Mission Automation for "A Train" Correlative Measurements

EOS Dynamic Replanning Using the Earth Phenomena Observing System

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Outline

- **Overview**
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  - Technical team
- **Technical approach**
  - EPOS 4.0 architecture
  - Concept of operations
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- **Progress**
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  - Sensor modeling
- **Future work**
  - EO-1 observation planning
  - Additional concepts of operations
    - **Virtual observatory**
    - **Validation/science campaign**

Overview – Previous AIST Effort

- **Developed technologies for an automated mission manager that:**
  - Efficiently utilizes a complementary and cooperative suite of heterogeneous Earth-observing space-based pointable and taskable sensor platforms
  - Responds to significant events, providing enhanced understanding of ephemeral Earth phenomena that impact human life and property, e.g., hurricanes, volcanoes, biomass burning (e.g., forest fires)
  - Provides for long-term data gathering
- **Developed EPOS (Earth Phenomena Observing System) v1.0 – v3.0**
  - Moved from TRL 1/2 to TRL 3/4
  - EPOS 1.0
    - **Optimized dynamic replanning with potentially maneuvering satellites, few targets**
  - EPOS 2.0
    - **Optimized dynamic replanning with many coasting satellites/sensors (tested with up to 105), many targets, multiple targets (tested with up to 1450)**
  - EPOS 3.0
    - **Modeled existing EOS satellites (and satellites to be launched in the near future)**
    - **MODIS Cloud Mask data used as input by EPOS**

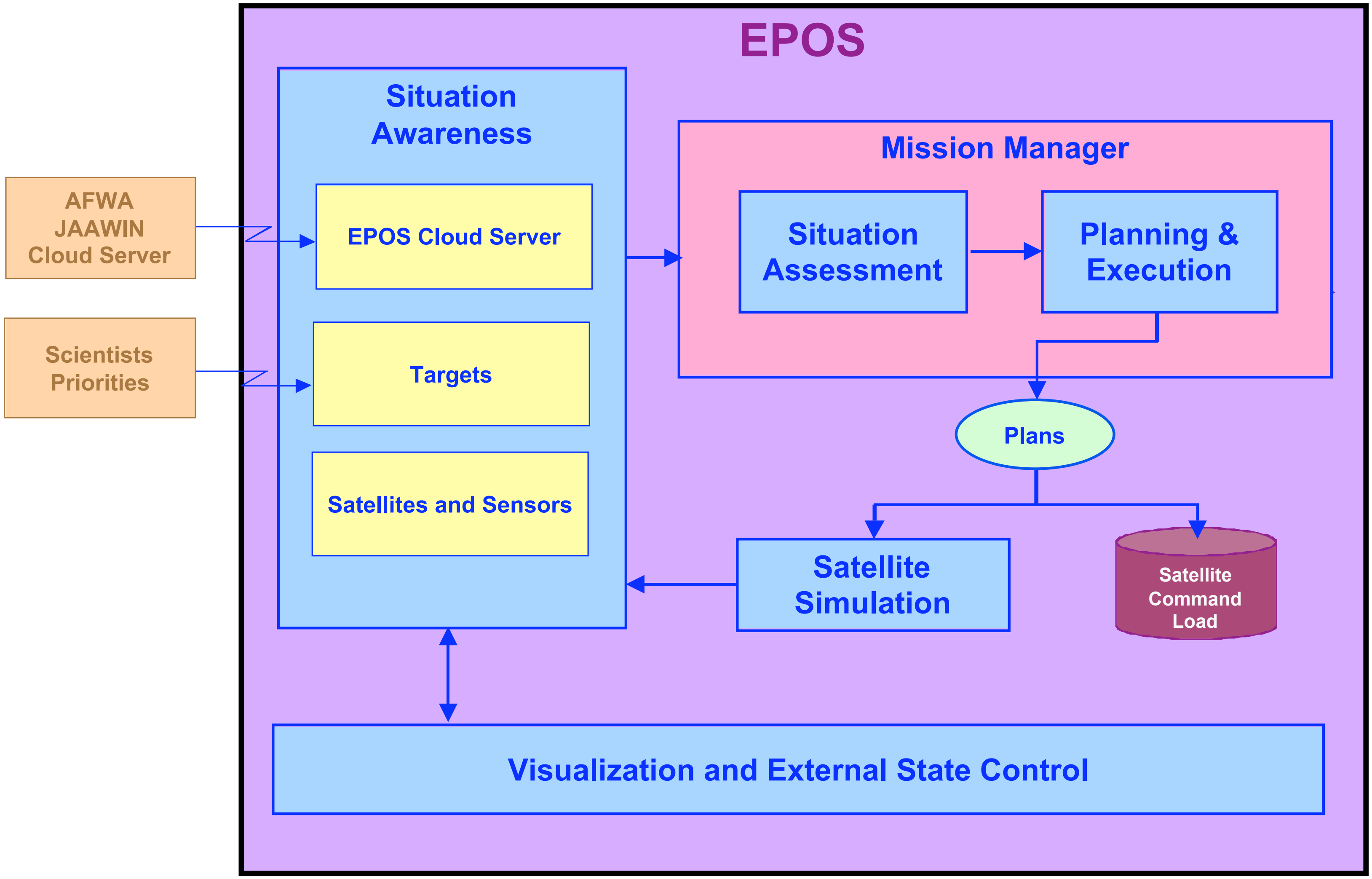
Overview – Current AIST Effort

- **Objective**
  - Increase the value of science data gathered by a confederation of Earth observing satellites
    - **Change the non-interacting nature of a confederation to allow interactions among data gathering activities**
- **Approach**
  - Develop concepts of operation
  - Extend and enhance EPOS
    - **Situation awareness/assessment**
      - **Cloud coverage forecasts**
      - **Observation science value functions**
    - **Planning and execution – e.g.,**
      - **Science-optimized mode selection and sensor pointing for Aura's HIRDLS and TES**
      - **Science-optimized sensor pointing for EO-1's Hyperion**
  - Utilize optimization-based, hierarchical, real-time mission planning and control technology

Draper AIST Technical Team

- Mark Abramson
- David Carter
- Brian Collins
- Paul Goulart (on-leave)
- Stephan Kolitz
- Peter Scheidler
- Charles Strauss

EPOS 4.0 System Architecture



- **USAF Joint Army Air Force Weather Information Network (JAAWIN) data used for cloud state estimates and forecasts**

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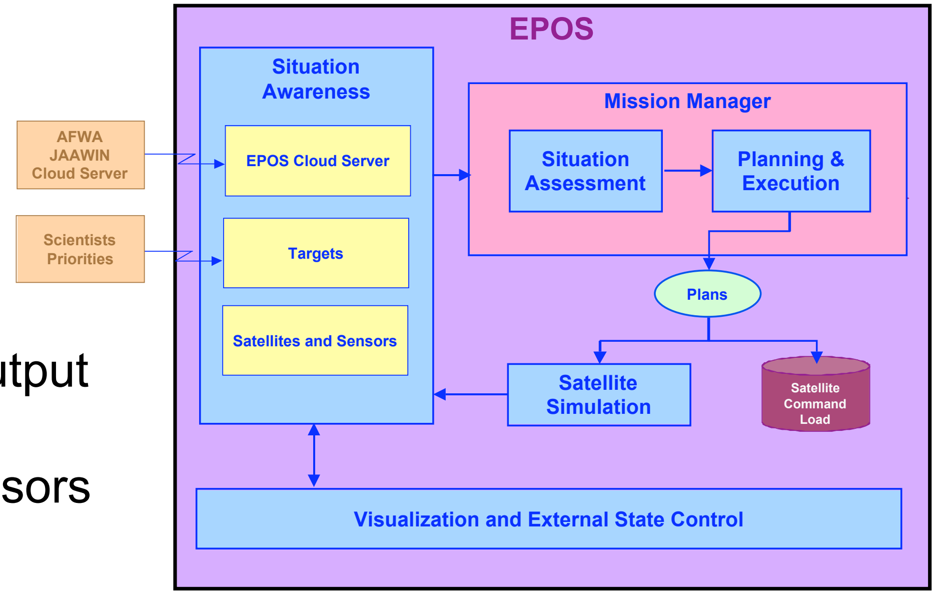
Current Year Concept of Operations

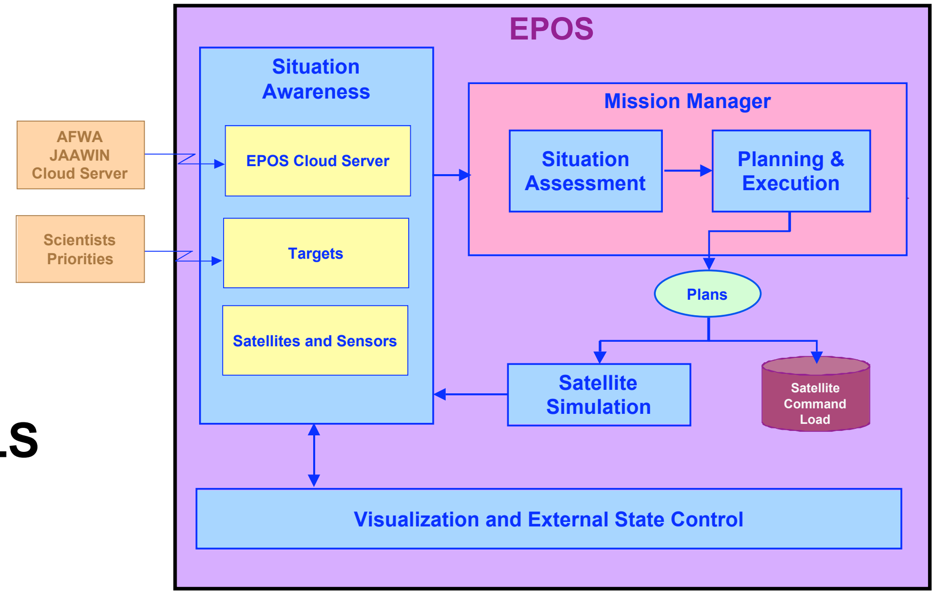
Single Sensor Dynamic Tasking – e.g., TES, HIRDLS



- **Inputs**
  - Scientists' prioritized requests
  - JAAWIN forecasts of cloud coverage
- **Situation Awareness**
  - Target, satellite and sensor model output fused with cloud forecasts to provide LOS/FOV value functions for the sensors
- **Situation Assessment**
  - Instigates either time-based or event-based replanning appropriately
- **Planning / replanning**
  - Optimization-based planning to maximize total science value gained from observations, e.g., cloud-free LOS/FOV to air column over volcanoes, urban areas, forest fires
  - Execution is performed by creating appropriate sensor commands with sufficient lead time for uploading

Progress Summary

- **Implemented access to JAAWIN cloud data**
  - Current estimate
  - Forecasts



- **Developed and implemented HIRDLS and TES models**

- **Situation assessment**
  - Translated JAAWIN cloud data into use in EPOS Cloud Server for both off-nadir pointing and limb sounding
  - Projects sensor LOS/FOV to targets through EPOS cloud model

