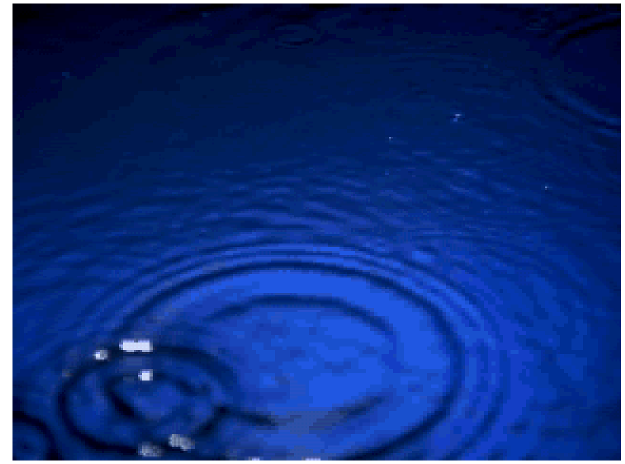
GPM



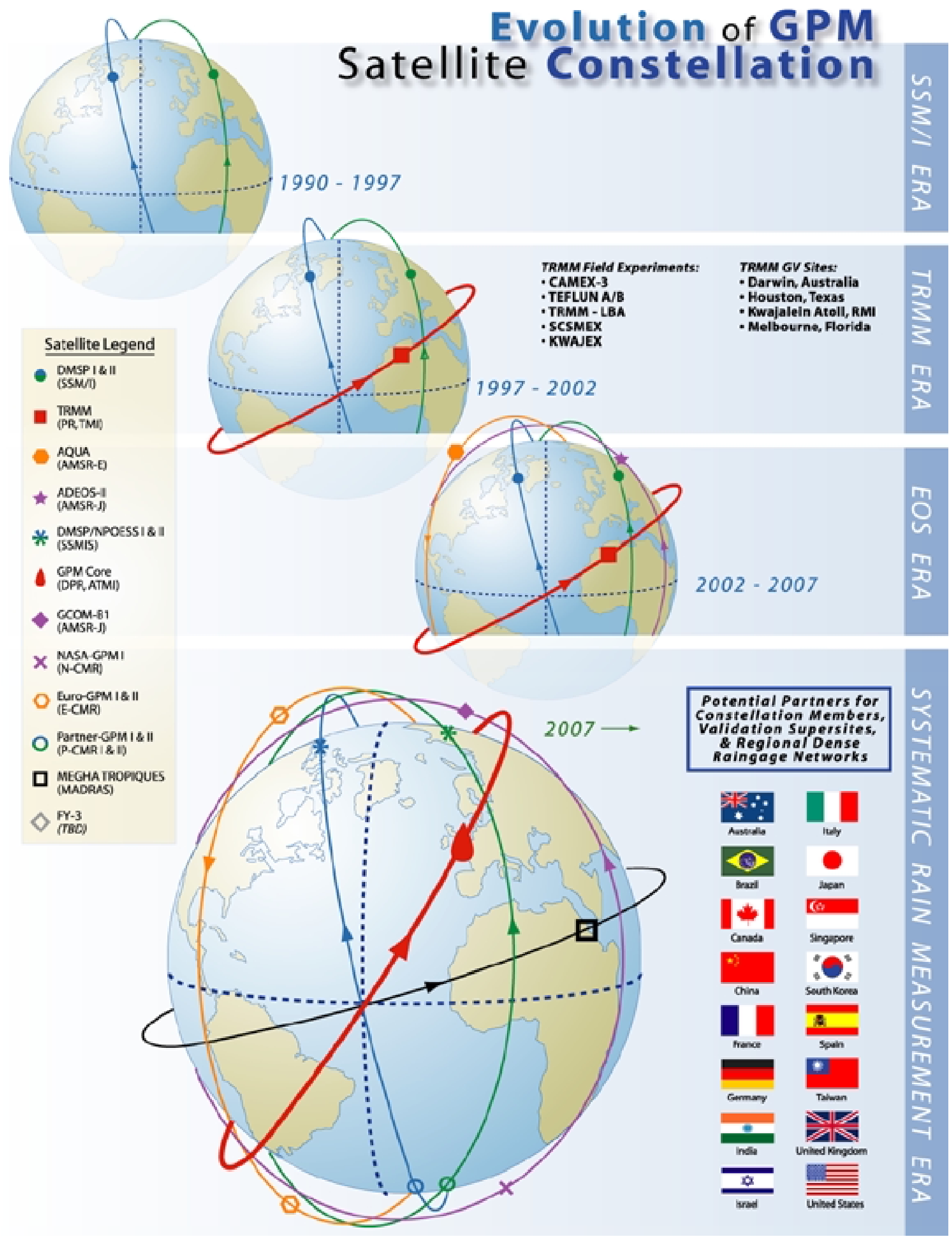
GPM

Global Precipitation Measurement

Satellites, Orbits, and Coverage

May 2001

Dave Everett
Goddard Space Flight Center



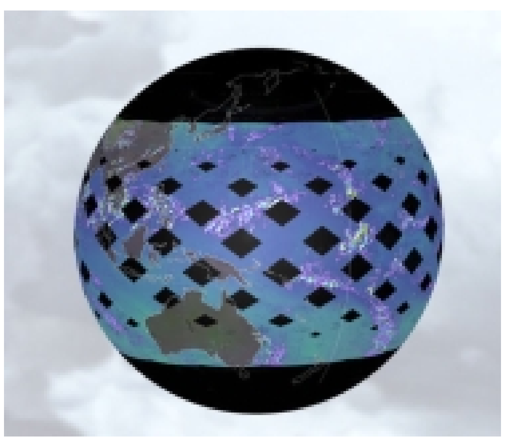
SSM / I Era

TRMM Era

EOS Era

GPM Era

TRMM 1-day coverage



Objectives & Strategy

OBJECTIVES

Provide satellite coverage and sampling strategy to:

(1) reduce uncertainty in short-term rainfall accumulation

(2) resolve main features of diurnal precipitation cycle

(3) improve probability of detection of extreme rain events

- *coverage Region: 90 N to 90 S latitude*
- *goal: 3-hour maximum revisit interval*

STRATEGY

Form rain measuring constellation using Co-op satellites from other programs with suitable passive microwave radiometers & Drone satellites dedicated to GPM mission.

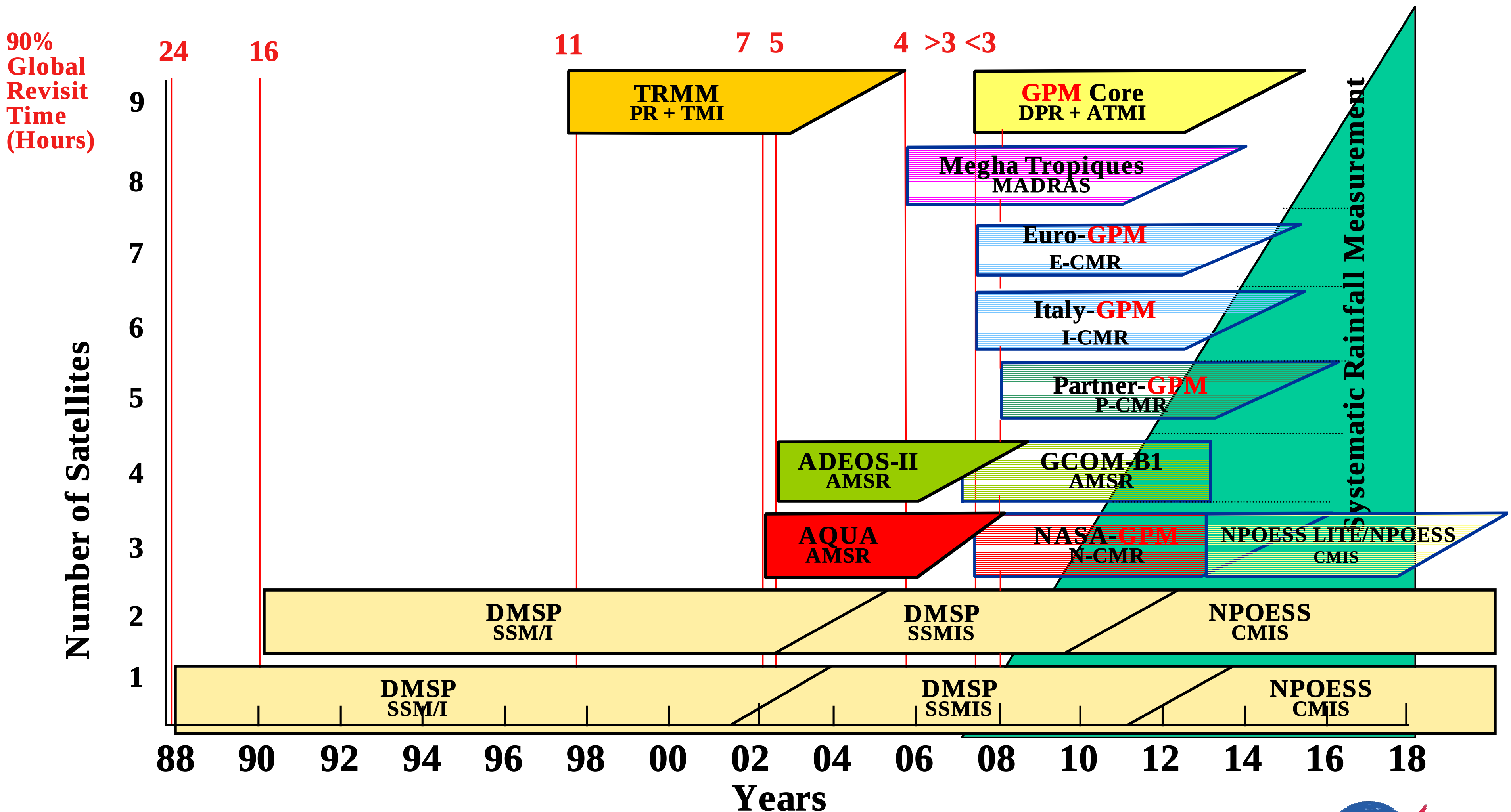
- *Co-op satellites placed in fixed orbits (externally defined to achieve independent program needs)*
- *Drone satellites placed in flexible orbits (internally defined to achieve desired GPM coverage & sampling)*

