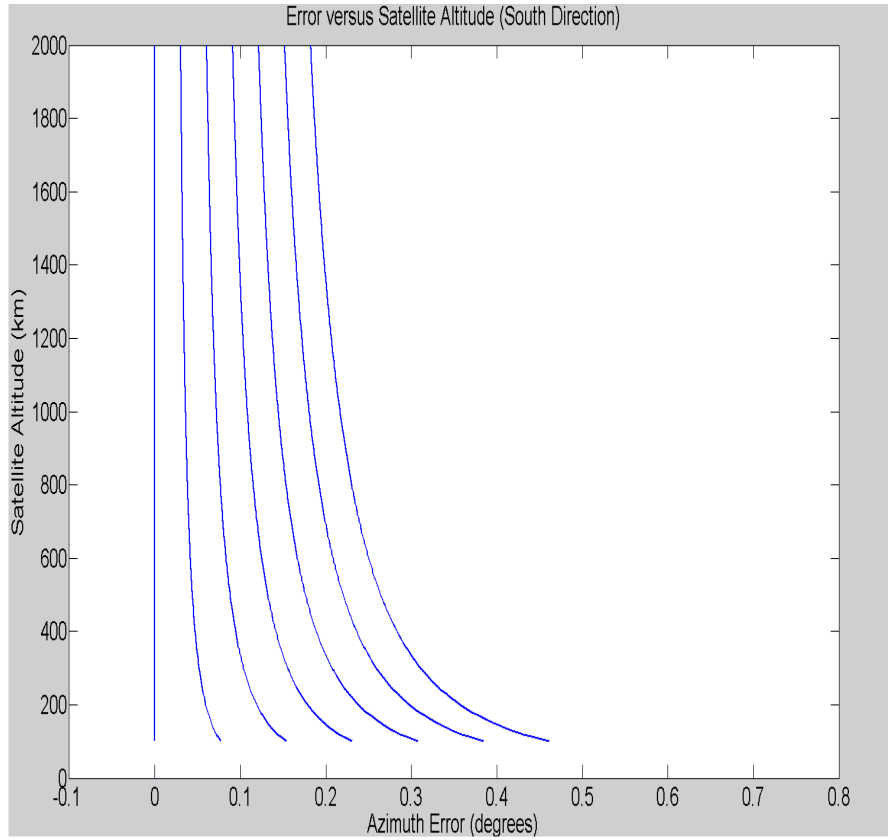
North/South Directions Viewed from 45° N
DUT1 = 0, 5, 10, 15, 20, 25, 30 sec