- **Developed a formulation and initial implementation of an optimization-based planning and execution approach**

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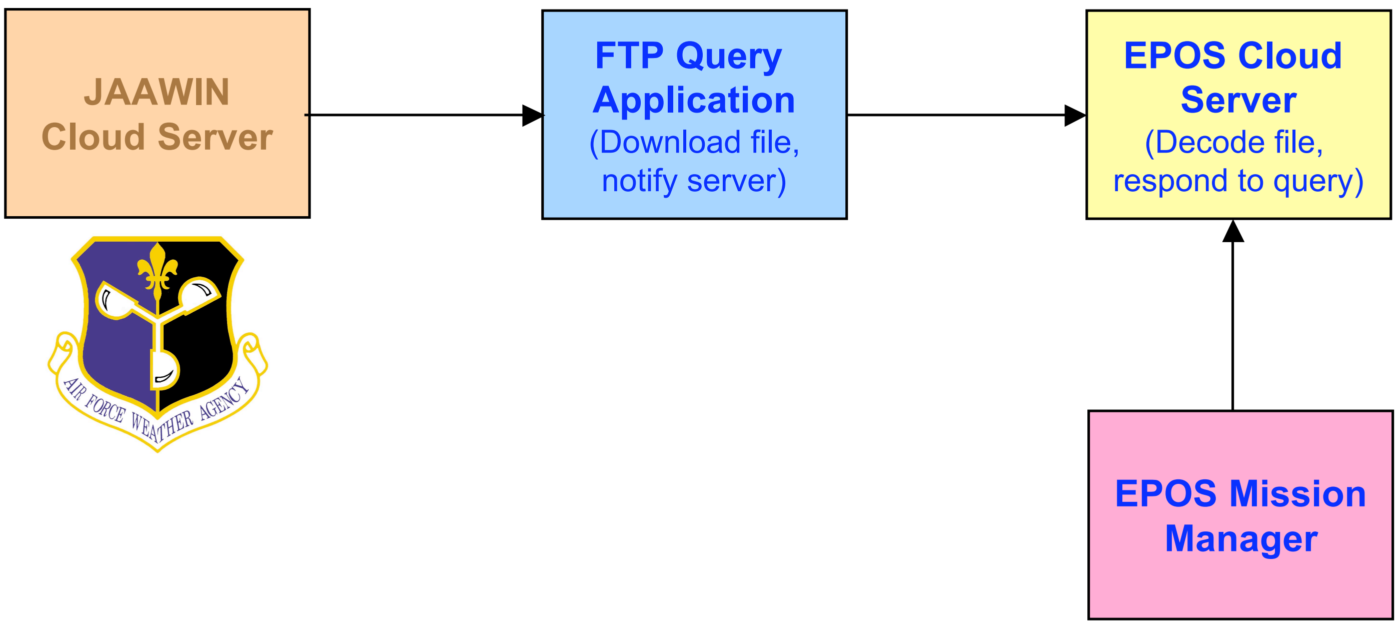
JAAWIN Cloud Data

Joint Army Air Force Weather Information Network



JAAWIN Products

- **World Wide Merged Cloud Analysis**
  - Generated hourly by the Cloud Depiction and Forecast System II (CDFS II)
  - Cloud coverage derived from analysis of five geosynchronous and four polar orbiting satellite data sets

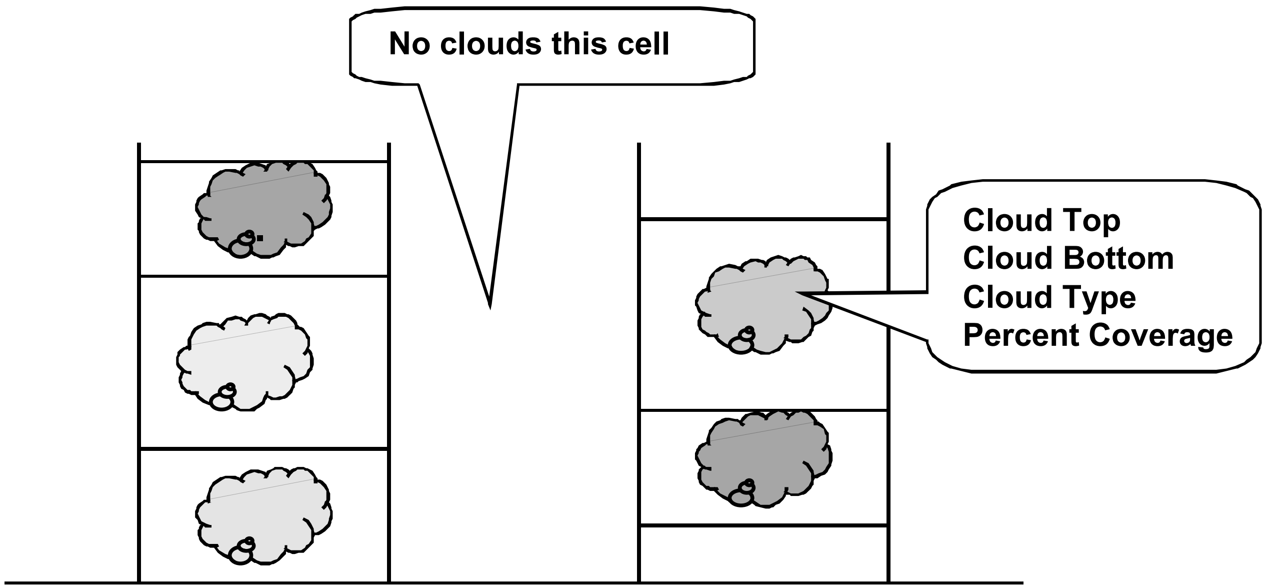
- **Forecasts**
  - Generated every six hours
  - Hourly for 30 hours

- **Data includes**
  - Total cloud cover
  - Up to four layers of cloud information
    - **Percent coverage, cloud type, cloud top, cloud base**

JAAWIN Cloud Data

- GRIB – Gridded Binary (meteorology format)
- Data is presented compressed in a polar stereographic grid
- One 1024 by 1024 grid for each hemisphere
- Each grid point ~24 km on a side (60° latitude)
- Files are ~22 mb each and download from the JAAWIN web site in 4 minutes using half a T1 line.

Side view of
3 grid cells



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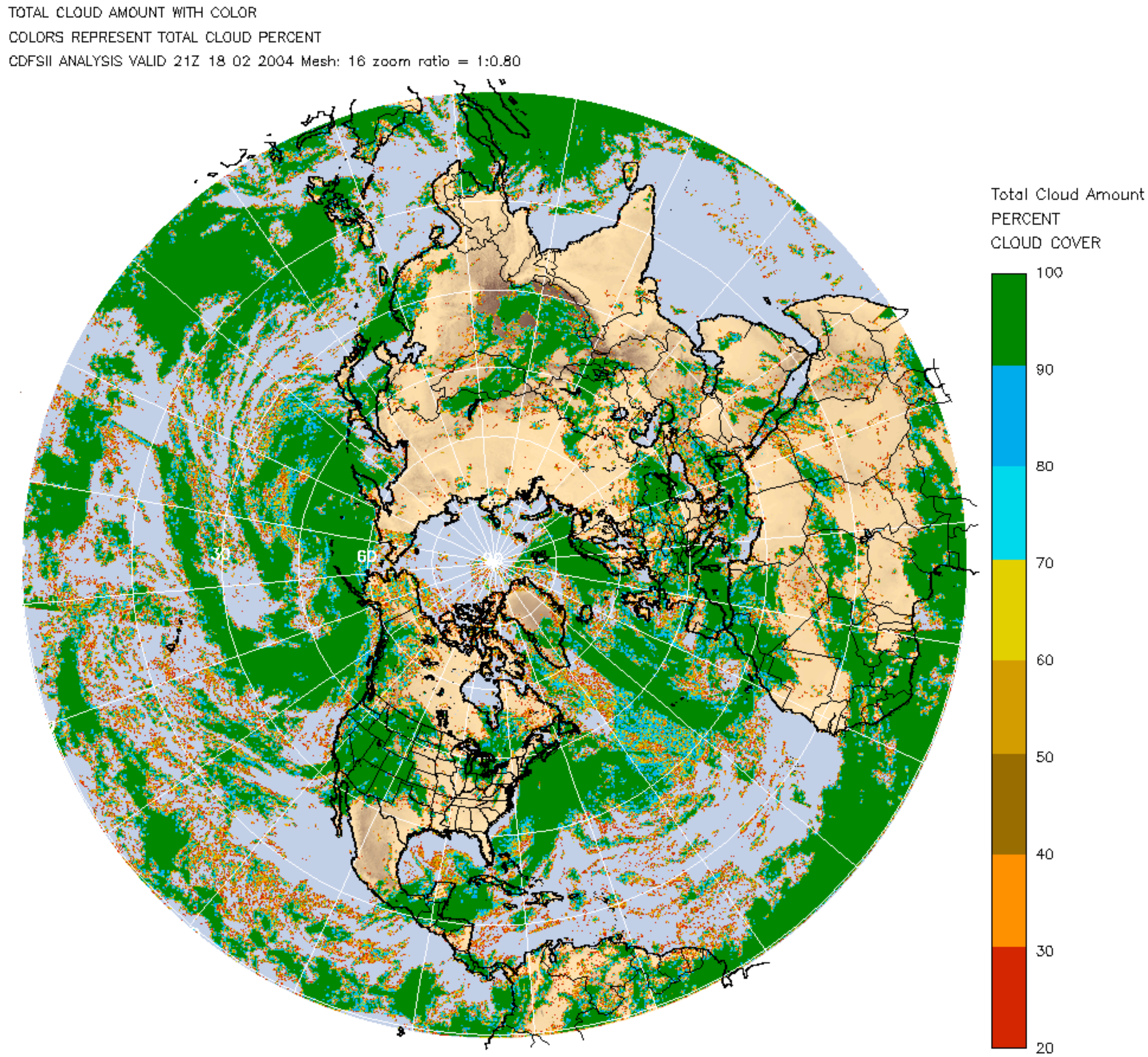
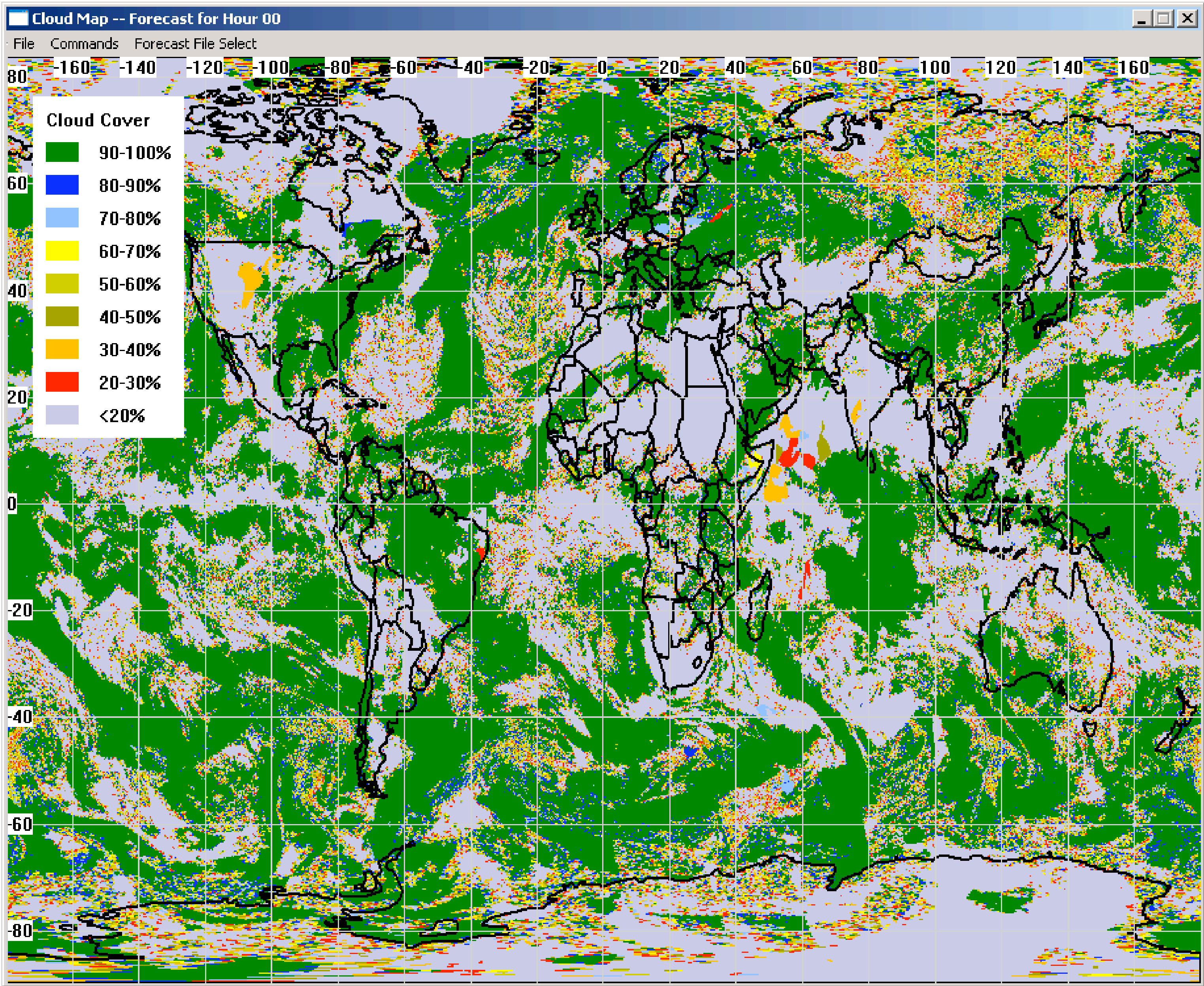
Visualized JAAWIN Cloud Data