Coverage, Revisit, & Sampling

- ***COVERAGE*** *refers to portion of spatial region that is viewed during specific time interval*
  - *spatial region may not be 100% covered*
  - *view of same locations within spatial region by multiple satellites does not increase total coverage*
  - *coverage gaps typically are viewed in different time intervals*
- ***REVISIT*** *refers to interval between samples at same location*
  - *revisit intervals can vary considerably*
    - *two satellites can simultaneously view same location*
    - *coverage gaps produce worst-case revisit intervals*
- ***SAMPLING*** *refers to times of viewing*
  - *sampling times require optimization to minimize "aliasing" key diurnal properties*

Coverage, revisit, & sampling characteristics will vary with time & for individual spatial regions

Implementation of International GPM Satellite Constellation



EOS Era Coverage 2002 Time Frame

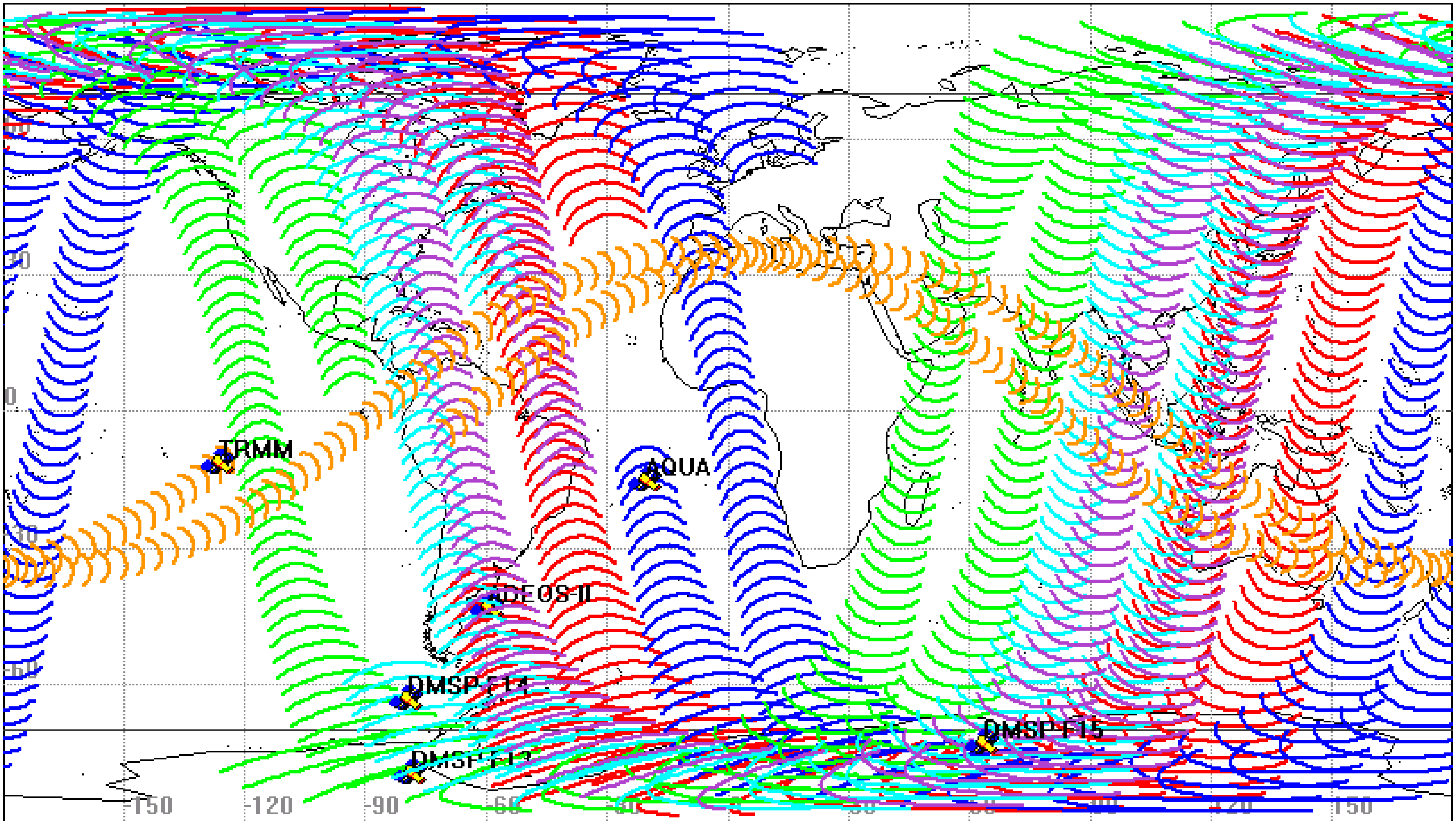
Current Satellites Providing Rain Measurements

EOS Era Coverage: 2002 Time Frame

1. ***TRMM:*** *350 km, 35 Inc (Non-Sun-Synch)*
   TMI: 46 km Footprint @ 10.65 GHz, 760 km Swath
   53 km Footprint @ 10.65 GHz, 870 km Swath (@ 400 km)
2. ***DMSP-F13****: 833 km, 98.7 Inc (Sun-Synch), 0530 (D)* *[notional]*
   SSM/I: 55 km Footprint @ 19.35 GHz, 1400 km Swath
3. ***DMSP-F14:*** *833 km, 98.7 Inc (Sun-Synch), 0830 (D)* *[notional]*
   SSM/I: 55 km Footprint @ 19.35 GHz, 1400 km Swath
4. ***DMSP-F15:*** *833 km, 98.7 Inc (Sun-Synch), 0915 (D)* *[notional]*
   SSM/I: 55 km Footprint @ 19.35 GHz, 1400 km Swath
5. ***AQUA (EOS-PM):*** *705 km, 98.2 Inc (Sun-Synch), 0130 (D)*
   AMSR-E: 36 km Footprint @ 10.65 GHz, 1450 km Swath
6. ***ADEOS-II:*** *803 km, 98.6 Inc (Sun-Synch), 1030 (D)*
   AMSR: 35 km Footprint @ 10.65 GHz, 1600 km Swath

EOS Era Coverage

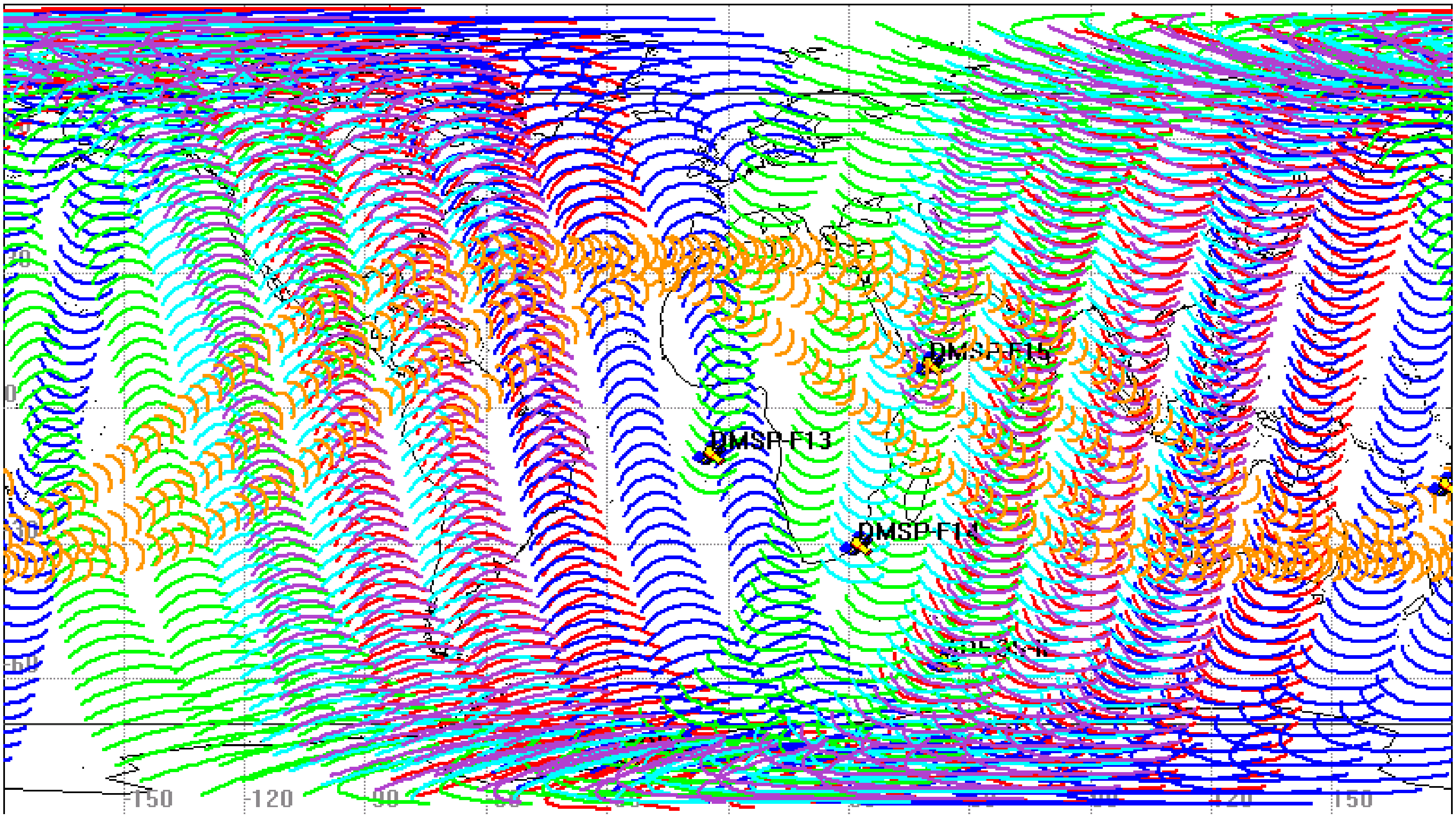
TRMM, DMSP-F13, DMSP-F14, DMSP-F15, AQUA, ADEOS-II