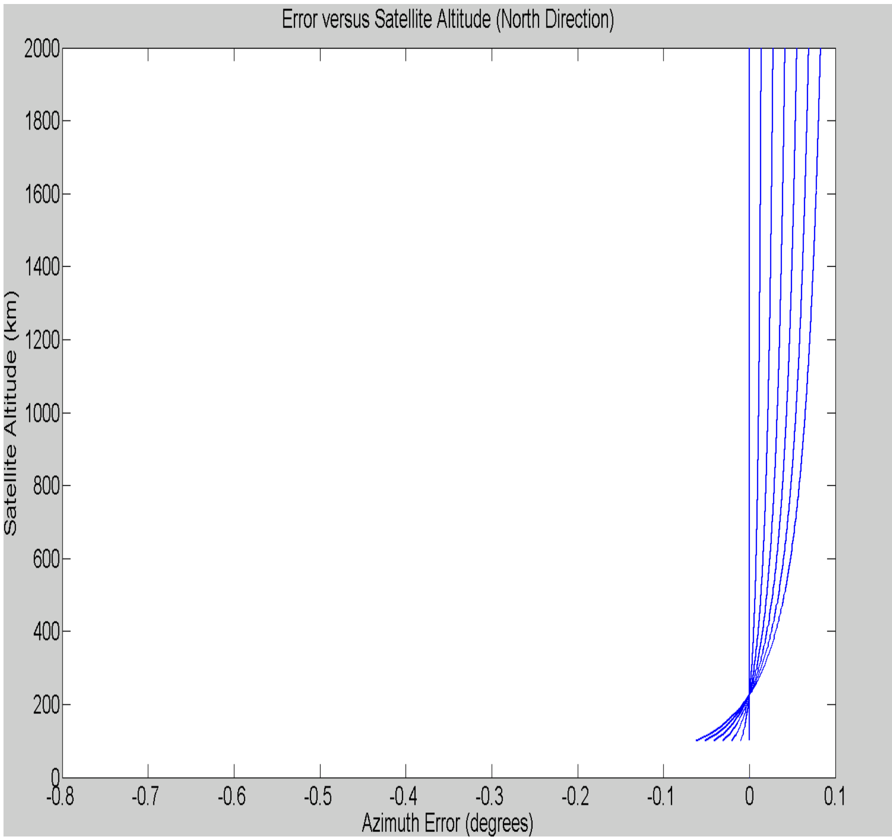


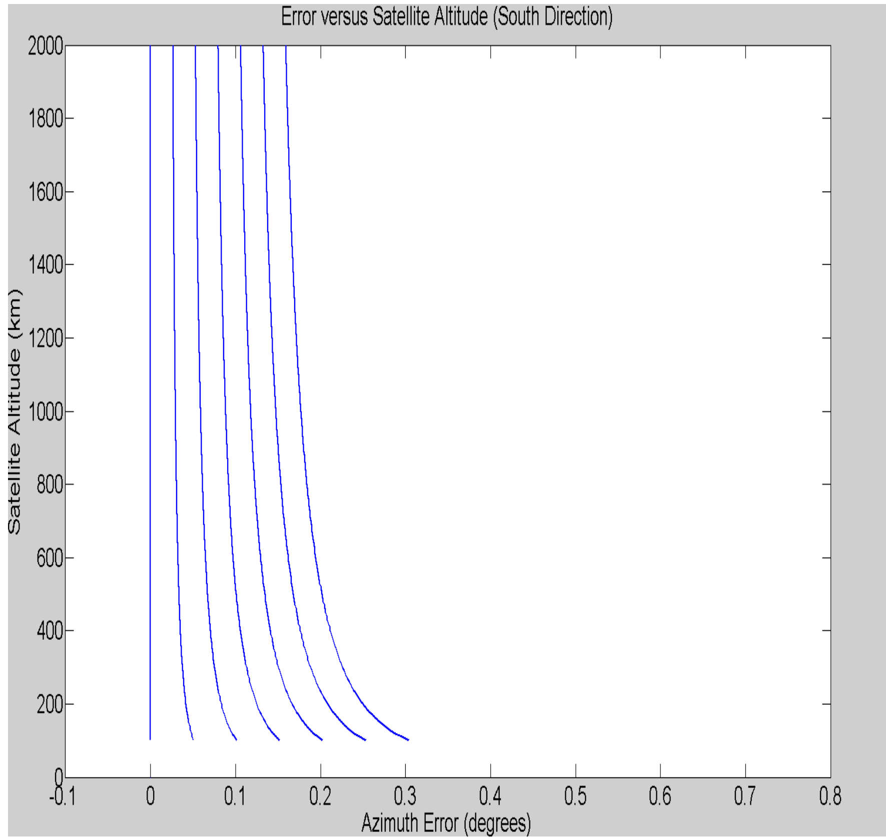
North/South Directions Viewed from 60° N
DUT1 = 0, 5, 10, 15, 20, 25, 30 sec



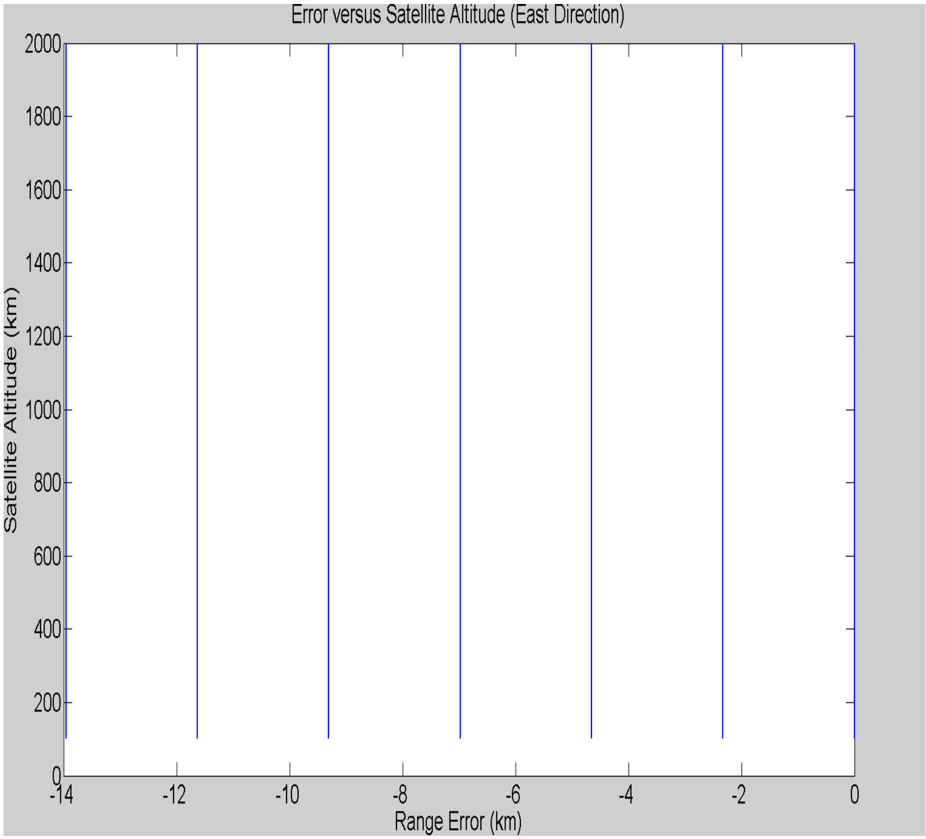


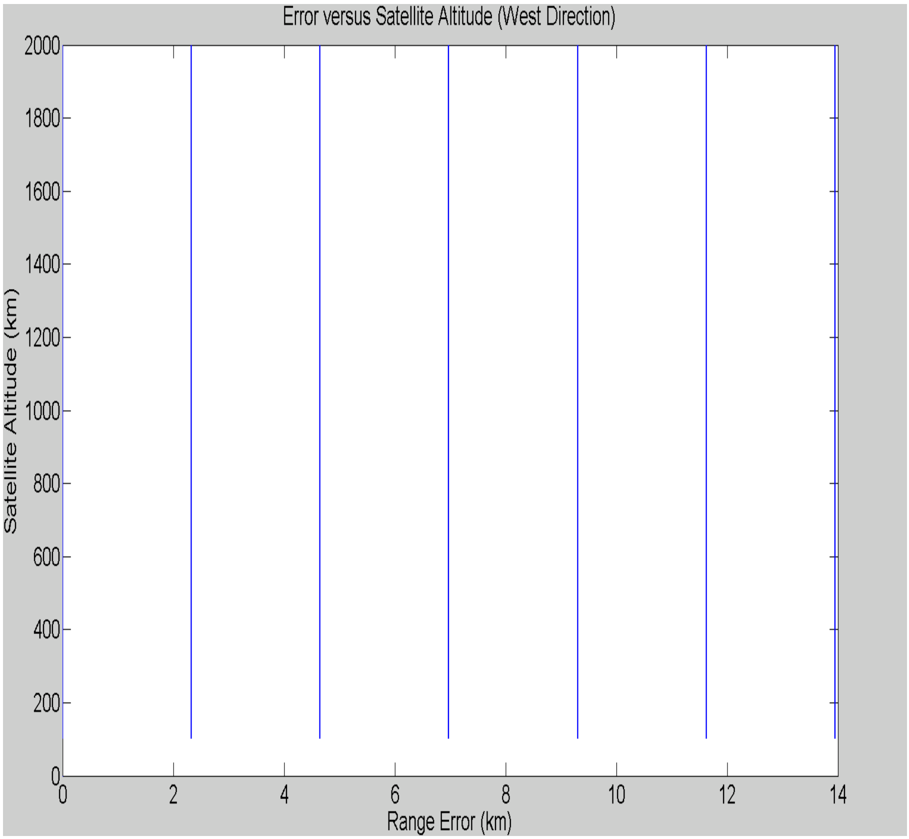
North/South Directions Viewed from 75° N
DUT1 = 0, 5, 10, 15, 20, 25, 30 sec