Latitude/Longitude View of Cloud Data



Sensor Modeling

- **For selected EOS sensors (HIRDLS, TES,…)**
  - Develop realistic software model of line of sight and field of view
  - Account for
    - **Satellite motion**
    - **Sensor mode + any commandable parameters**
    - **Time mode is initiated**

- **Optimized sensor tasking**
  - Assumption: cloud density along LOS/FOV affects science value
  - Sensor tasking decisions
    - **When should mode transitions occur?**
    - **What values for mode parameters?**
  - Objective is to maximize total science value

HIRDLS Observing Modes

- **Each HIRDLS mode is a fixed scan pattern**
  - Scan patterns are modeled by sequences of azimuth and elevation
- **Global Observing Mode**
  - 6 vertical scans, at azimuths which correspond to 5 deg separation in the cross-track direction
  - Each vertical scan covers about 3 deg of elevation and takes approximately 10 seconds
  - Inflight calibration is included in the scan
  - Each instance requires approximately 66 seconds total
- **Alternative Global Observing Mode, Fine Horizontal Spacing Modes, Gravity Wave Mode, …**
  - Each is programmed as a fixed scan in azimuth and elevation
- **Selected Targets Mode**
  - Elevation scan over a fixed geographic location (e.g., volcano)

[Source: ATBD-HIR-02, p. 11]

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Primary References: HIRDLS

- HIRDLS: High Resolution Dynamics Limb Sounder, Algorithm Theoretical Basis Document, ATBD-HIR-01/SW-HIR-168, 10/4/1999, http://www.atm.ox.ac.uk/user/wells/atbd.html

- High Resolution Dynamics Limb Sounder, Level-2 Algorithm Theoretical Basis Document, A. Lambert et. al., ATBD-HIR-02, 10/2/1999 http://eospso.gsfc.nasa.gov/eos_homepage/for_scientists/atbd/viewInstrument.php?instrument=HIRDLS

- [Title unknown, document not yet received: SP-HIR-198]
  - "A more comprehensive set of profiles, and the way in which they have been derived, will be found in SP-HIR-198." (from ATBD-HIR-01, p. 6)

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Functional Description of HIRDLS Model

Inputs:

- Time & Date
- S/C ephemeris
- mode
- Time at start of mode
- Scan table for mode

Model:

- Compute spacecraft ECI position and velocity
- Compute ECI coordinates of nominal spacecraft body frame
  - z-axis points to nadir
  - y-axis along the negative of orbital angular momentum
  - x-axis along cross product of y and z (approx velocity)
- Compute HIRDLS azimuth and elevation angles
  - linear interpolation in scan table for current mode
- Construct transformation matrix from body frame to HIRDLS view frame
  - rotation about z-axis through azimuth followed by rotation about y-axis through elevation
- Construct ECI unit vector in direction of geometric LOS
  - Using transformation matrices
- Compute geodetic coordinates of LOS tangent point

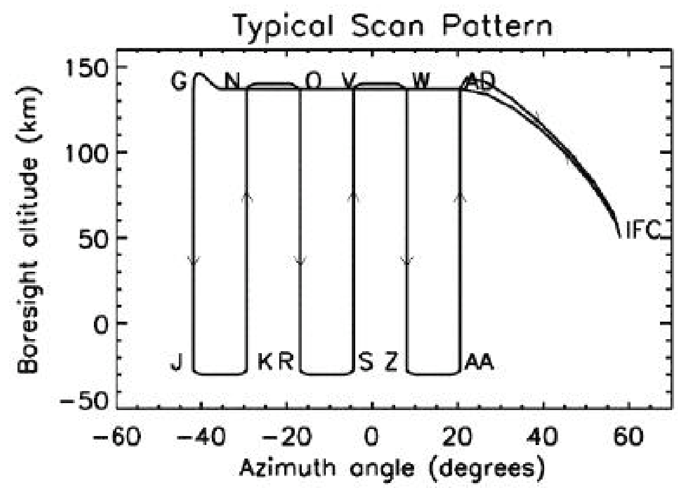
Outputs:

- Instrument LOS
- Latitude, longitude, altitude of tangent point

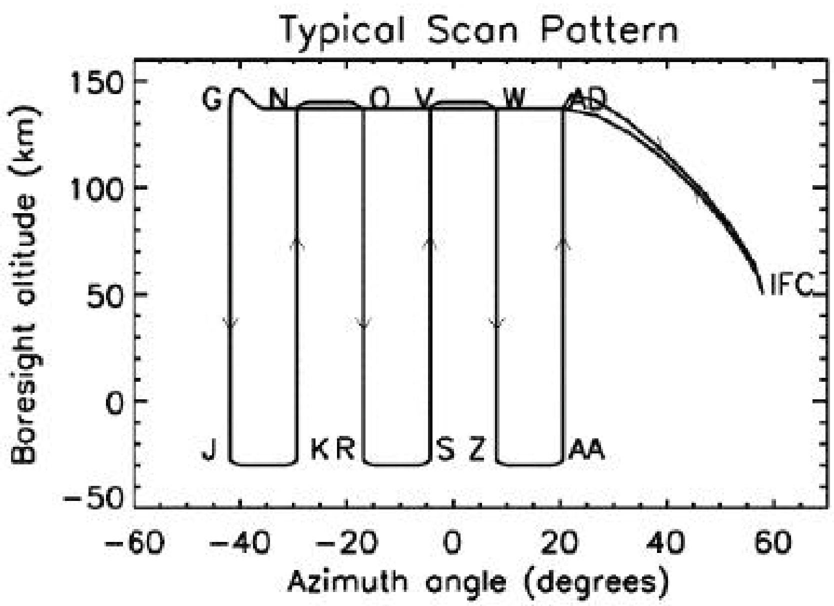
HIRDLS: A Representative Mode

Taken from ATBD-HIR-01, pp. 6-7

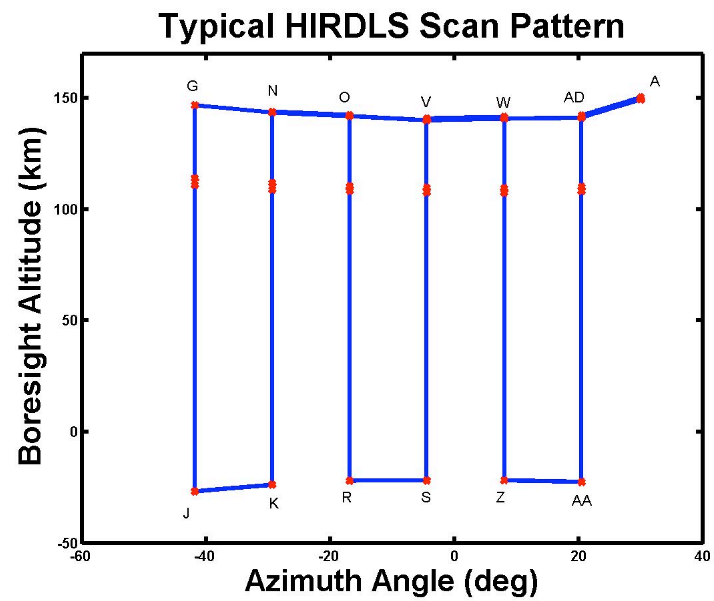
	Elevation shaft angle (deg) Low	Nominal	High	Azimuth shaft angle (deg)	Time (s)	Tangent point height (km)	
A	TBD	TBD	TBD	TBD	0.00	N/A	Start at IFC view
B	-1.64	-1.11	-0.53	10.25	1.87	137.0	Azimuth scan at space
C	-1.62	-1.10	-0.52	4.02	2.16	137.0	view elevation
D	-1.61	-1.09	-0.52	-2.21	2.44	137.0	
E	-1.63	-1.11	-0.53	-8.44	2.79	137.0	
F	-1.67	-1.13	-0.54	-14.67	3.23	137.0	
G	-1.72	-1.17	-0.56	-20.90	4.31	137.0	Elevation scan 1 (down)
H	-1.37	-0.83	-0.23	-20.90	5.31	105.4	
I	-1.34	-0.80	-0.20	-20.90	5.41	103.0	
J	0.03	0.53	1.09	-20.90	13.15	-27.0	
K	0.03	0.51	1.05	-14.67	14.15	-27.0	Elevation scan 2 (up)
L	-1.30	-0.77	-0.20	-14.67	21.89	103.0	
M	-1.32	-0.80	-0.22	-14.67	21.99	105.4	
N	-1.67	-1.13	-0.54	-14.67	23.00	137.0	
O	-1.63	-1.11	-0.53	-8.44	23.99	137.0	Elevation scan 3 (down)
P	-1.29	-0.78	-0.21	-8.44	24.99	105.4	
Q	-1.27	-0.76	-0.19	-8.44	25.09	103.0	
R	0.03	0.50	1.03	-8.44	32.83	-27.0	
S	0.03	0.50	1.01	-2.21	33.83	-27.0	Elevation scan 4 (up)
T	-1.25	-0.75	-0.19	-2.21	41.57	103.0	
U	-1.28	-0.77	-0.21	-2.21	41.67	105.4	
V	-1.61	-1.09	-0.52	-2.21	42.67	137.0	
W	-1.62	-1.10	-0.52	4.02	43.67	137.0	Elevation scan 5 (down)
X	-1.28	-0.77	-0.21	4.02	44.67	105.4	
Y	-1.26	-0.75	-0.19	4.02	44.77	103.0	
Z	0.03	0.50	1.02	4.02	52.51	-27.0	
AA	0.03	0.50	1.03	10.25	53.51	-27.0	Elevation scan 6 (up)
AB	-1.27	-0.76	-0.19	10.25	61.24	103.0	
AC	-1.30	-0.78	-0.22	10.25	61.34	105.4	
AD	-1.64	-1.11	-0.53	10.25	62.34	137.0	
AE	TBD	TBD	TBD	TBD	64.78	N/A	Dwell at IFC view
A	TBD	TBD	TBD	TBD	65.28	N/A	