3-hour Ground Trace

EOS Era Coverage

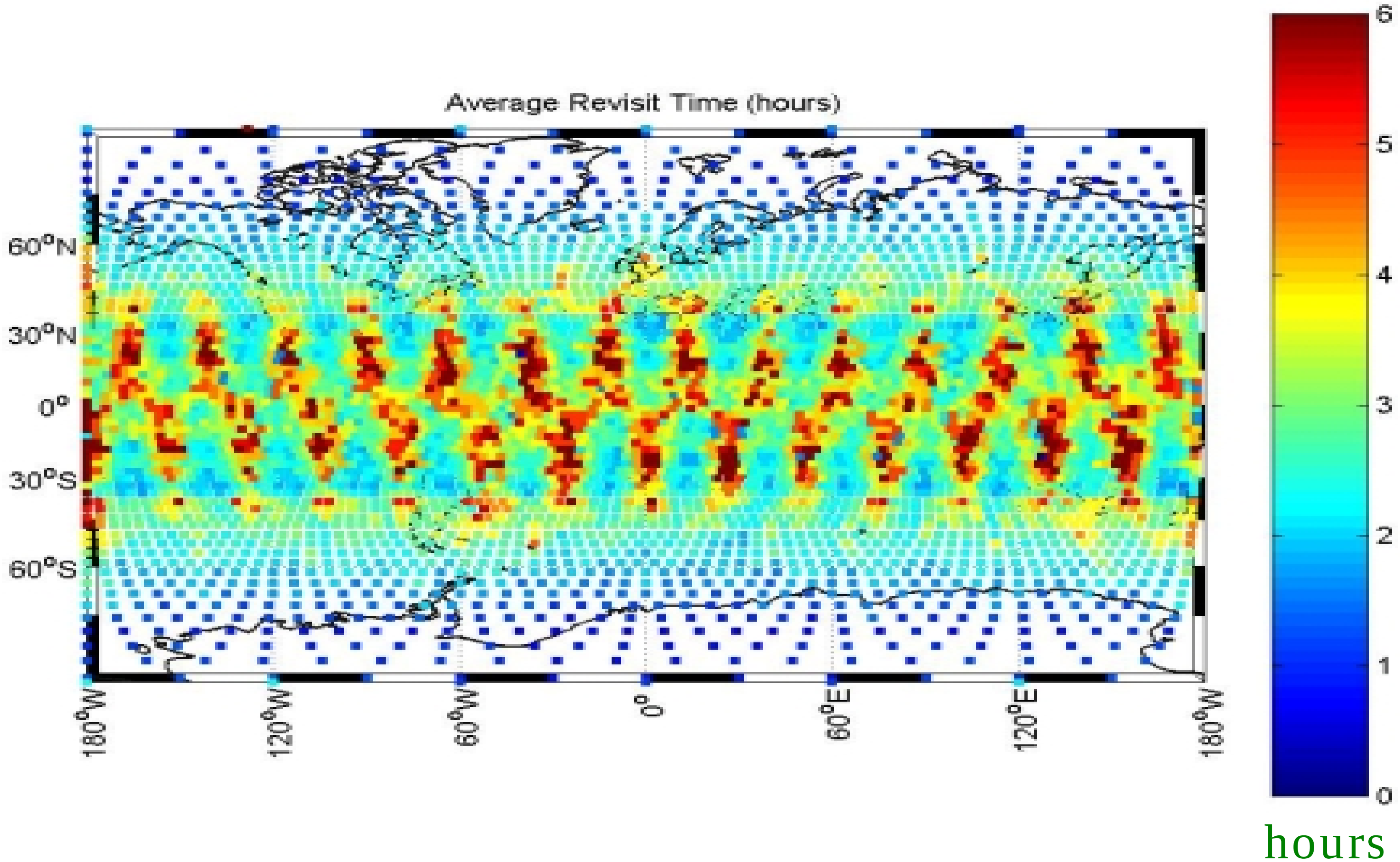
TRMM, DMSP-F13, DMSP-F14, DMSP-F15, AQUA, ADEOS-II