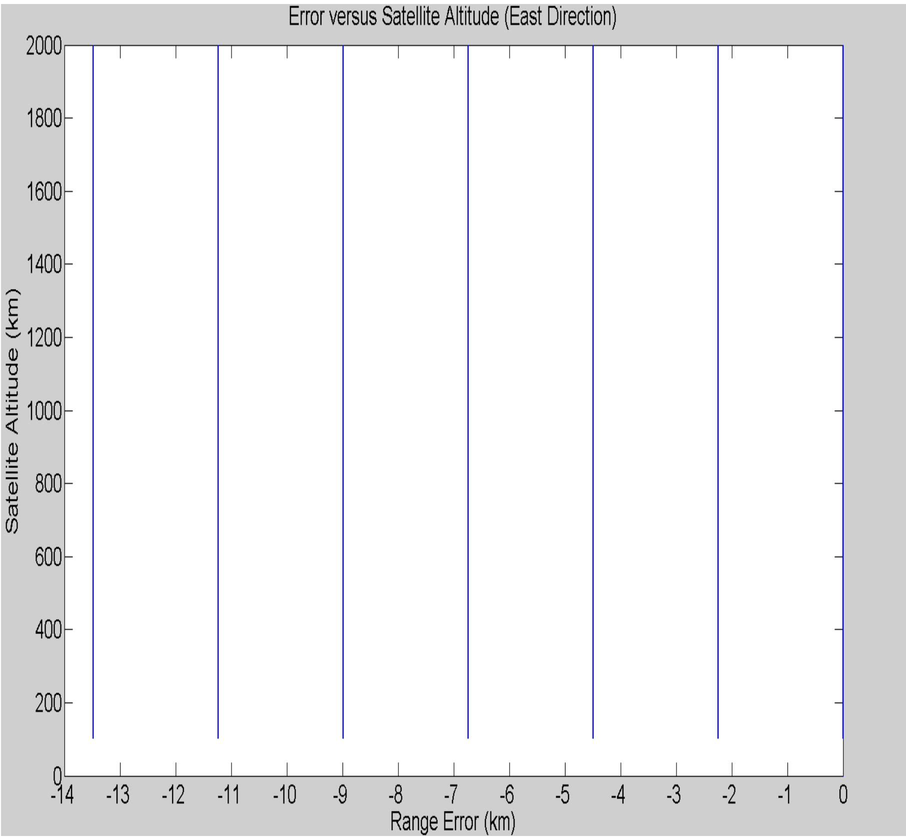


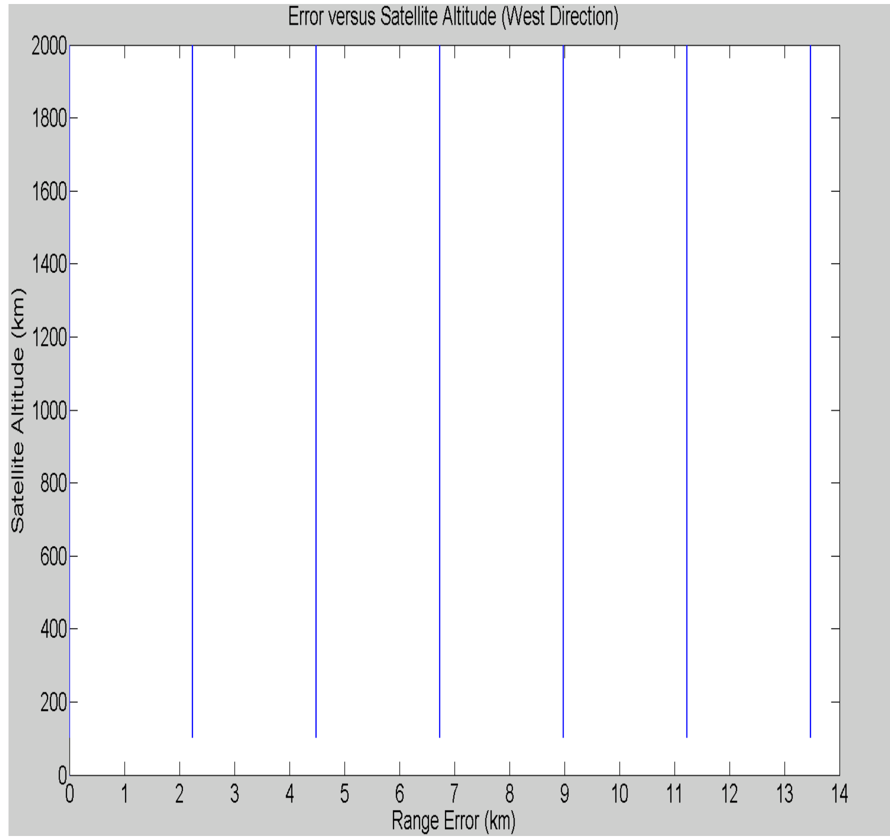
East/West Directions Viewed from Equator
DUT1 = 0, 5, 10, 15, 20, 25, 30 sec