HIRDLS Model Comparison

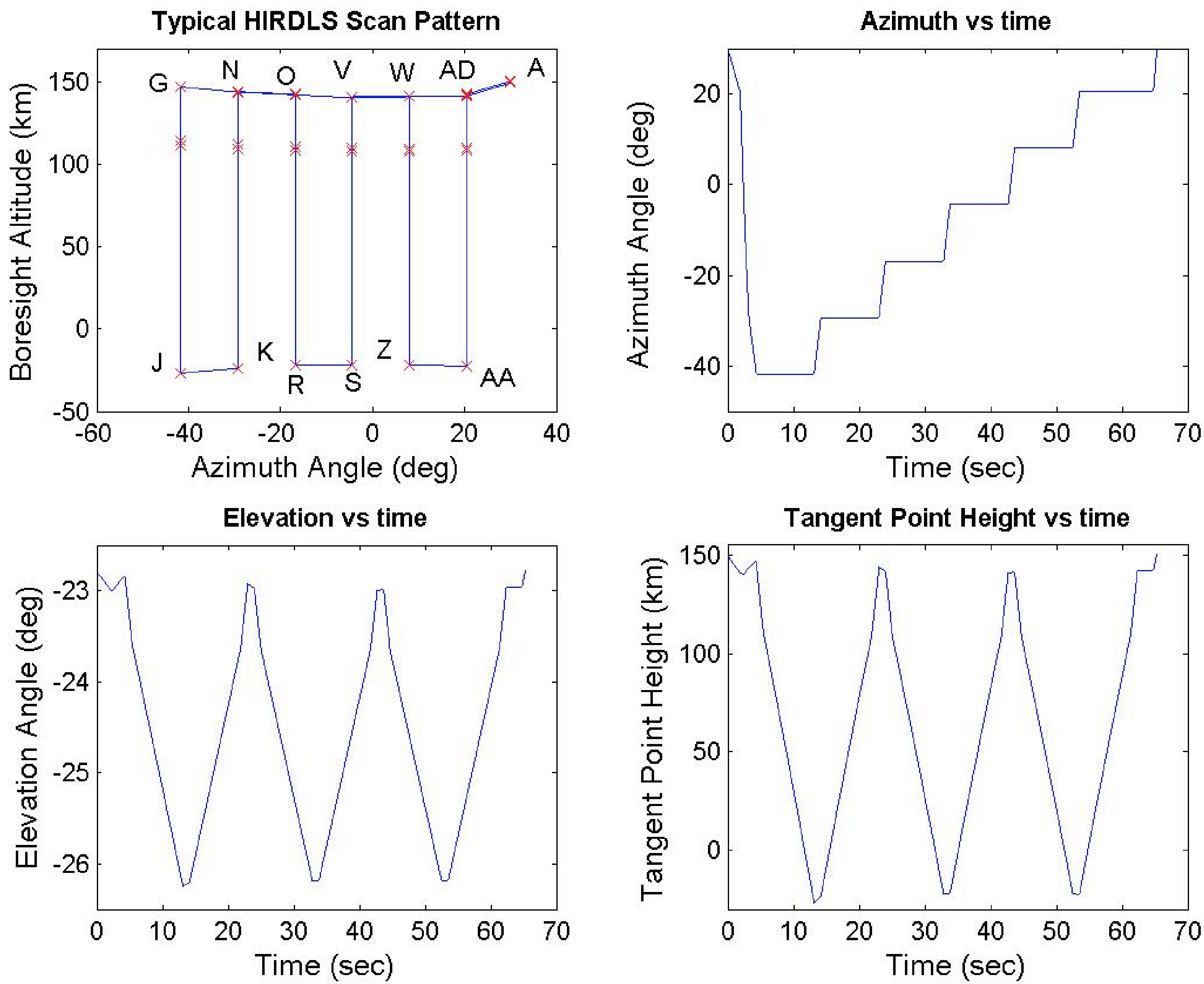


Taken from ATBD-HIR-01, pp. 6-7



Generated by HIRDLS model (MATLAB)

HIRDLS Model Results



TES Observing Modes

- **TES operates in two primary modes**
  - Global Survey Mode
    - **Generates TES standard products.**
    - **Makes continuous sets of nadir and limb observations (plus calibrations) on a 1-day-on, 1-day-off cycle (16 orbits each)**
  - Special Observation Modes
    - **During the "off" days, TES is not actually powered down. These are the times for making extensive calibrations and for the Special Product modes**
      - **E.g., observations of volcanoes, biomass burning, pollution events, and intercomparisons**
    - **Sensor is pointable in this mode within 45° of nadir (cross-track and in-track)**
    - **Almost everywhere on Earth can be reached some time during a 16 day interval**

TES Global Survey Mode

[Source: Beer et. al., Applied Optics 40(15), 20 May 2001, p. 2364]

- **TES obtains its data using sequences of 2 nadir observations (4 sec each), 3 limb observations (16 sec each), and 3 calibration periods (4 sec each)**
  - Each sequence requires 81.2 seconds (including slews)
  - Basic sequence is repeated continuously for 16 orbits
- **The pairs of nadir observations in each sequence are co-located and the limb observations correspond geographically to nadir observations made 437 seconds earlier**
  - This data will be combined into ‘observation sets’ containing collocated limb and nadir observations
  - Each observation set will then be analyzed as a unit [ATBD-TES-01, p. 5]

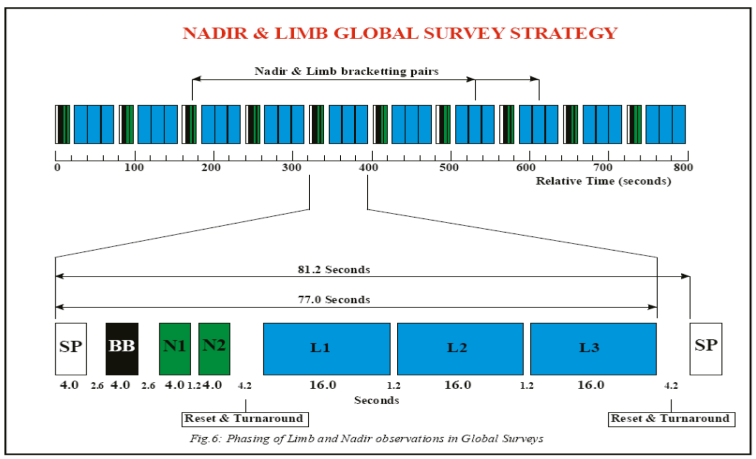


Fig.6: Phasing of Limb and Nadir observations in Global Surveys

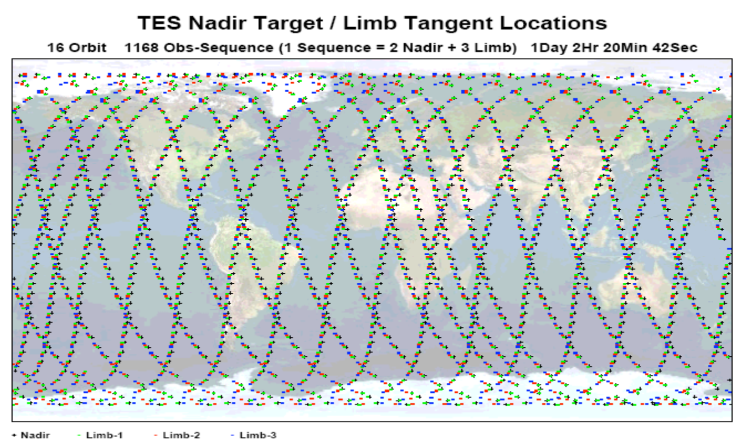


Figure 1-1. TES ground locations of nadir ground targets and limb tangents for a global survey period of 16 orbits.