6-hour Ground Trace

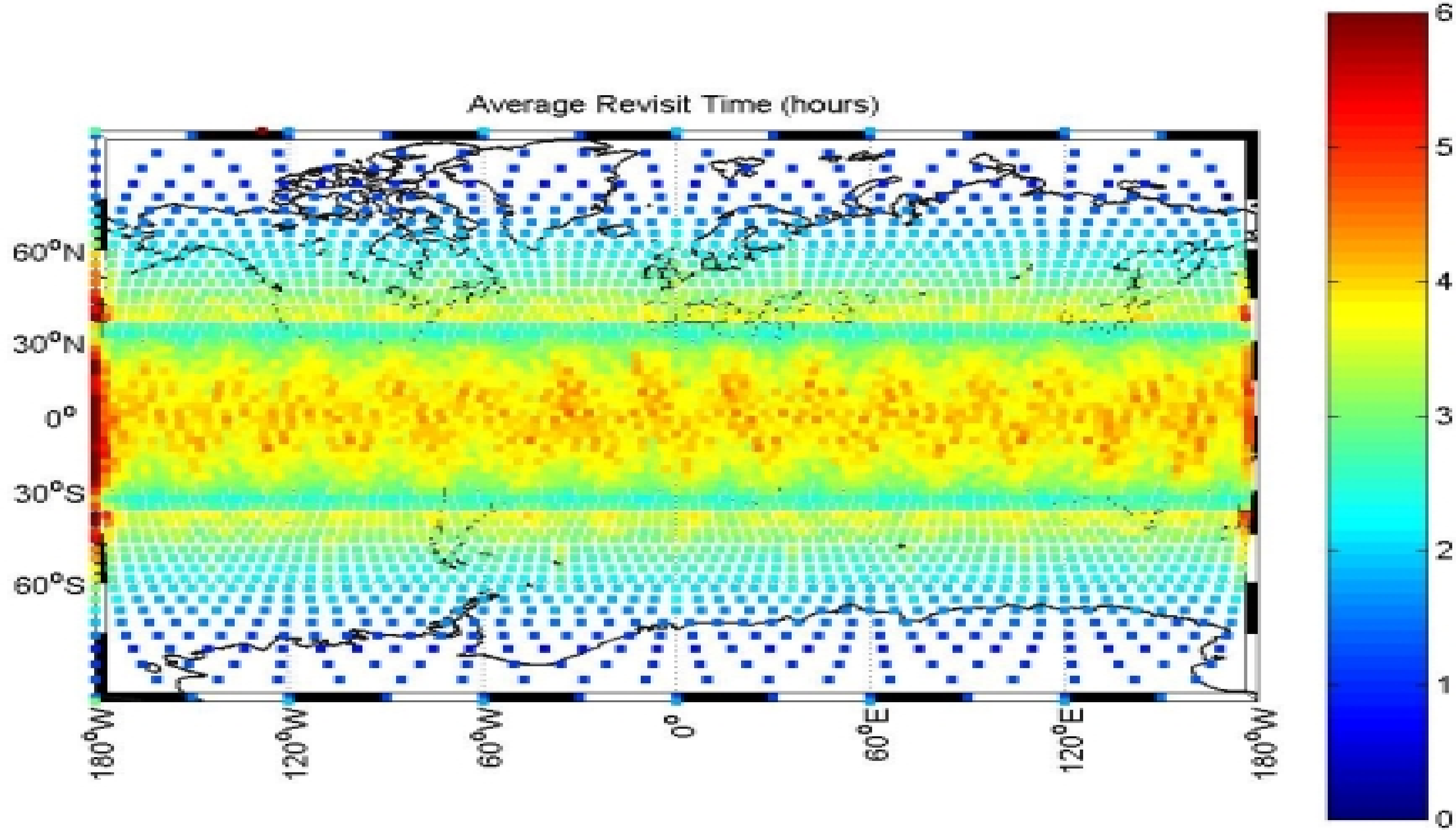
1-Day Average Revisit Time

EOS Era



7-Day Average Revisit Time

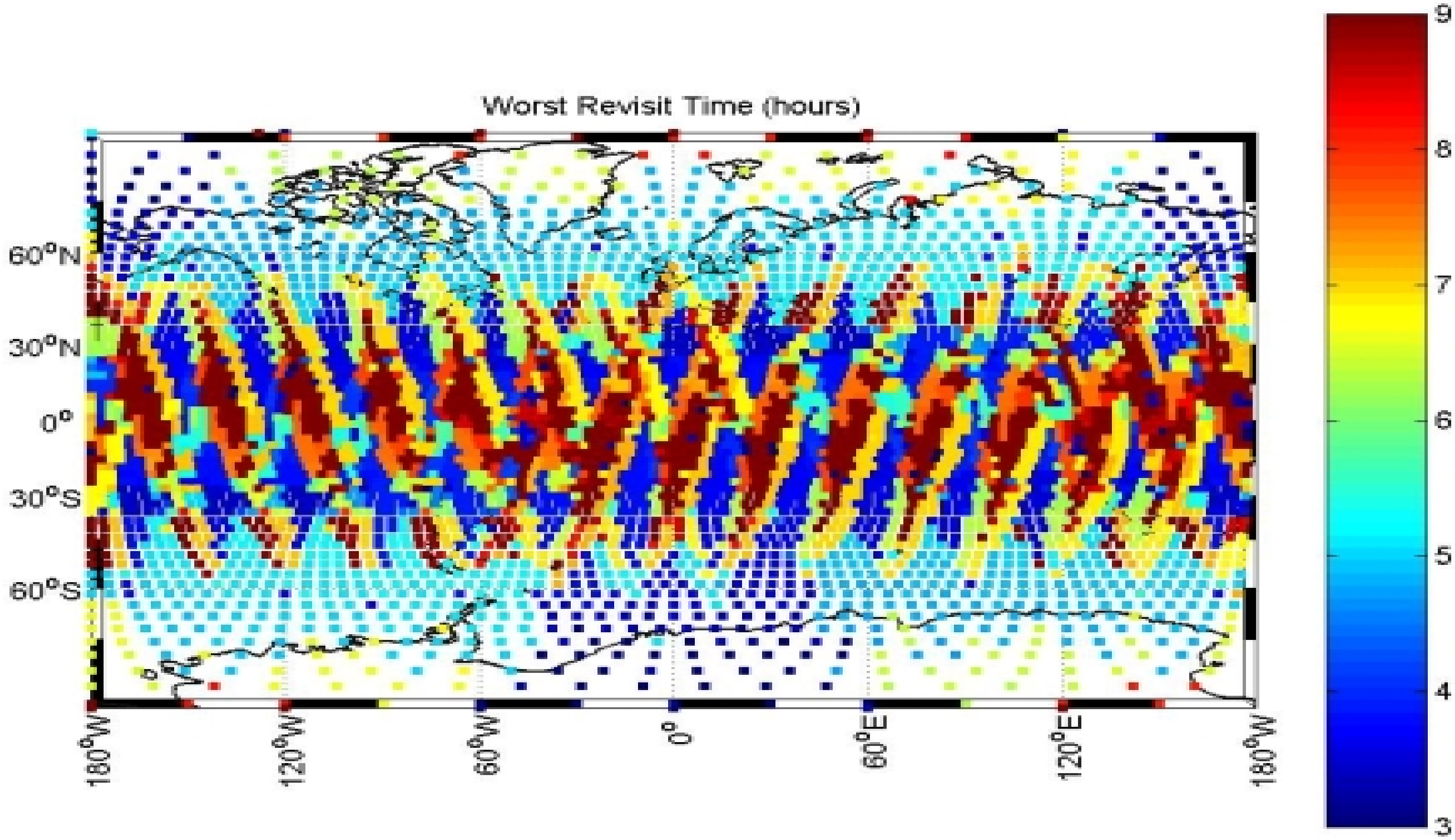
EOS Era



hours

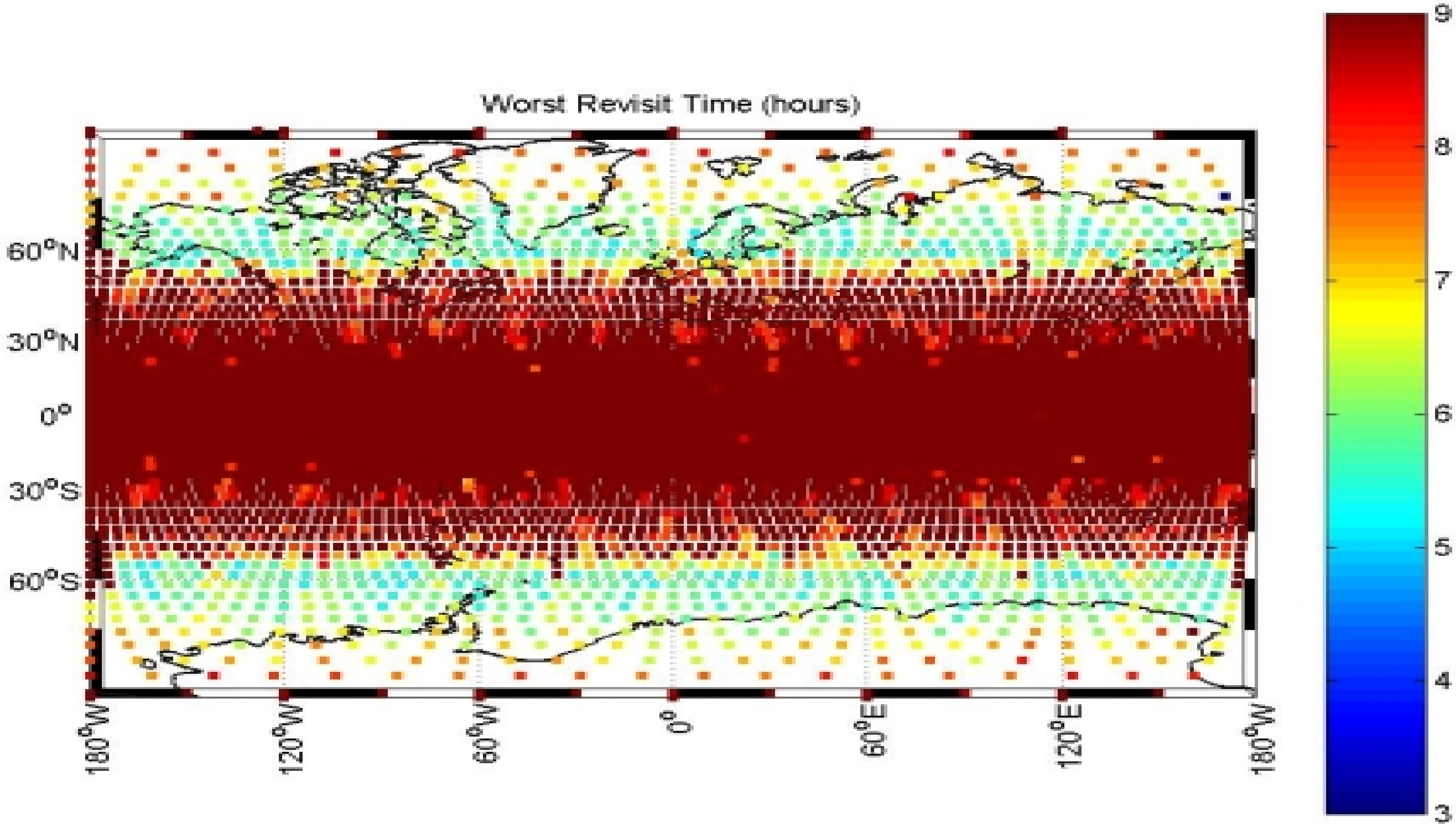
1-Day Worst Case Revisit Time

EOS Era



7-Day Worst Case Revisit Time

EOS Era



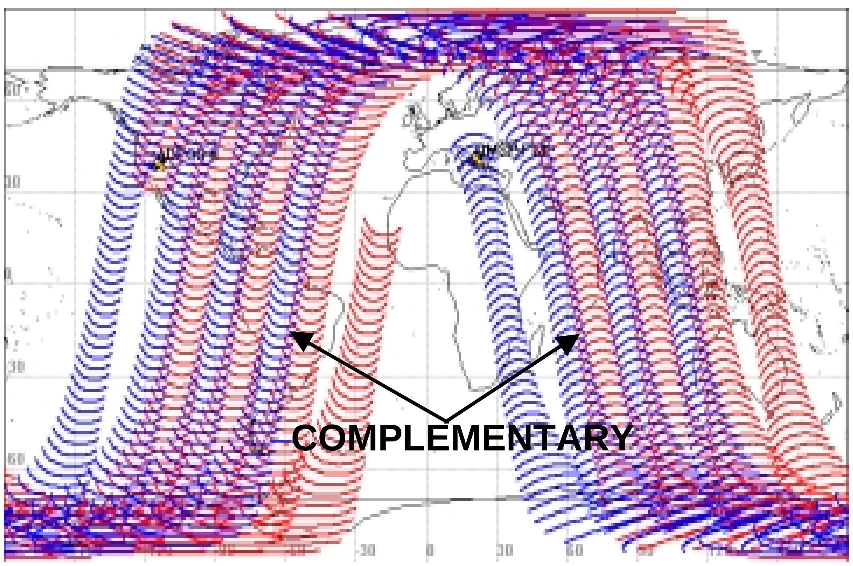
hours

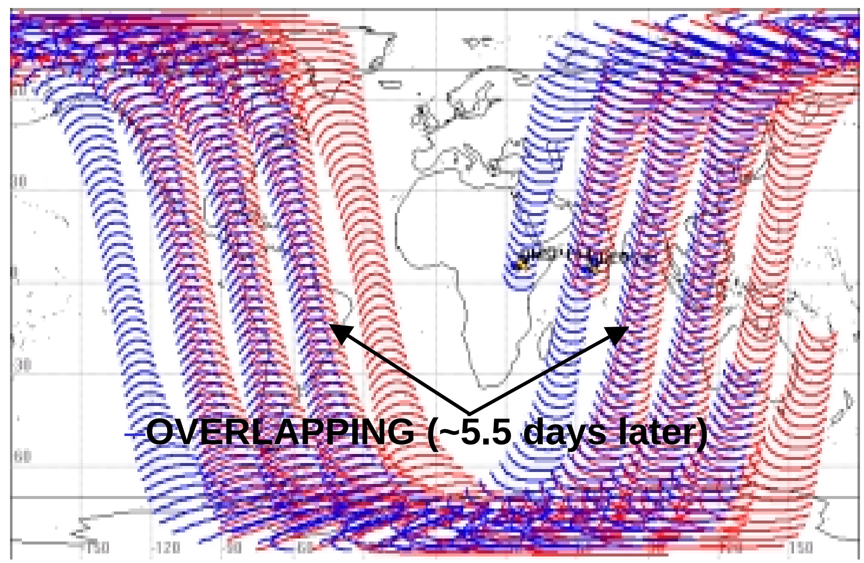
“Gap Blinking”

Total coverage varies over time when using satellites at different altitudes

- *Difference in orbital period changes satellite relative phasing, thus;*
- *Coverage swaths shift relative to each other, and;*
- *Coverage may complement or overlap, and;*
- *Phase shift period depends on difference in altitudes.*

For example, ADEOS-II @ 803 km & DMSP @ 833 km produces ~11 day phase shift period





GPM Era Coverage
2007 Time Frame

GPM Core Satellite Characteristics

Provides instruments for cloud physics research & calibration of radiometers on constellation satellites

- *Orbit: ~400 km at ~65 Inclination*
- *Baseline Instruments:*
  - *Advanced TMI radiometer*
    (1.0 m aperture; ±65 conical scanning with 55   EIA)
  - *Dual-frequency Ku/Ka Band Precipitation Radar (DPR)*
    (2.4/1.0 m apertures; ±17 /±7-17   nadir scanning)
- *Advanced TMI Radiometer Characteristics*
  - *10.65, 19.35, 37.0, 85.5 GHz dual-pol & 22.3 GHz v-pol*
  - *34 km footprint @ 10.65 GHz; ~920 km swath width*
- *DPR Radar Characteristics*
  - *Ku/Ka band (13.6/35.5 GHz) non-coherent with 17/15 or 11 dBZ sensitivities*
  - *5 km footprints; ~245/100-245 km swath widths; 0.25/0.25 or 0.5 km vertical resolutions*