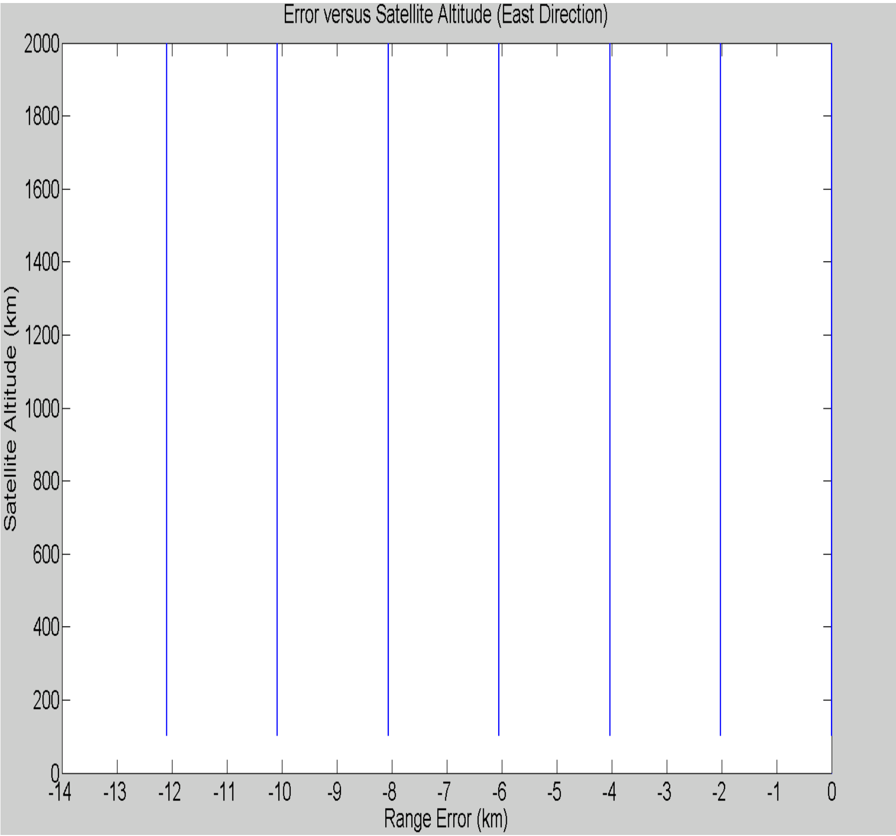


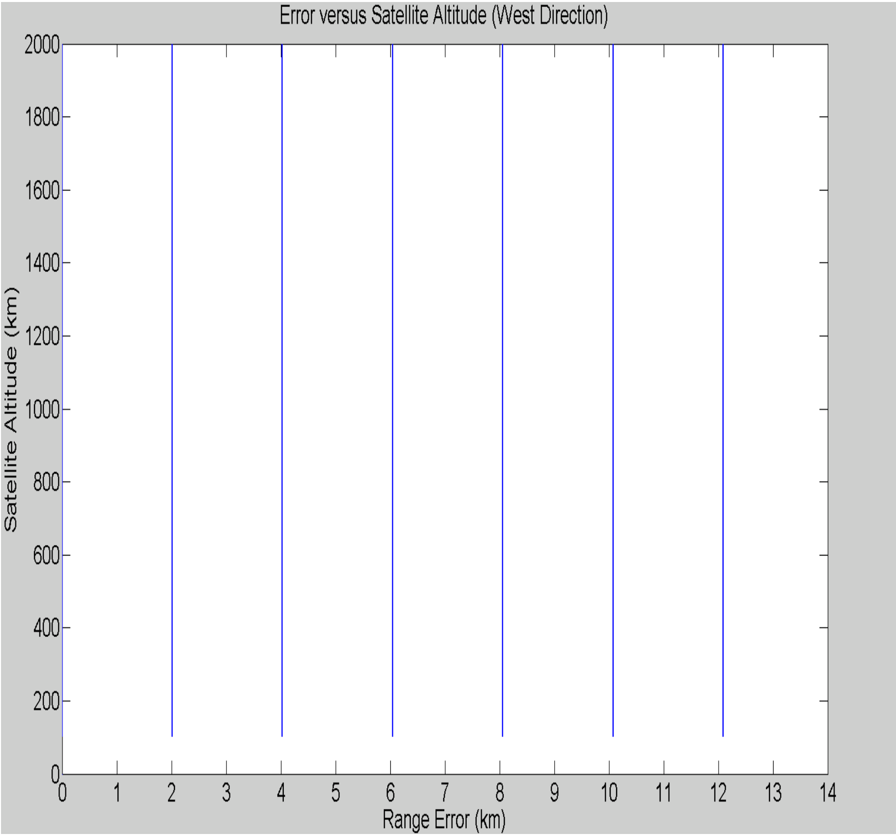
East/West Directions Viewed from 15° N
DUT1 = 0, 5, 10, 15, 20, 25, 30 sec