Primary References: TES

- **Tropospheric emission spectrometer for the Earth Observing System's Aura satellite, R. Beer, T. Glavich, D. Rider, Applied Optics vol. 40, no. 15, 5/20/2001, pp. 2356-2367.**

- **Tropospheric Emission Spectrometer (TES) Level 1B Algorithm Theoretical Basis Document, version 1.1, H. Worden, K. Bowman, ATBD-TES-01/JPL D-16479, 9/30/1999,**
  http://eospso.gsfc.nasa.gov/eos_homepage/for_scientists/atbd/viewInstrument.php?instrument=TES

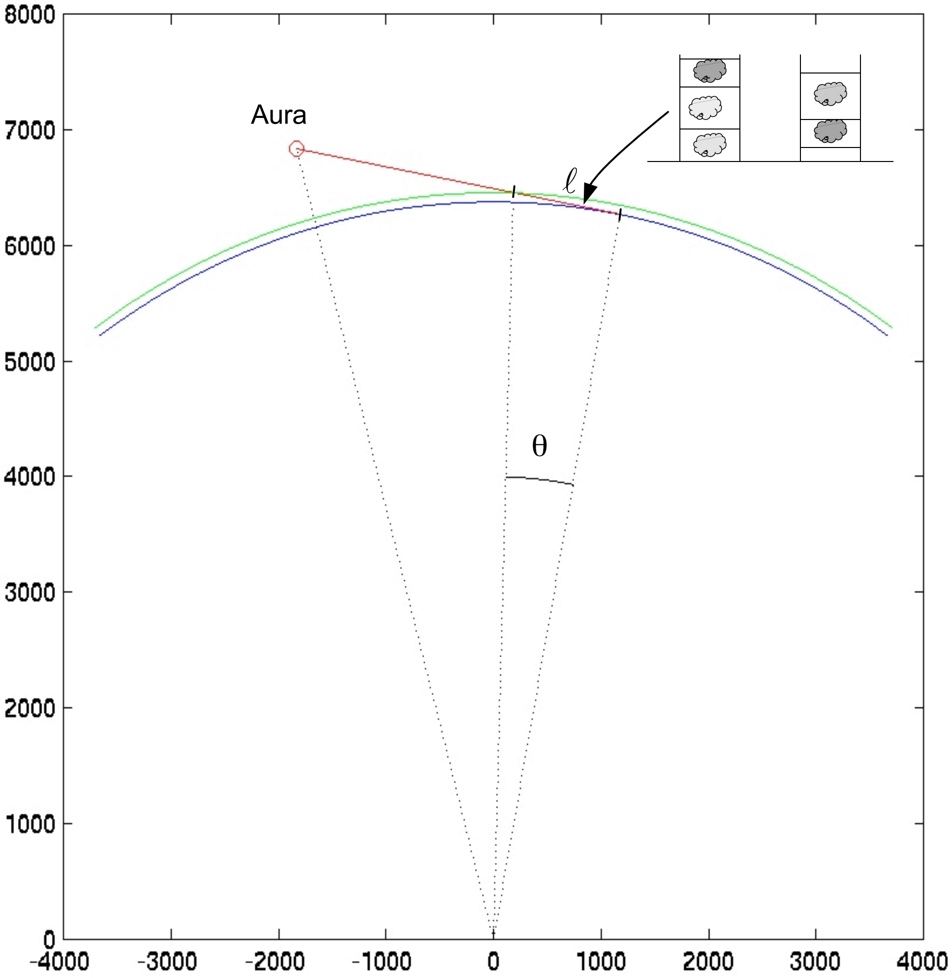
- **Tropospheric Emission Spectrometer (TES) Level 2 Algorithm Theoretical Basis Document, R. Beer et. al., ATBD-TES-02/JPL D-16474, 10/1/1999**
  http://eospso.gsfc.nasa.gov/eos_homepage/for_scientists/atbd/viewInstrument.php?instrument=TES

TES LOS Modeling

- **Model TES global survey as a scan in latitude and longitude**
  - Consistent with planned operations
    - **Global surveys are triggered by the time of crossing of the Southern Apex, so observations are made at the same latitudes during each orbit**
  - TES observation planning combines techniques used in EPOS 3.0 and those being developed currently
    - **Select special observation mode (with specified target)**
    - **Or default to global survey mode (with its default targets)**

Limb Sounding Through Clouds

View of Limb through Atmosphere



h = height of cloud layers ≤ 20 km

r_e = earth radius = 6378 km

$$\cos\theta = \frac{r_e}{r_e + h}$$

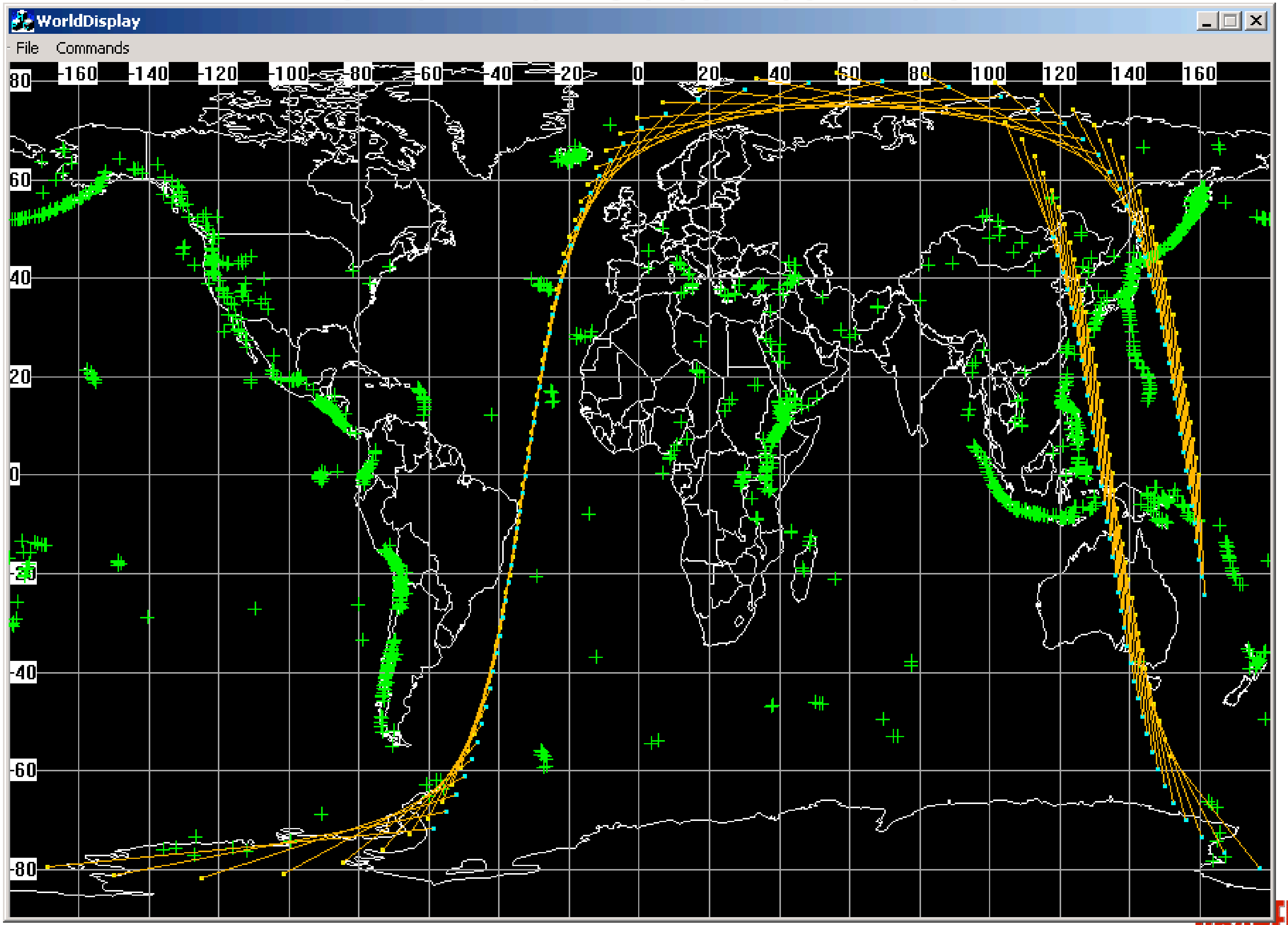
$$1 - \theta^2 \approx 1 - \frac{h}{r_e}$$