Co-op Satellites
Suitable for Rain Measurement

GPM era coverage: 2007 time frame

1. **DOD/IPO**

   DMSP-F17/F19: *833 km, 98.7 Inc (Sun-Synch), 0830(D)*

   SSMIS: 54 km Footprint @ 19.35 GHz, 1707 km Swath

2. **DOD/IPO**

   DMSP-F18: *833 km, 98.7   Inc (Sun-Synch), 0530(D)*

   SSMIS: 54 km Footprint @ 19.35 GHz, 1707 km Swath

3. **NASDA**

   GCOM-B1: *800 km, 98.6 Inc (Sun-Synch), 1030(D)*

   AMSR-FO: 35 km Footprint @ 10.65 GHz, 1600 km Swath

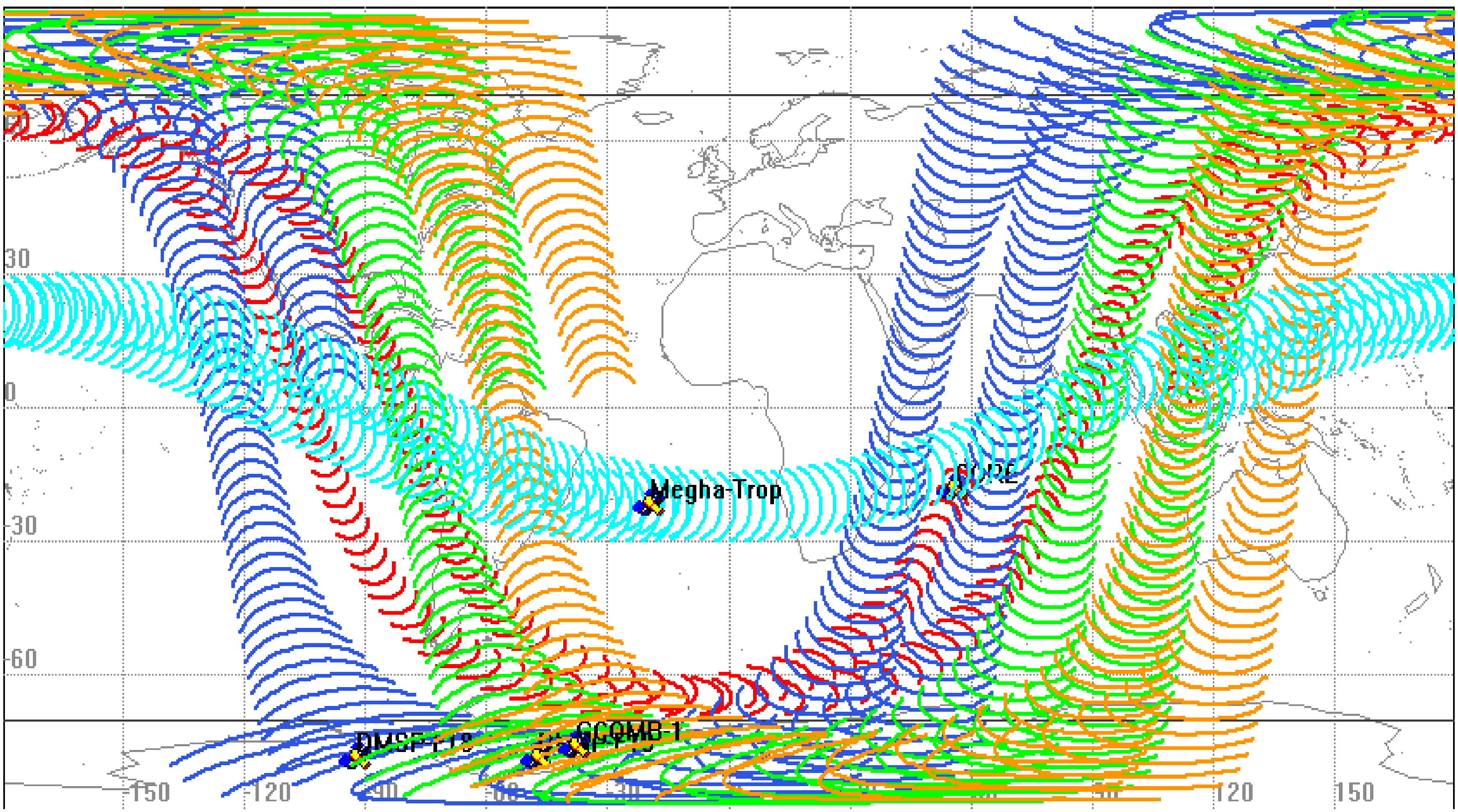
4. **ISRO/CNES**

   Megha-Tropiques: *867 km, 22 Inc (Non-Sun-Synch)*

   MADRAS: 54 km Footprint @ 18 GHz, ~1700 km Swath

GPM Era Coverage (Core & 4 Co-ops)

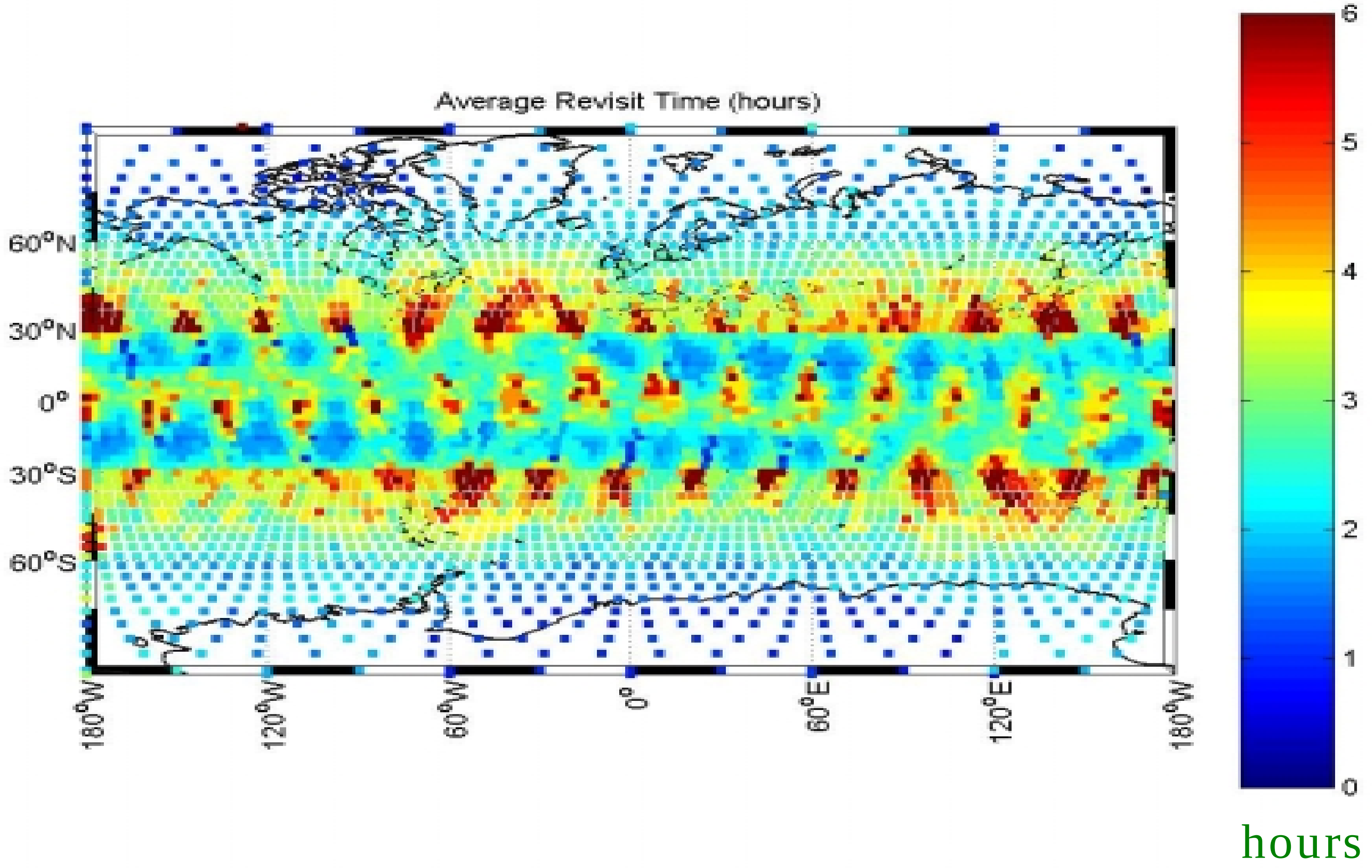
GPM Core, DMSP-F18, DMSP-F19, GCOM-B1, Megha-Tropiques