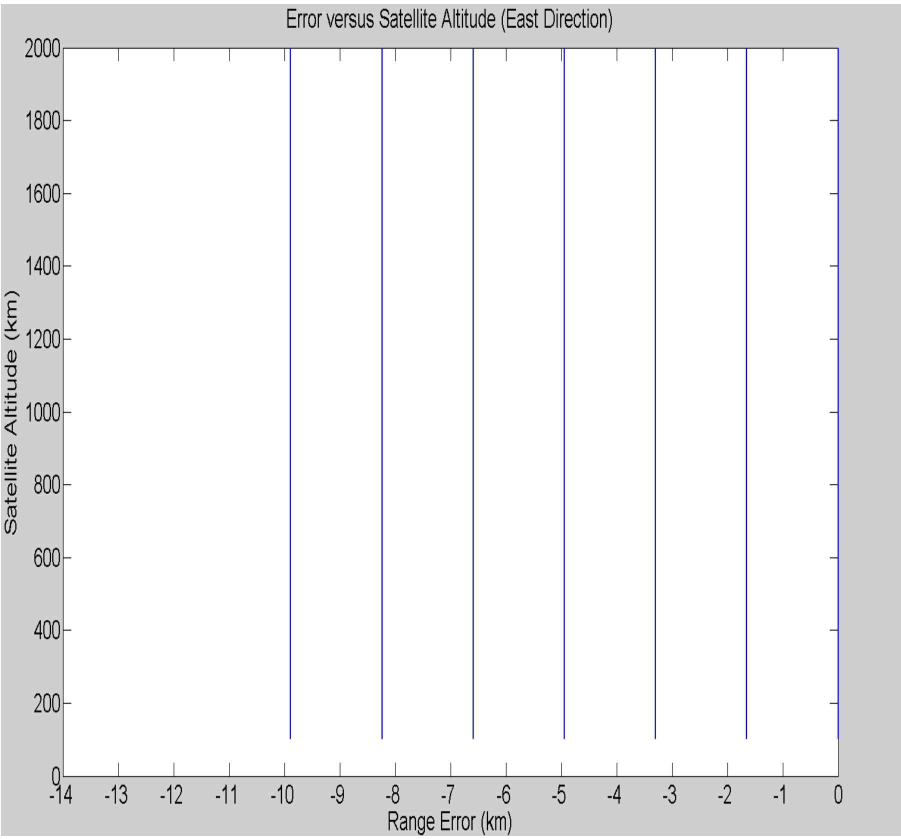


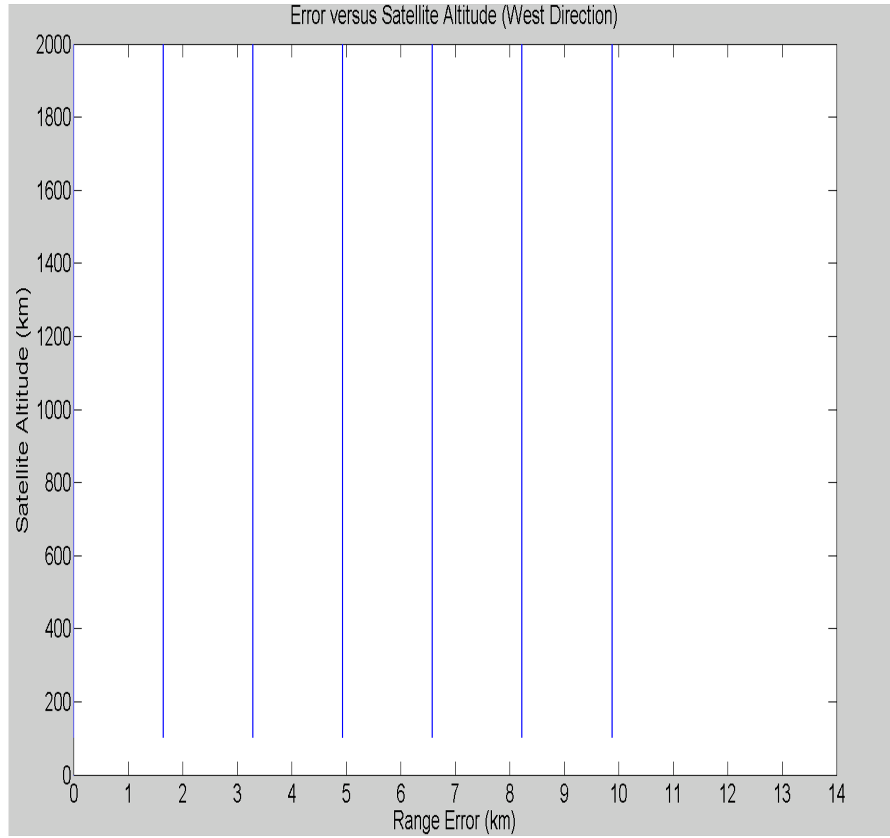
East/West Directions Viewed from 30° N
DUT1 = 0, 5, 10, 15, 20, 25, 30 sec