$$\theta \approx \sqrt{\frac{h}{r_e}}$$

$$\ell \approx r_e\theta \approx \sqrt{hr_e} \approx 350\text{ km}$$

number of cloud cells LOS goes through at 60º latitude ≈ 350/24 ≈ 15

World with Satellite Track



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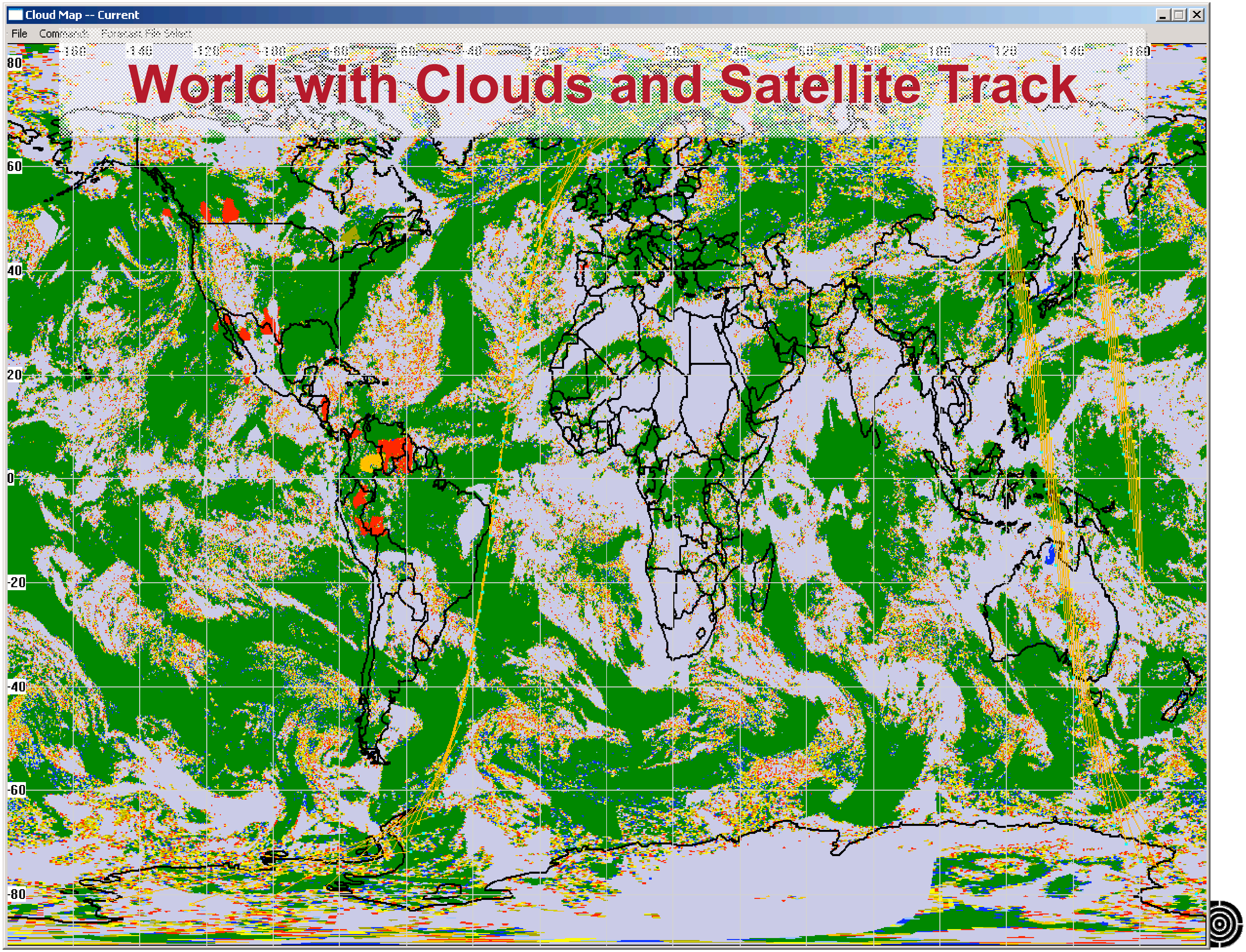
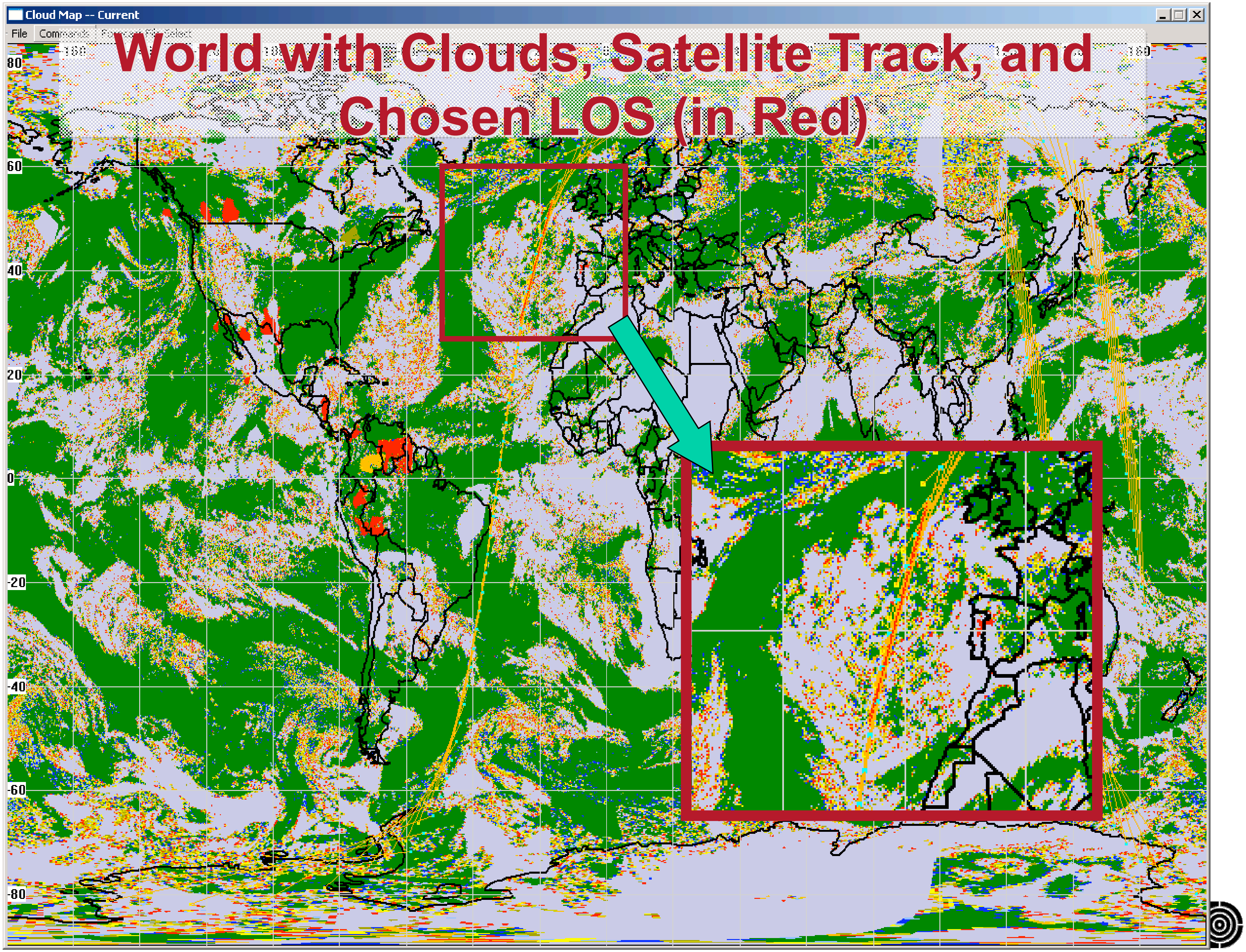
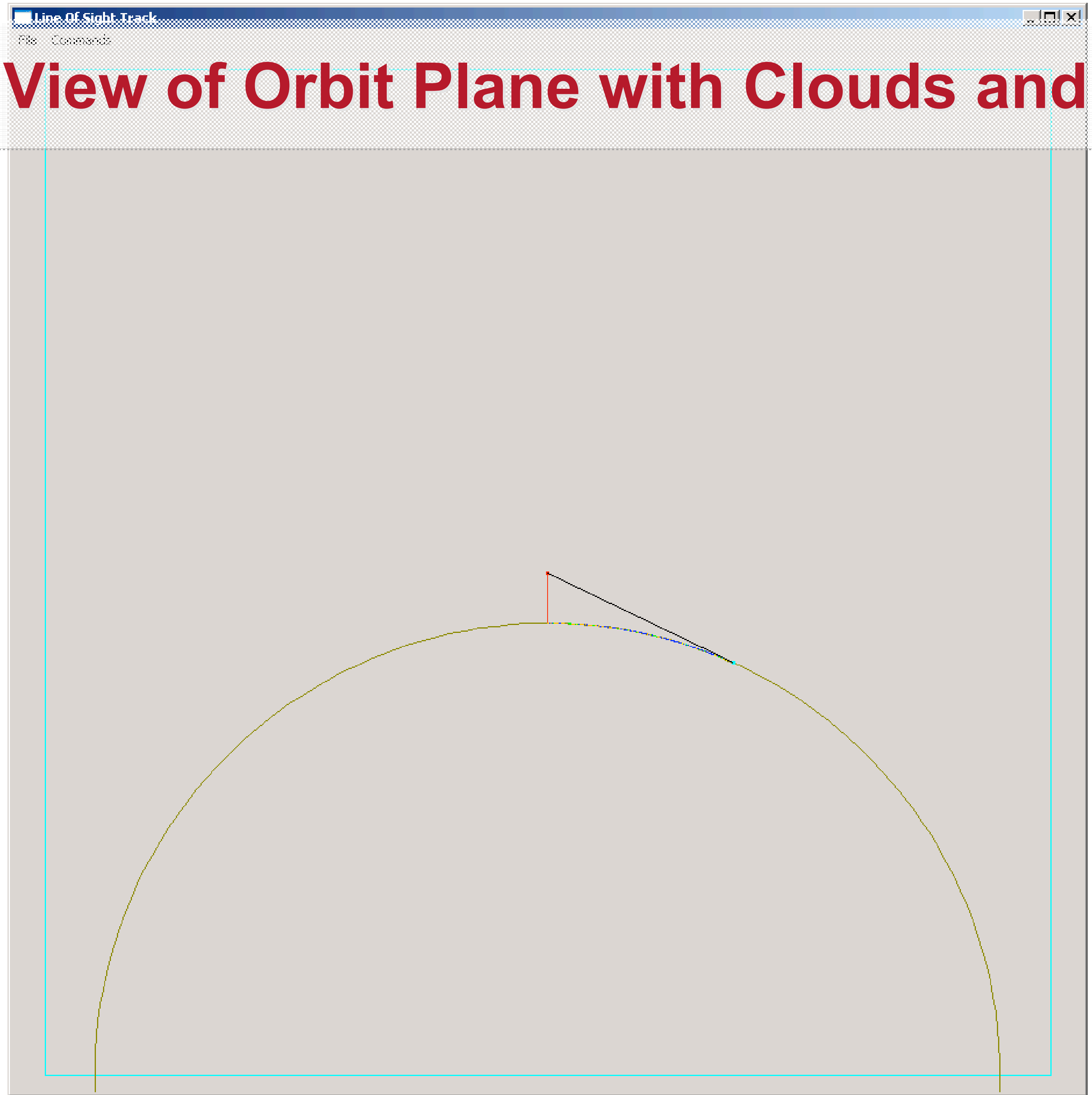
World with Clouds and Satellite Track



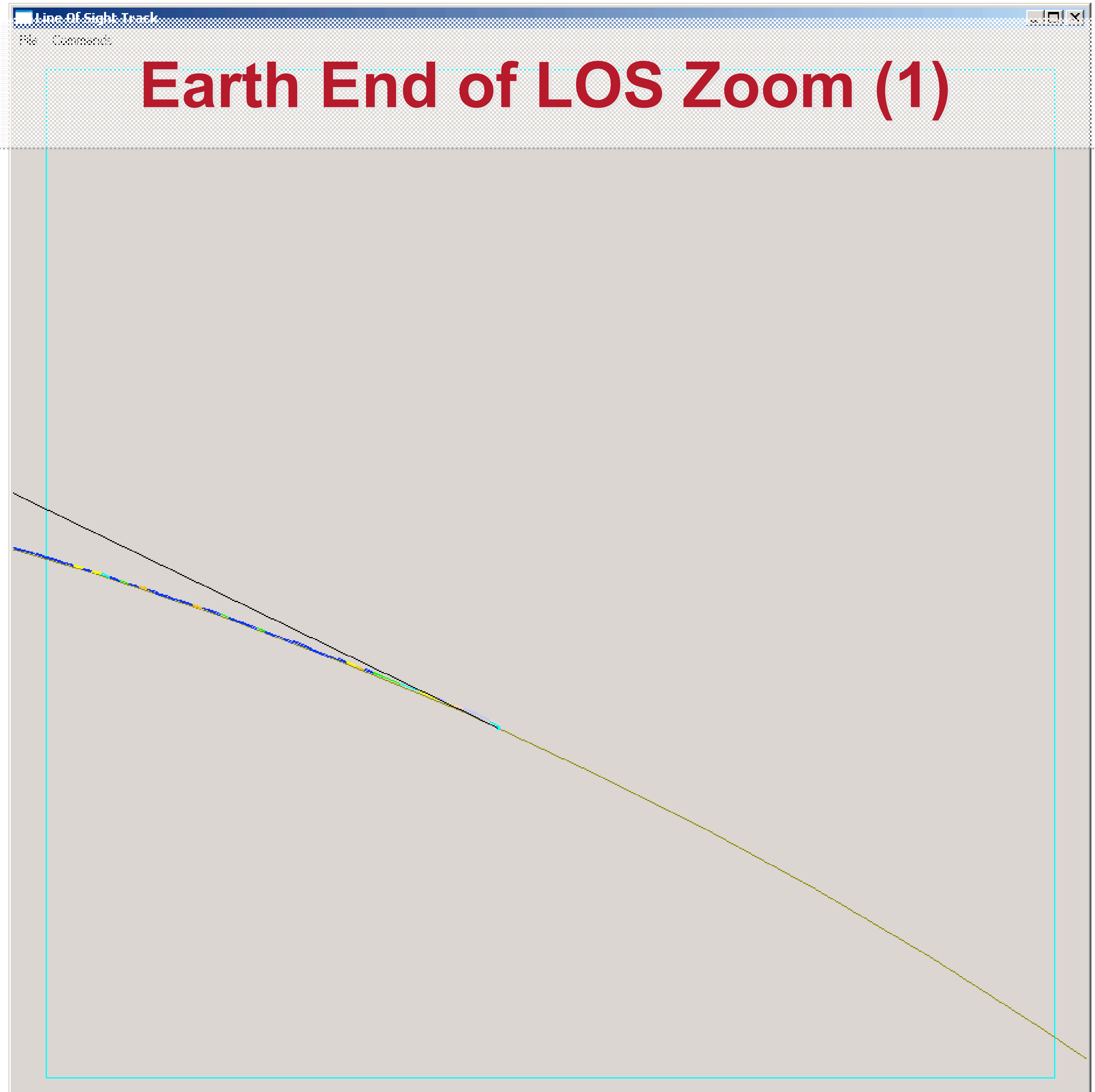
World with Clouds, Satellite Track, and Chosen LOS (in Red)