3-hour Ground Trace

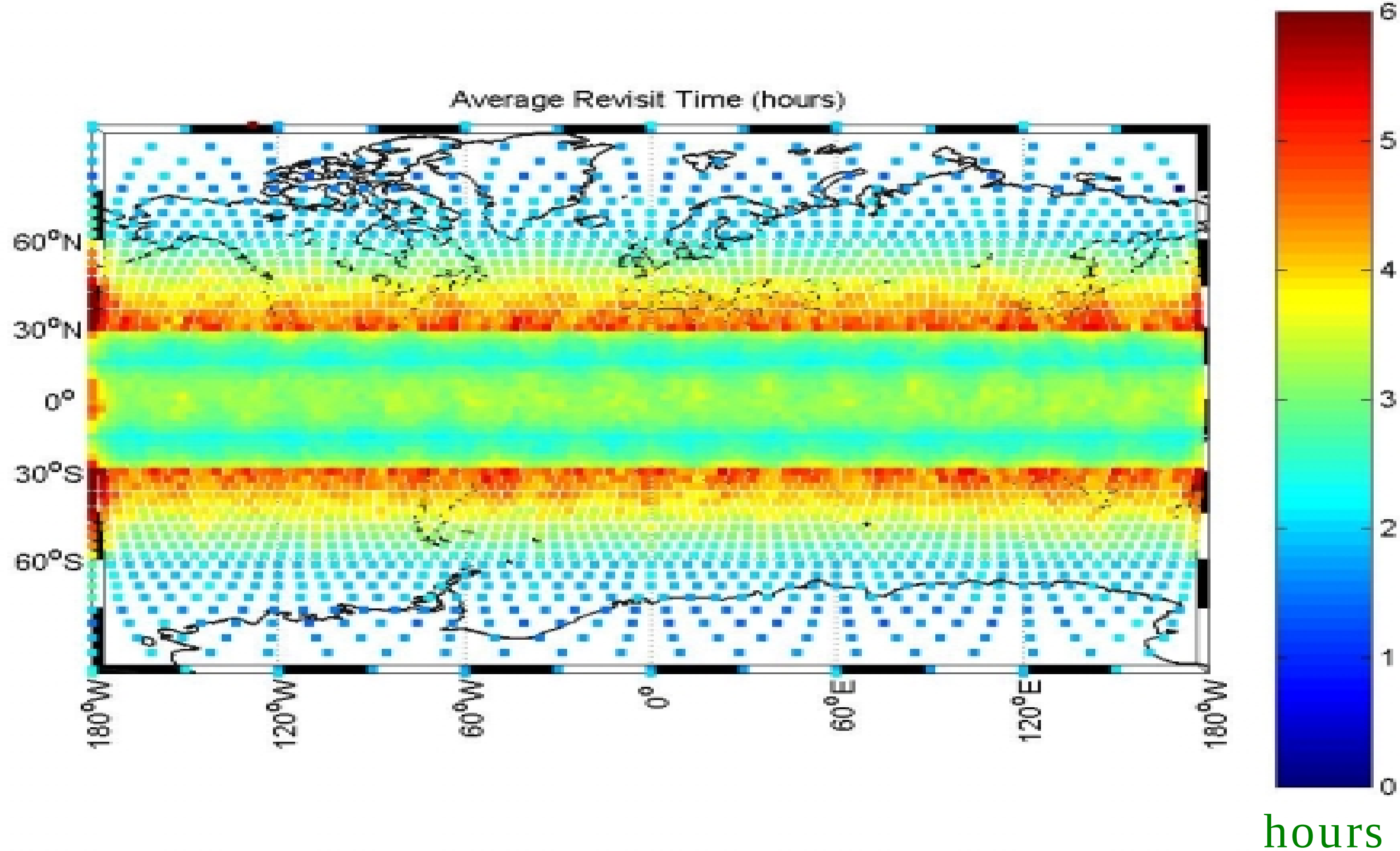
1-Day Average Revisit Time

GPM Era (Core & 4 Co-ops)



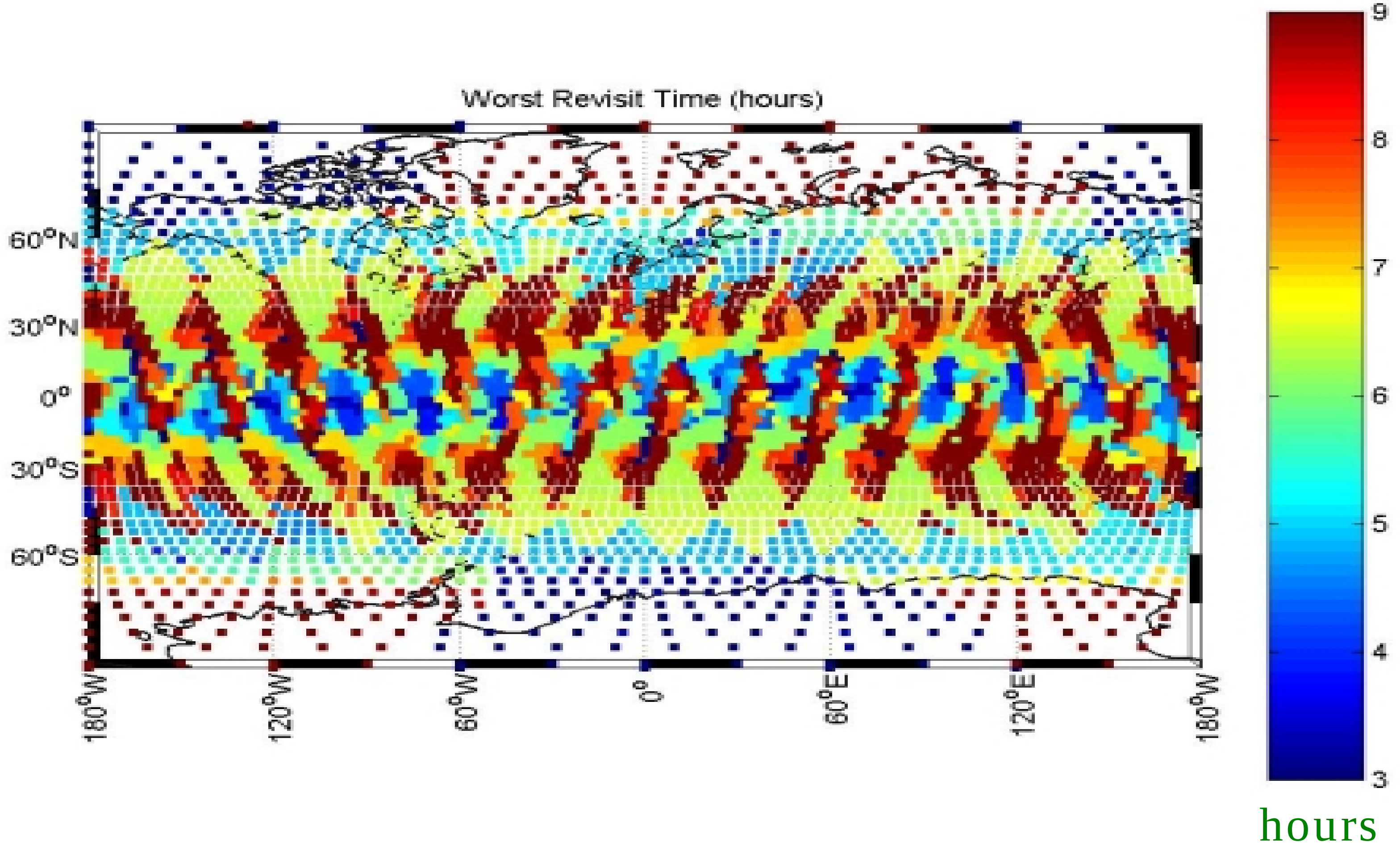
7-Day Average Revisit Time

GPM Era (Core & 4 Co-ops)

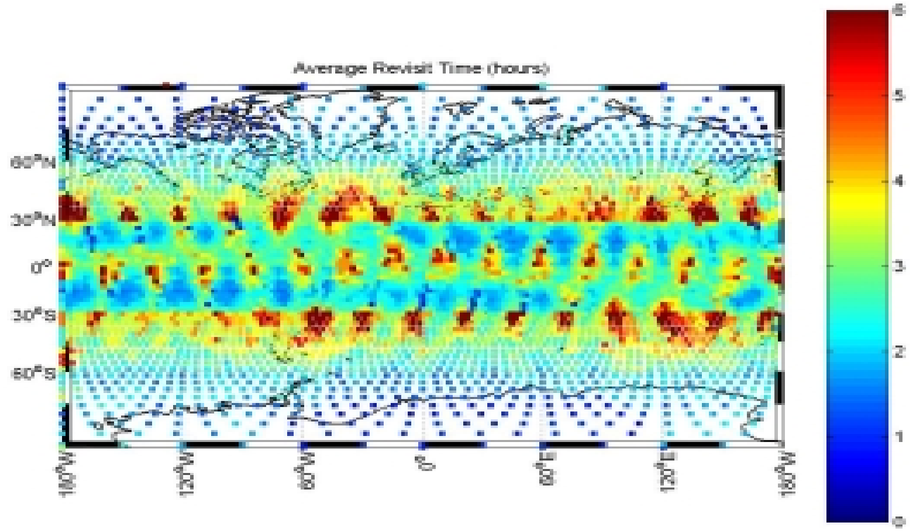


1-Day Worst Case Revisit Time

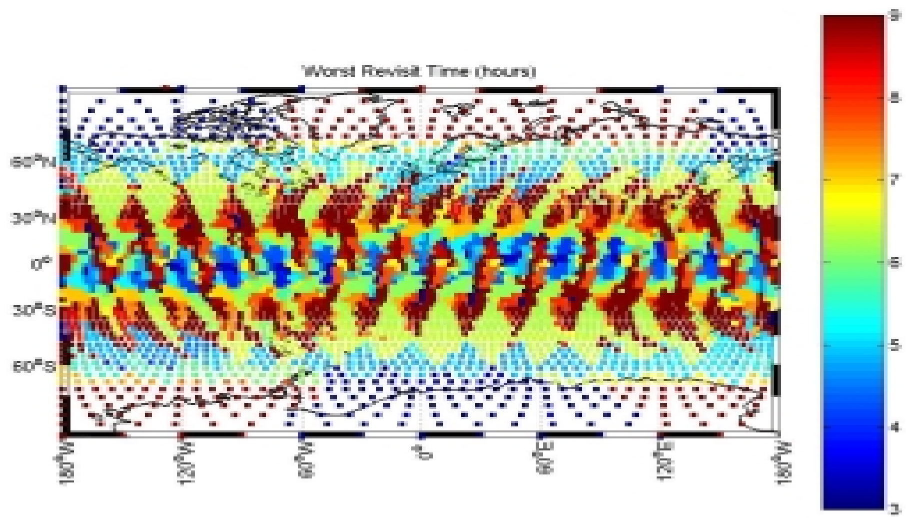
GPM Era (Core & 4 Co-ops)



GPM Era (Core & 4 Co-ops)