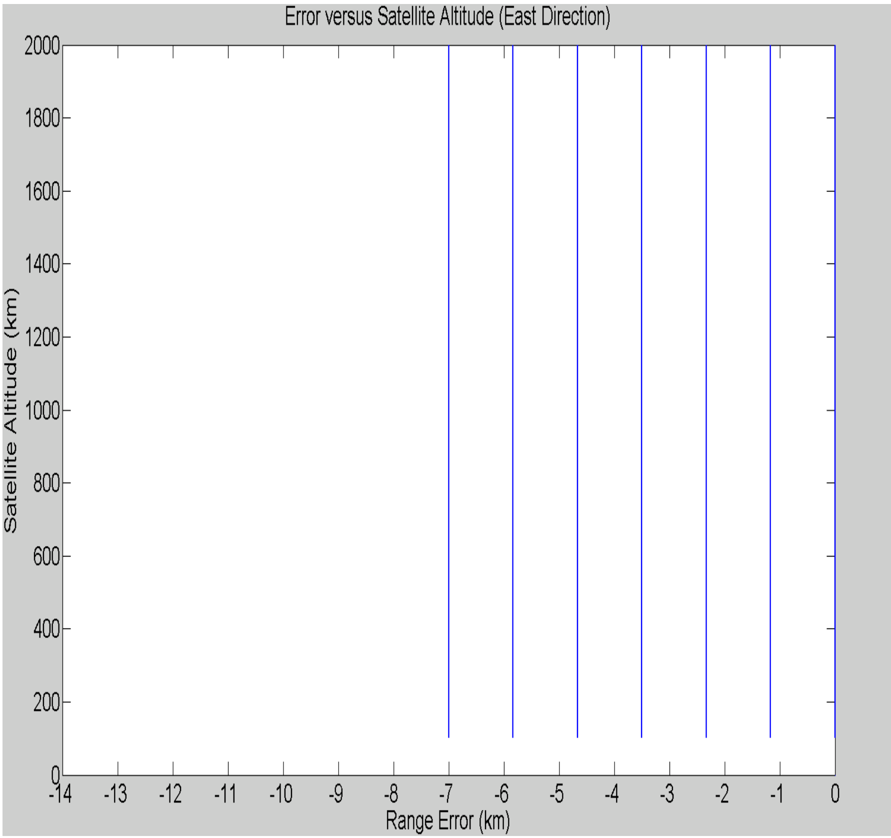


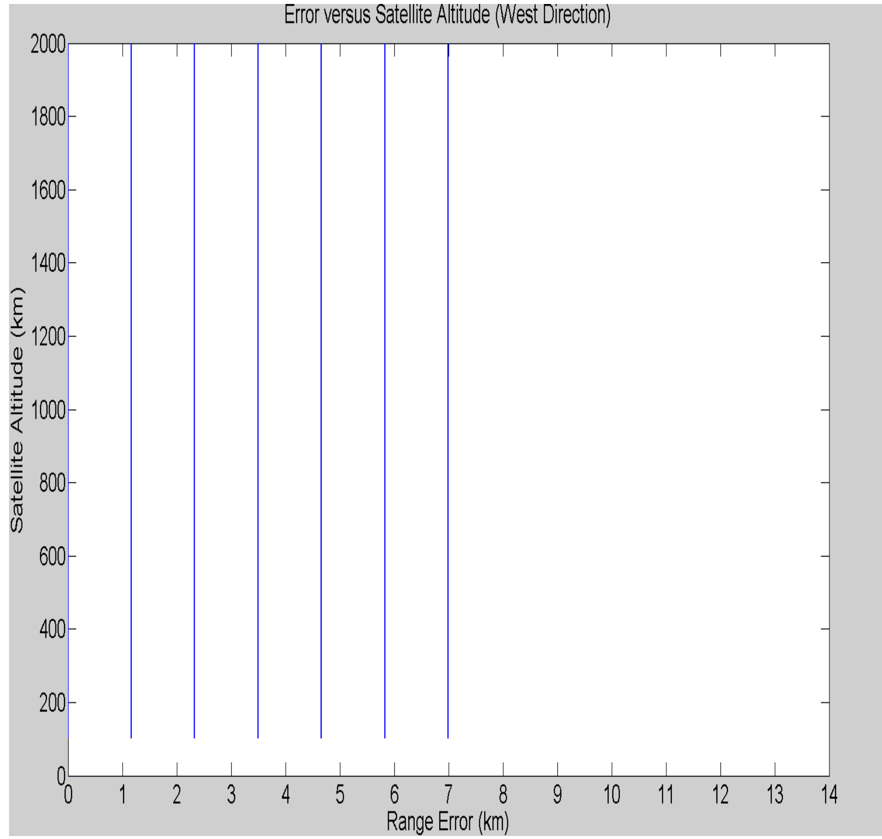
East/West Directions Viewed from 45° N
DUT1 = 0, 5, 10, 15, 20, 25, 30 sec