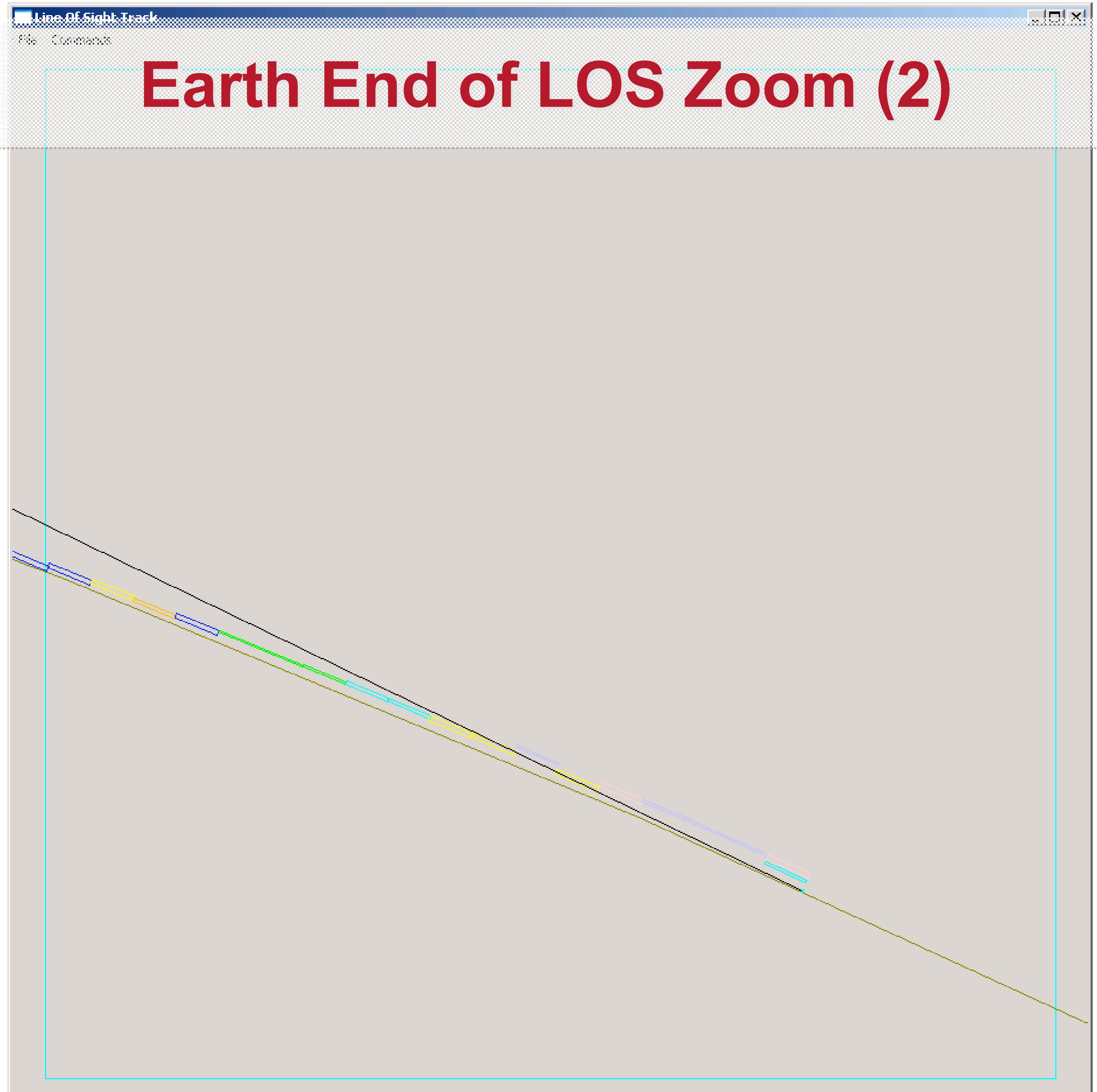
Side View of Orbit Plane with Clouds and LOS



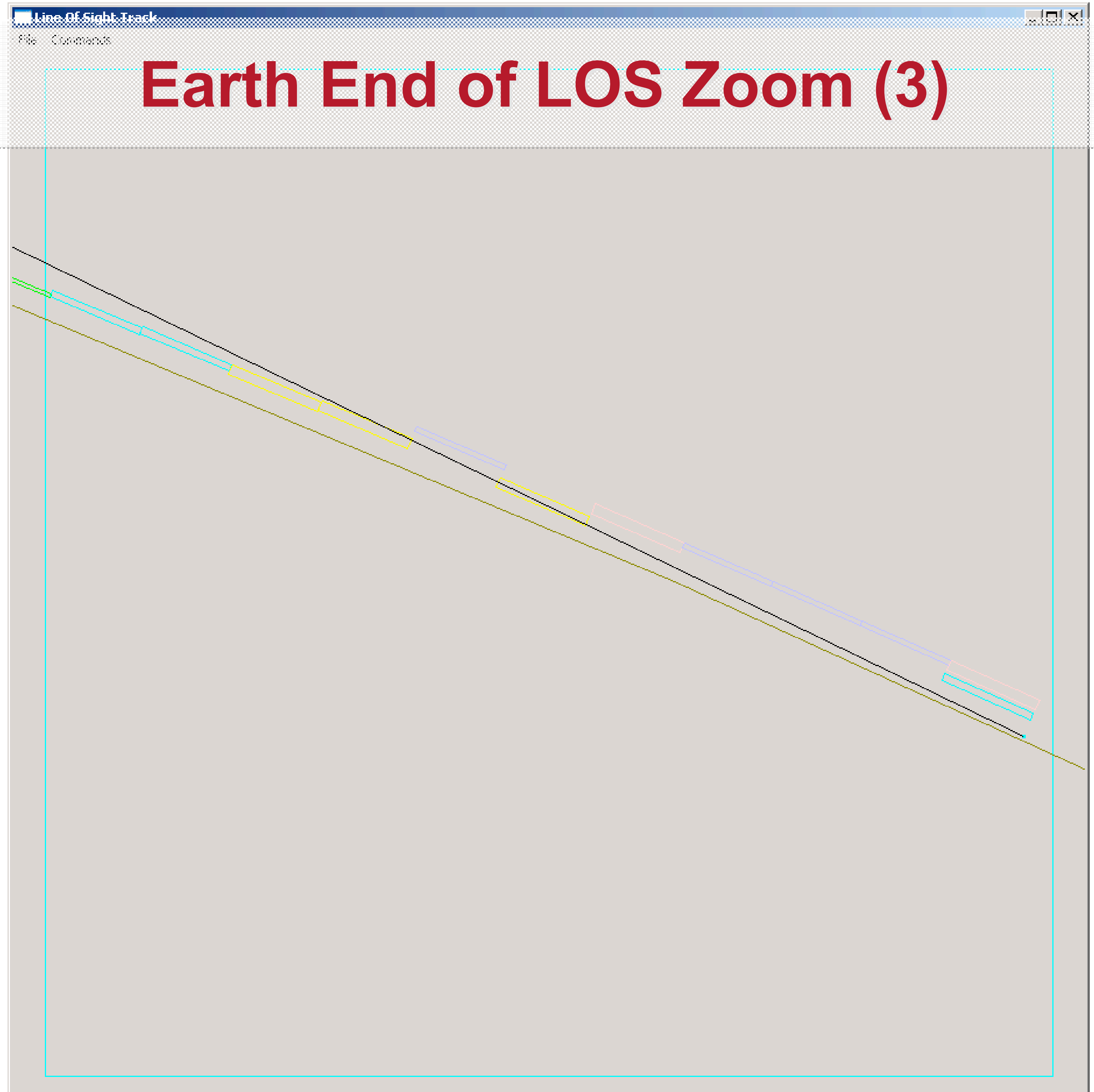
Earth End of LOS Zoom (1)



Earth End of LOS Zoom (2)



Earth End of LOS Zoom (3)