1-Day Average Revisit Time



1-Day Worst Case Revisit Time

hours

“Fleet” Approach

- *Provides coverage using satellites in different orbits*
- *Not fixed constellation; satellites’ relative locations vary*
- *Coverage, revisit interval, & sampling times vary*
- *Requires use of optimizing tool for design & analysis:*
  - *Varies orbit parameters to specified criterion, e.g.,*
    - *coverage percentage (over equal area grid in coverage region)*
    - *maximum revisit time*
    - *“hits” per specific time interval*
  - *Can optimize by changing only specific parameters (leaving others fixed)*
  - *Optimizes coverage using equal area points in coverage region*
  - *Uses graphical user interface & Matlab-based functions for flexibility & ease of use*

Extending GPM Coverage

GPM will obtain valuable coverage benefits from Co-op satellites, but:

- *they do not operate like orthodox constellation*
- *They do not have equal periods because orbit altitudes are different*
- *they are not spaced to enable optimal coverage "fill"*
- *there are not enough to fufill 3-hour sampling goal*

Therefore GPM will extend coverage with Drone satellites

- *Greatest coverage is produced by high altitude Drones (e.g., 850 km)*
- *Highest resolution is produced by low altitude Drones (e.g., 600 km)*
- *Drones orbit selections may be constrained by owner considerations other than coverage*

GPM needs Drone satellite approach in which:

- *Drones provided by various partners -- collaboratively*
- *Drones produce adequate coverage & revisit intervals -- statistically*
- *Drones move relative to each other -- consistently*

Planned or Proposed Drone Missions

1. GPM-1 ∅ NASA GPM Constellation (NGPM)

   [approved for formulation]

2. GPM-2 ∅ ASI (Italy) GPM Constellation (IGPM)

   [proposed -- down selected -- awaiting decision]

3. GPM-3 ∅ ESA GPM Constellation (EGPM)

   [being proposed -- proposal due Sep 30]

Possible Constellation Optimization Strategies

One or more following constellation optimization strategies could be used

1. *1. Maximize coverage within coverage region for specific time interval*
2. *2. Minimize variation in coverage for given time interval with time*
3. *3. maximize coverage in specific areas using areal weights (e.g., tropics or maximum rain areas)*
4. *4. Minimize average revisit interval (uniform or weighted)*
5. *5. Maximize coverage within region for maximum revisit interval (uniform or weighted)*
6. *6. Maximize number of 3-hour periods in day that are sampled over coverage region (uniform or weighted)*
7. *7. Provide sample times uncorrelated with diurnal cycle*
8. *8. Provide seasonal sample sets (e.g., four or eight sets per year)*

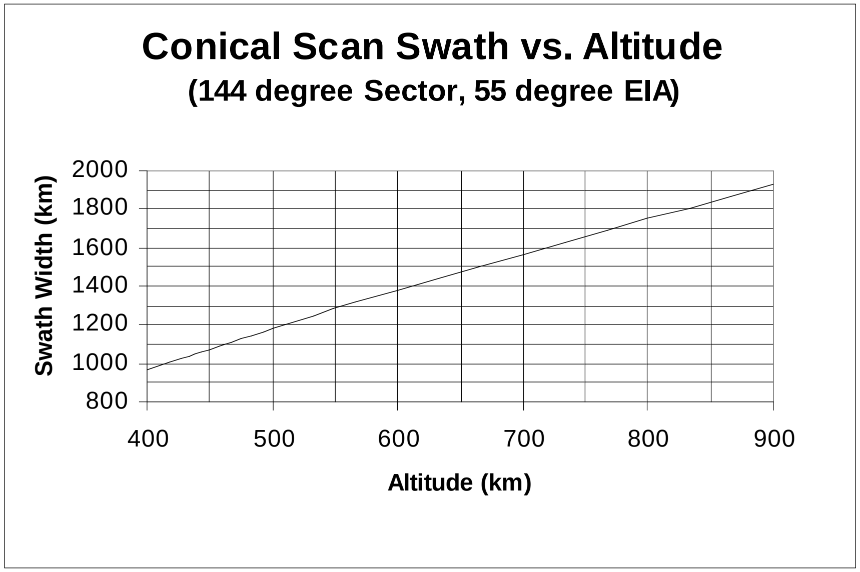
Autonomous Orbit Control

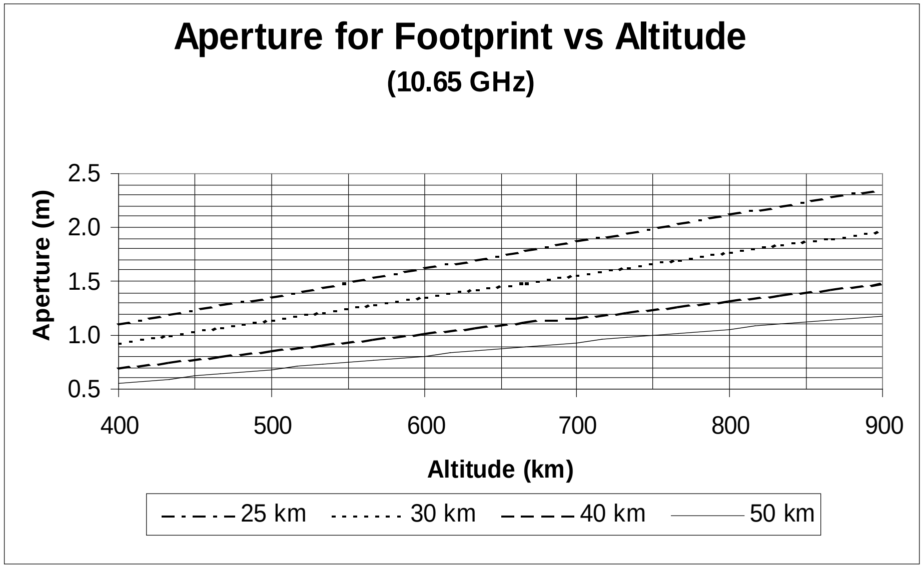
- Coverage deteriorates if relative orbit relationships are changed from optimum because of orbit drift
- Coverage is very sensitive to precision of orbit control
- Orbits can be maintained precisely via on-board GPS-drived autonomous orbit control sytem involving frequent but small adjustments by thrusters

Drone Satellite Altitude

coverage & resolution are competing altitude drivers

- *Widest coverage swath is at high altitude, e.g., 850 km;*
- *High resolution requires low altitude, although;*
- *Below ~400 km requires significant fuel for drag make-up.*





Drone Satellite Inclination

- Sun-synchronous (~99)
  - *Samples at same local time each day, although;*
  - *Retrograde orbit requires more launcher capability, however;*
  - *There may be dual-launch opportunities (popular orbit), but;*
  - *If multiple launch, difficult to distribute satellites to different ascending nodes, nevertheless;*
  - *Constant sun angle allows simple solar array & thermal design.*
- Mid-inclination (~35-70)
  - *Provides low revisit intervals around inclination latitude, plus;*
  - *Easier to distribute multiple-launched satellites to desired orbits, and;*
  - *Satellites see sun at all (Beta) angles, thus:*
    - *solar array & thermal design more complex, &;*
    - *may require periodic satellite yaw maneuvers.*
- Low-inclination (~0-25)
  - *Good coverage and revisit in equatorial region, particularly;*
    - *diagonal swath across Equator provides good low altitude coverage, and;*
    - *entire coverage region not seen without more high inclination satellites.*
  - *Easiest to distribute multiple-launched satellites to desired orbits, and;*
  - *Limited range of sun angles simplifies solar array & thermal design.*

Coverage Completion with Drone Satellites

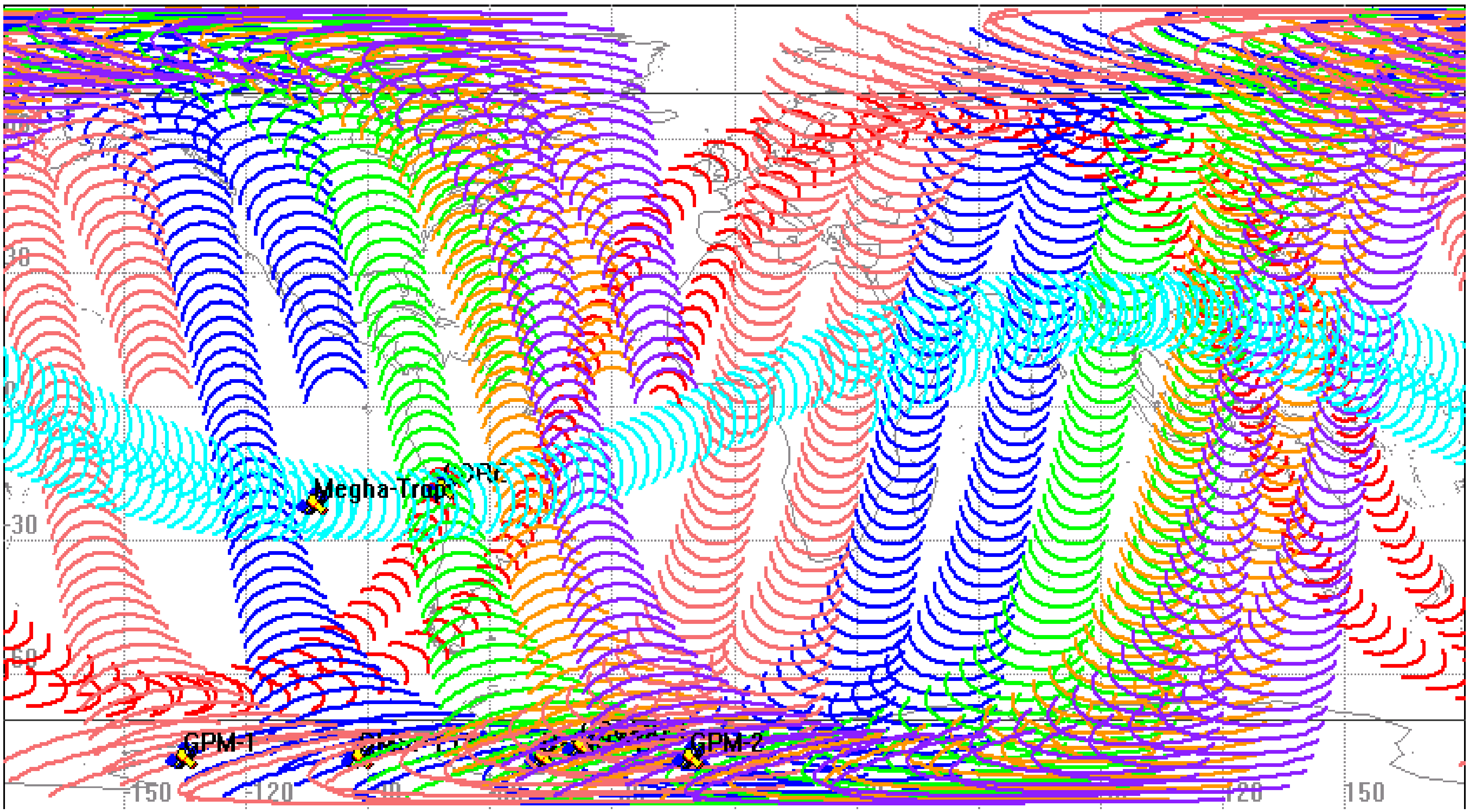
- *Orthodox constellation would require 8 dedicated Drones in homogeneous orbits -- along with Core*
- *Orthodox constellation is not possible when including Co-op satellites in heterogeneous orbits*
- *Thus "fleet" is required in orbits that provide statistically-optimized coverage*
- *Also "scalability" is desired such that adding Drones guarantees improved coverage*
- *Options for "Fleet" consist of:*
  - *Including additional sun-synchronous Drones at high- or mid-altitudes*
  - *Including additional non-sun-synchronous Drones in various mid-altitude/lower inclination orbits, optimized for coverage & revisit*