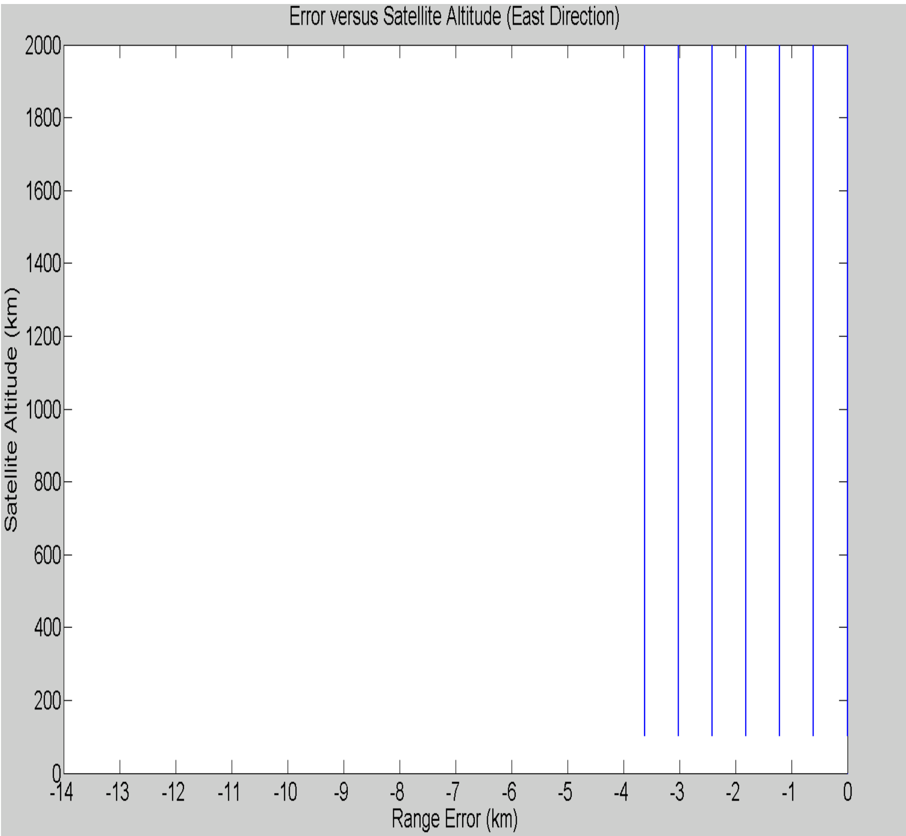


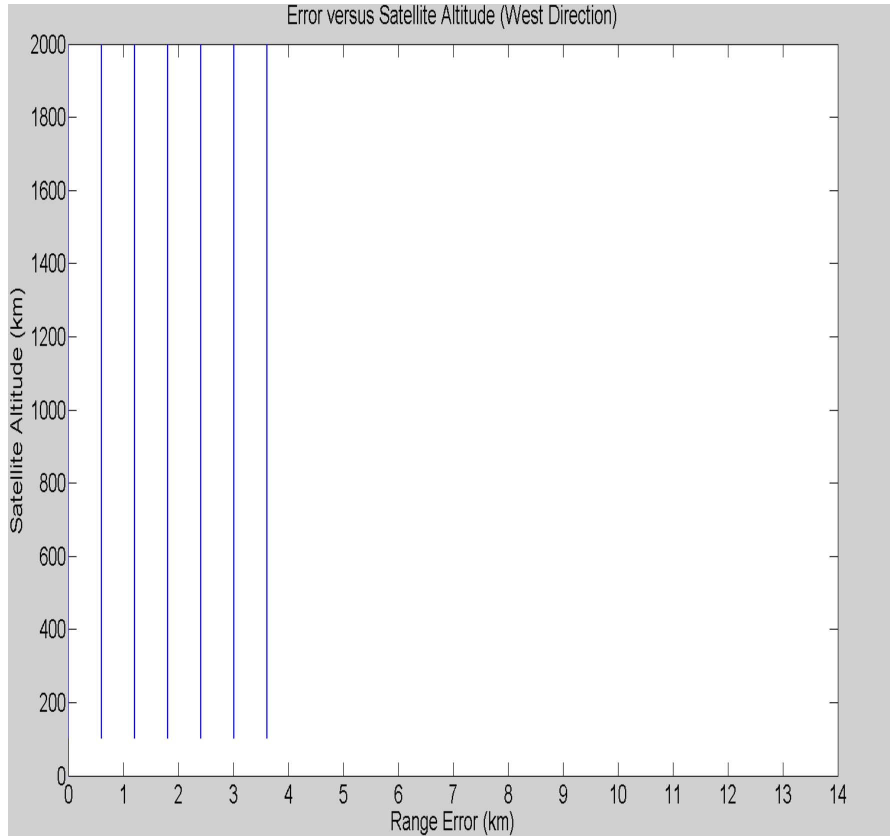
East/West Directions Viewed from 60° N
DUT1 = 0, 5, 10, 15, 20, 25, 30 sec