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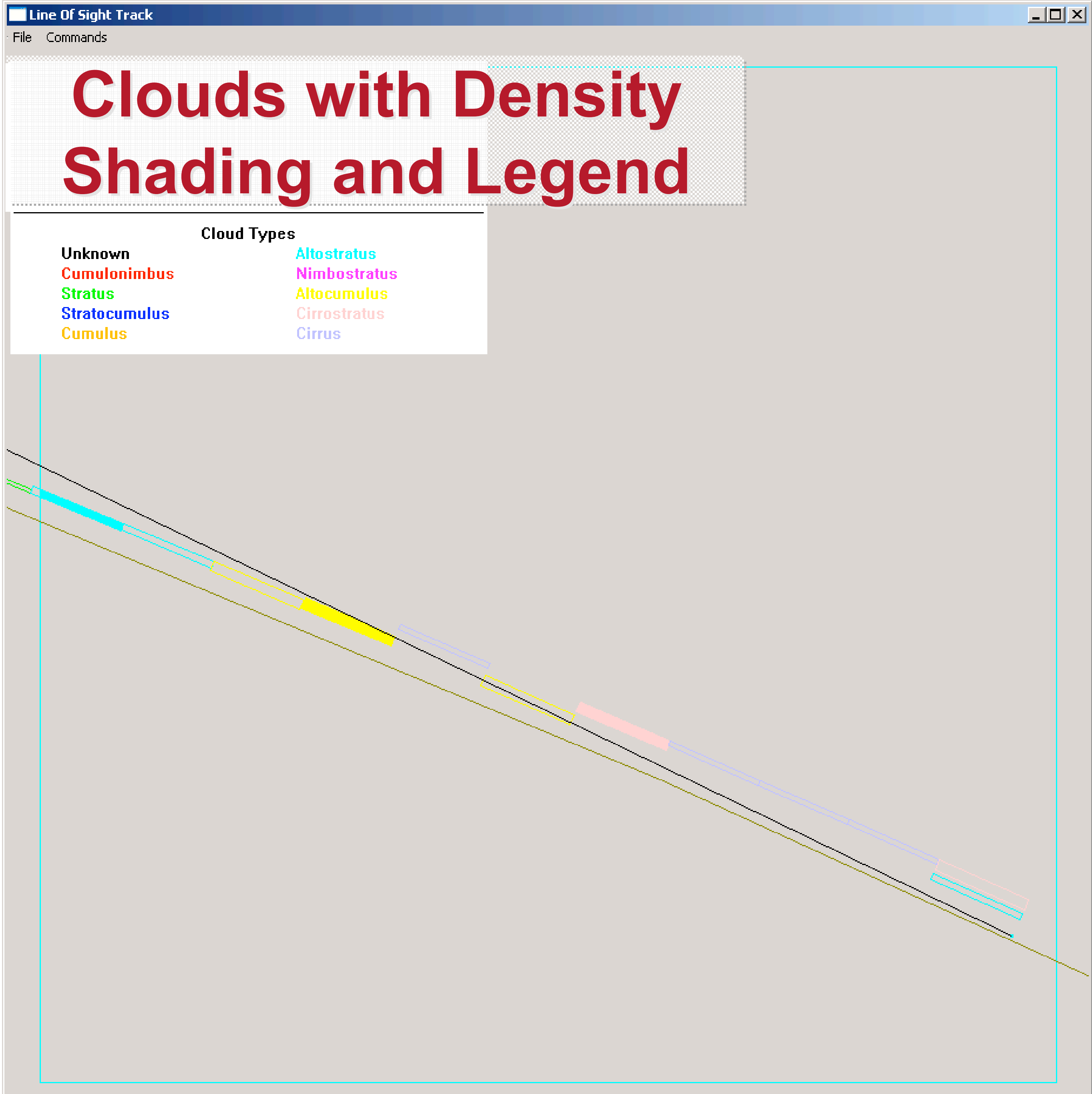
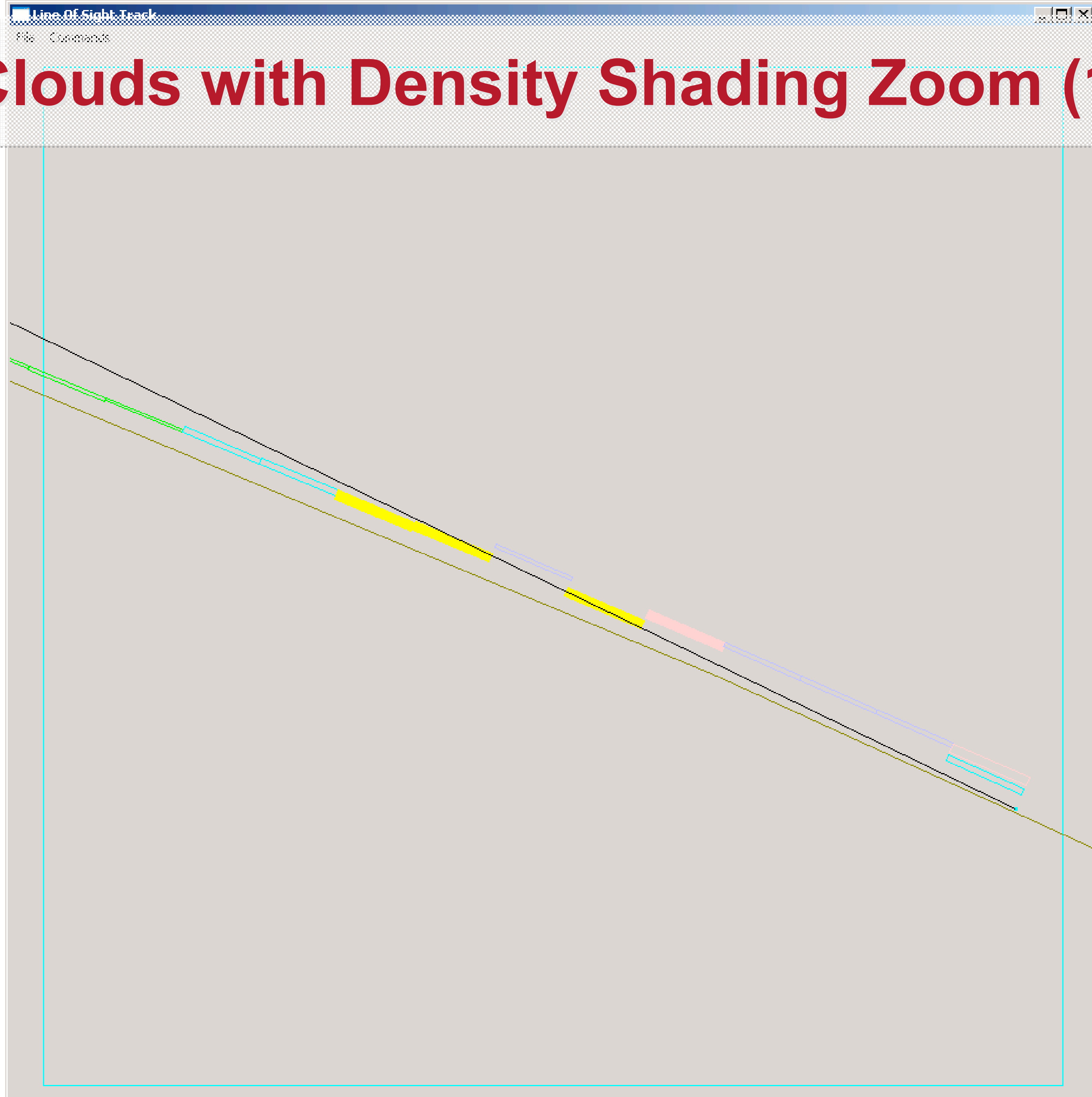
Clouds with Density Shading and Legend

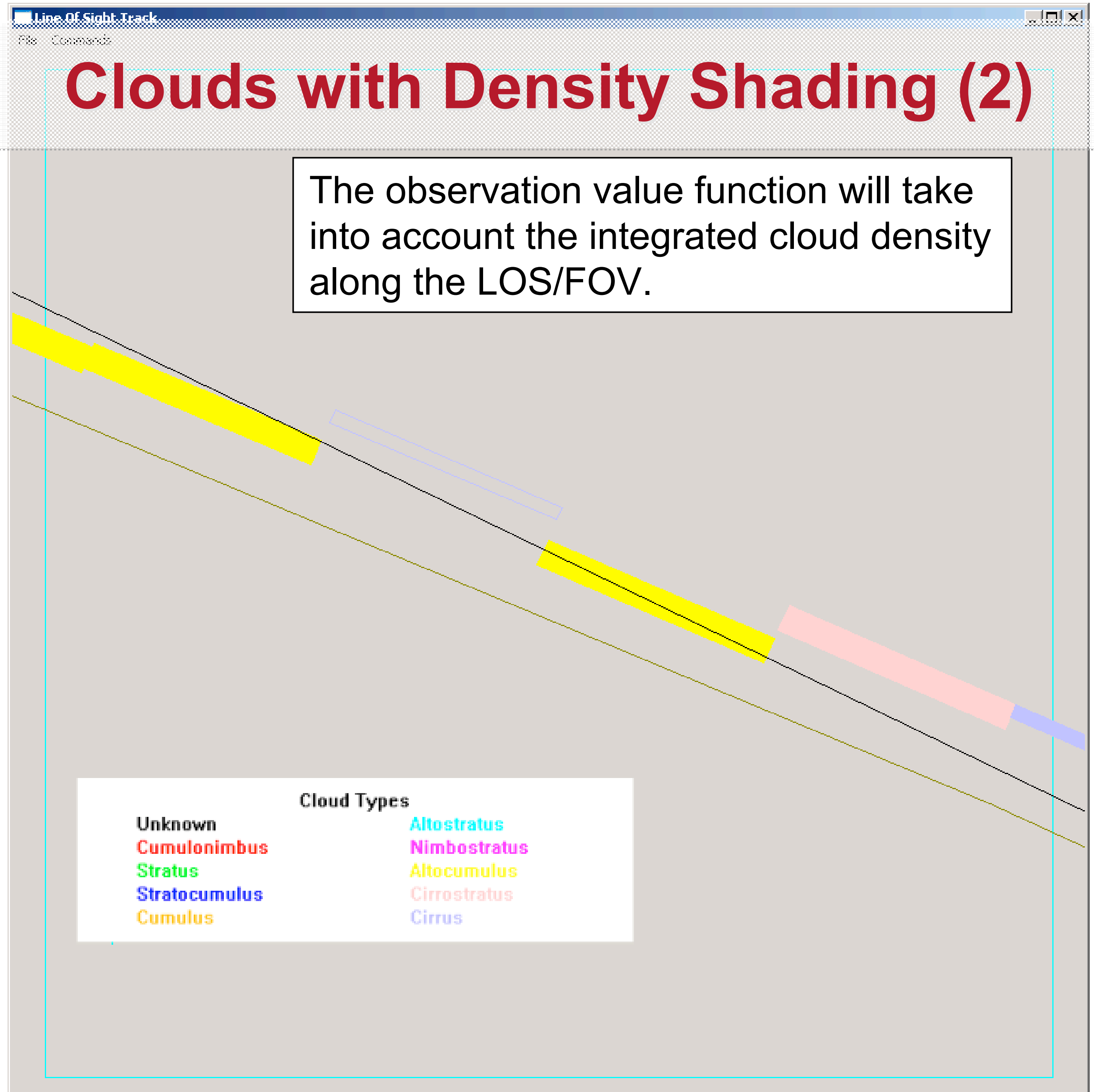


Clouds with Density Shading Zoom (1)



Clouds with Density Shading (2)

The observation value function will take into account the integrated cloud density along the LOS/FOV.



Future Work

Develop an Observation Plan for EO-1

- **EO-1 follows within 1 minute of Landsat-7**
- **Instrument of interest is Hyperion**
  – Hyperspectral imager
- **In discussions with EO-1 mission operators**
  – Use EPOS to select targets for Hyperion to observe
  – Can use Landsat-7 observations to simulate correlative observations

Virtual Observatory

- **Generalization of single-sensor scenario**
- **Generalization with respect to inputs**
  - Science requests come in to the system as a *whole*, with many sensor resources at its disposal, *not* for a particular sensor
  - Requests are for *data products*, *not* specific sensor output
  - Must consider constraints on operational modes of *all relevant satellite* resources over planning period
- **Generalization with respect to planning and replanning – two possible modes**
  - EPOS used to provide schedule and “quality” (cloud state of observed targets) of available data products – no sensor retasking
  - EPOS used to schedule observations – sensor retasking

Validation / Science Campaign

- **Inputs**
  - Validation / campaign requests are received and prioritized
    - **The prioritized requests are translated into an observation value function over the relevant set of sensors, sets of sensors, times and targets**
  - Constraints on operational modes of all observation resources (including Earth-based) over the planning period are specified
  - Cloud coverage forecasts
- **Planning / replanning**
  - The EPOS mission manager produces a schedule with appropriate multiple sensor observations of targets

Summary

- **Developed concepts of operations for utilizing EPOS**
- **Implemented access to JAAWIN cloud data**
  - Current estimate
  - Forecasts
- **Developed and implemented HIRDLS and TES models**
- **Translated JAAWIN cloud data into use in EPOS Cloud Server for both off-nadir pointing and limb sounding**
- **Discussions on applying EPOS to EO-1 observation planning**