East/West Directions Viewed from 75° N
DUT1 = 0, 5, 10, 15, 20, 25, 30 sec

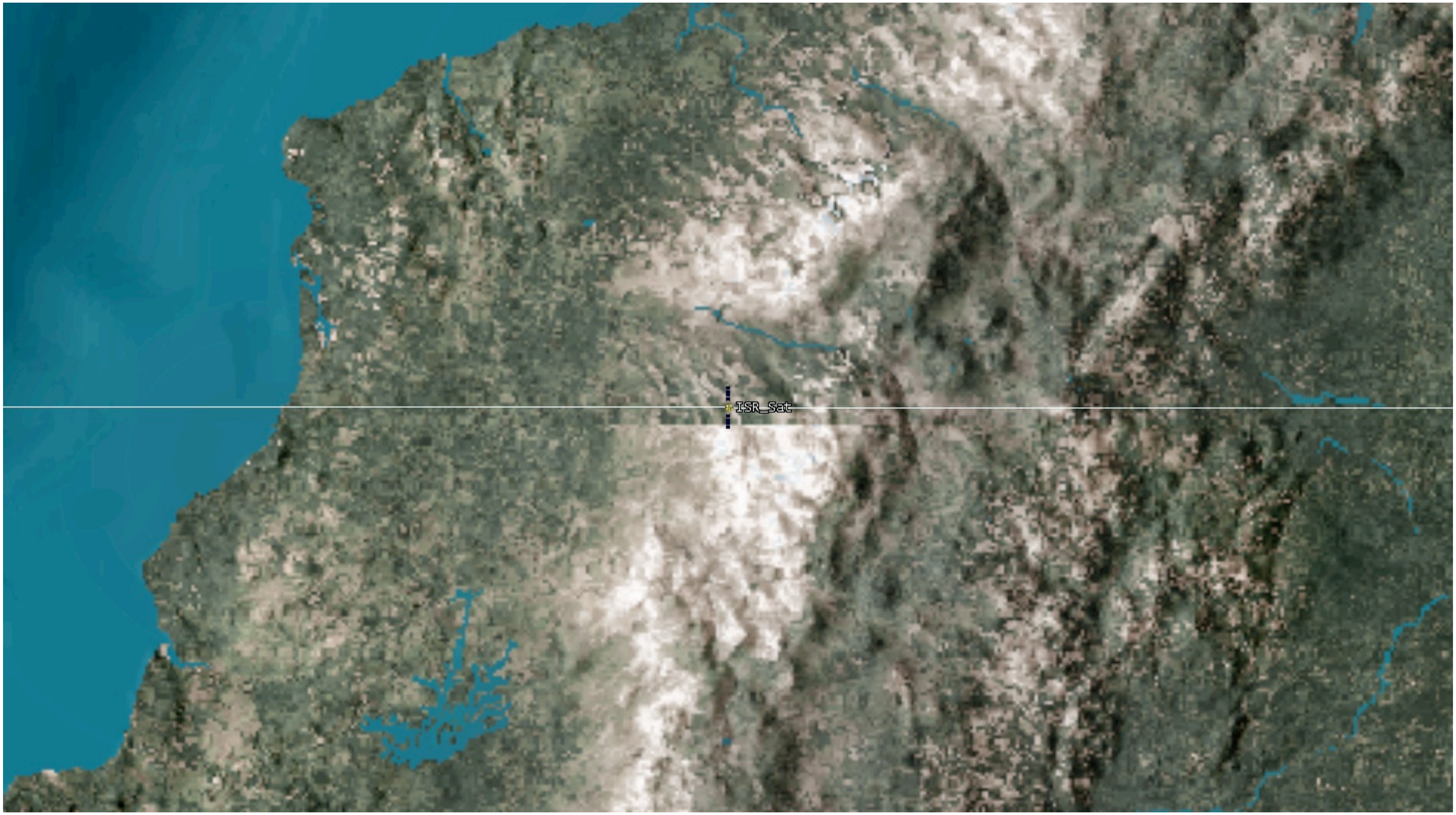




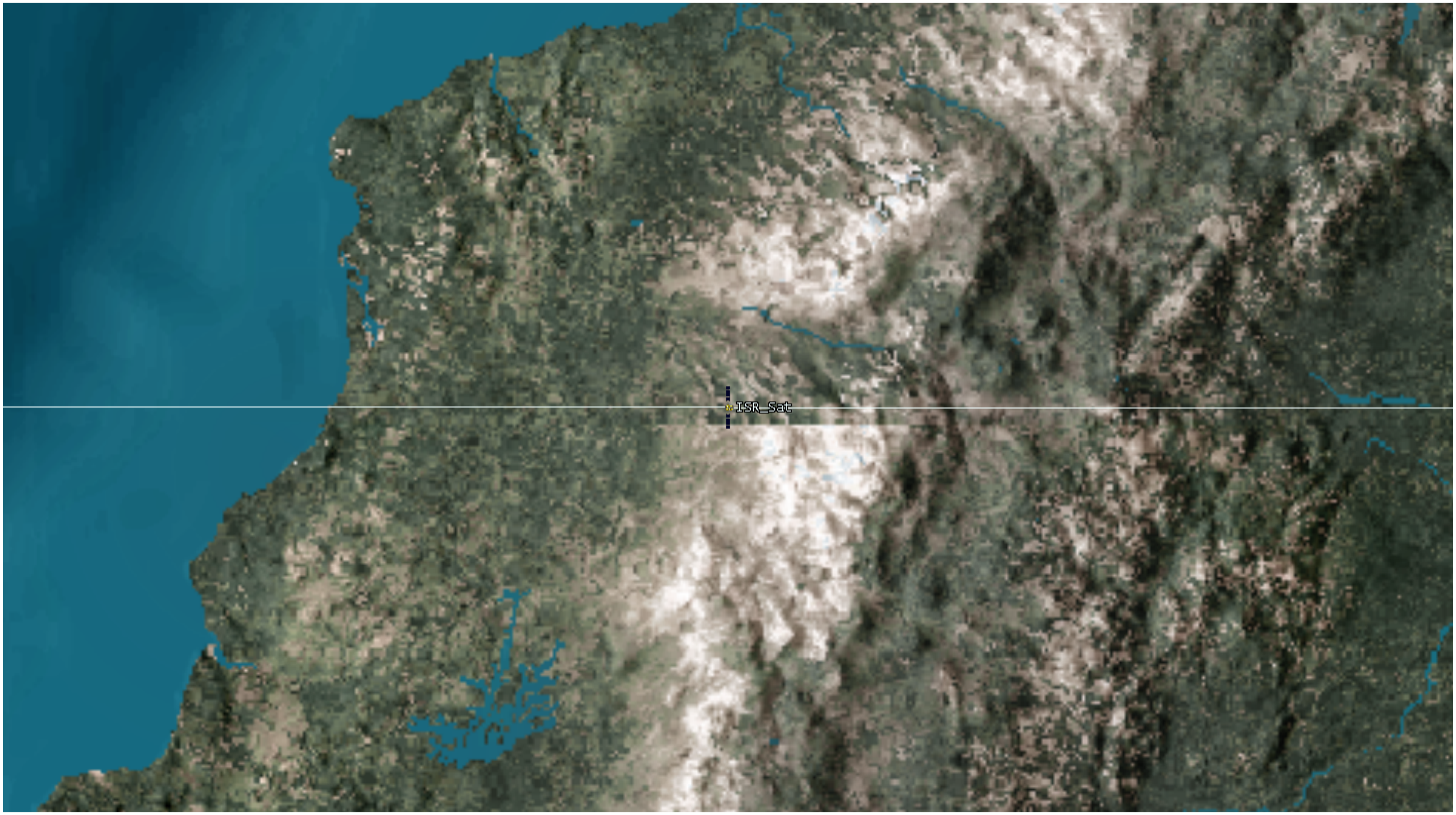
Impact on Space-based Sensors

- **The next two slides demonstrate the impact on space-based sensors**
  - **An ISR sensor looking down at the ground will compute look angles consistent with a target position on the surface that's too far to the east**
  - **The next two slides illustrate the error caused by a DUT1 of 30 seconds**
  - **This error causes a shift of the target's computed position of 1/8° in longitude to the east**
  - **At the Equator (slides show Andes mountains in Equador) this equates to about 7.5 nautical miles**

True Positioning of Earth



Erroneous Positioning of Earth (DUT1 = 30 sec)
(Earth is ~1/8° (7.5 nmi) too far to the East)



Conclusions

- **Discontinuing leap seconds would fundamentally change the way civil time is defined**
  - **Would no longer be kept close (within 1 sec) of Universal Time (UT1)**
  - **Would no longer be tied to the orientation of Earth relative to the sun**
  - **Would become like another atomic time (until the next adjustment)**
- **UT1 will still be needed to compute Earth orientation for space operations**
  - **Algorithms for computing or obtaining UT1 would have to be upgraded**
  - **Software upgrades would have to be thoroughly tested and integrated**
  - **Algorithms from these error tools may be used to fix operational software**

Space Community needs to develop a plan for upgrading operational software in case leap second discontinuance goes into effect