Completing Coverage with Sun-synchronous Drones

- *Ideally, additional sun-synchronous satellites should all be at equivalent, highest orbit altitude (i.e., DMSP altitude of 833 km);*
- *However, Co-op satellites are at different altitudes producing varied coverage;*
- *Therefore, phasing between Co-op satellites (i.e., spacing between swaths) is not optimal for coverage;*
- *Moreover, additional sun-synchronous satellites at lower altitudes, for better resolution, will have varying overlap & coverage*
- *Thus, aliasing will occur since sample times will periodically converge & diverge.*

GPM Era Coverage with 2 Sun-Synchs

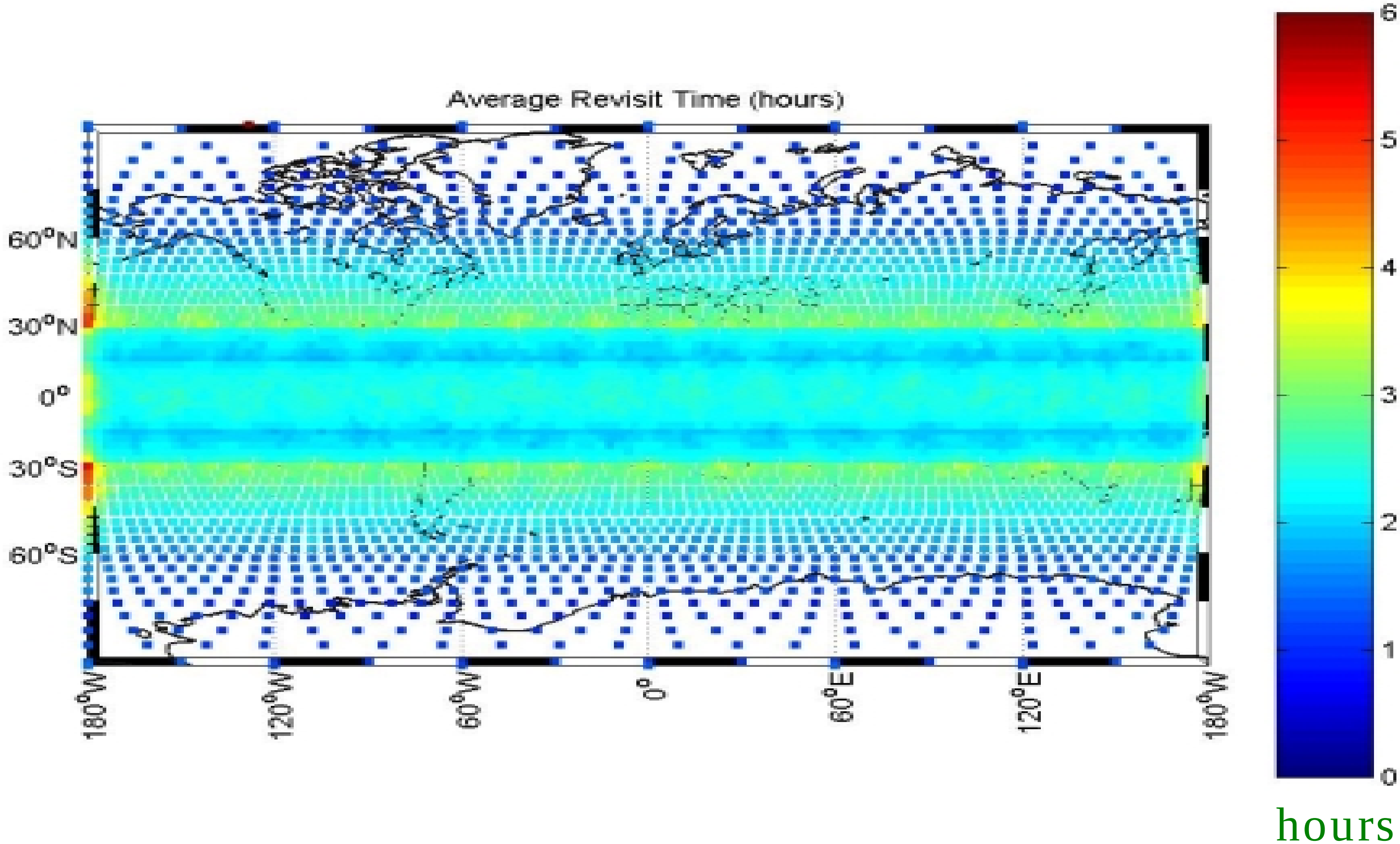
GPM Core, DMSP-F18, DMSP-F19, GCOM-B1, Megha-Tropiques,
& Two 833-km Sun-Synch Drones: GPM-1, GPM-2



3-hour Ground Trace

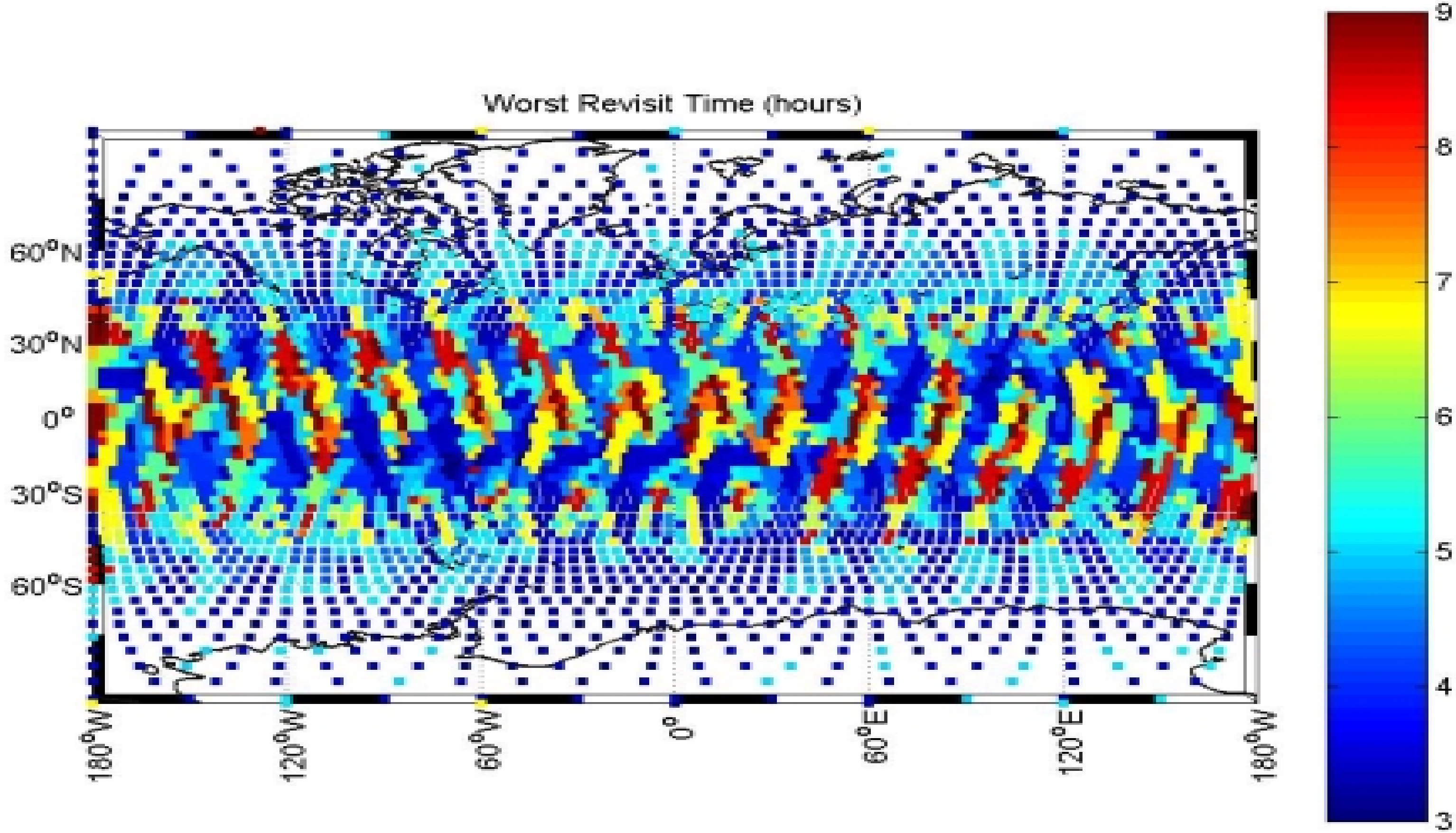
7-Day Average Revisit Time

GPM Core, Four Co-ops, & Two 833-km Sun-Synch Drones



1-Day Worst Case Revisit Time

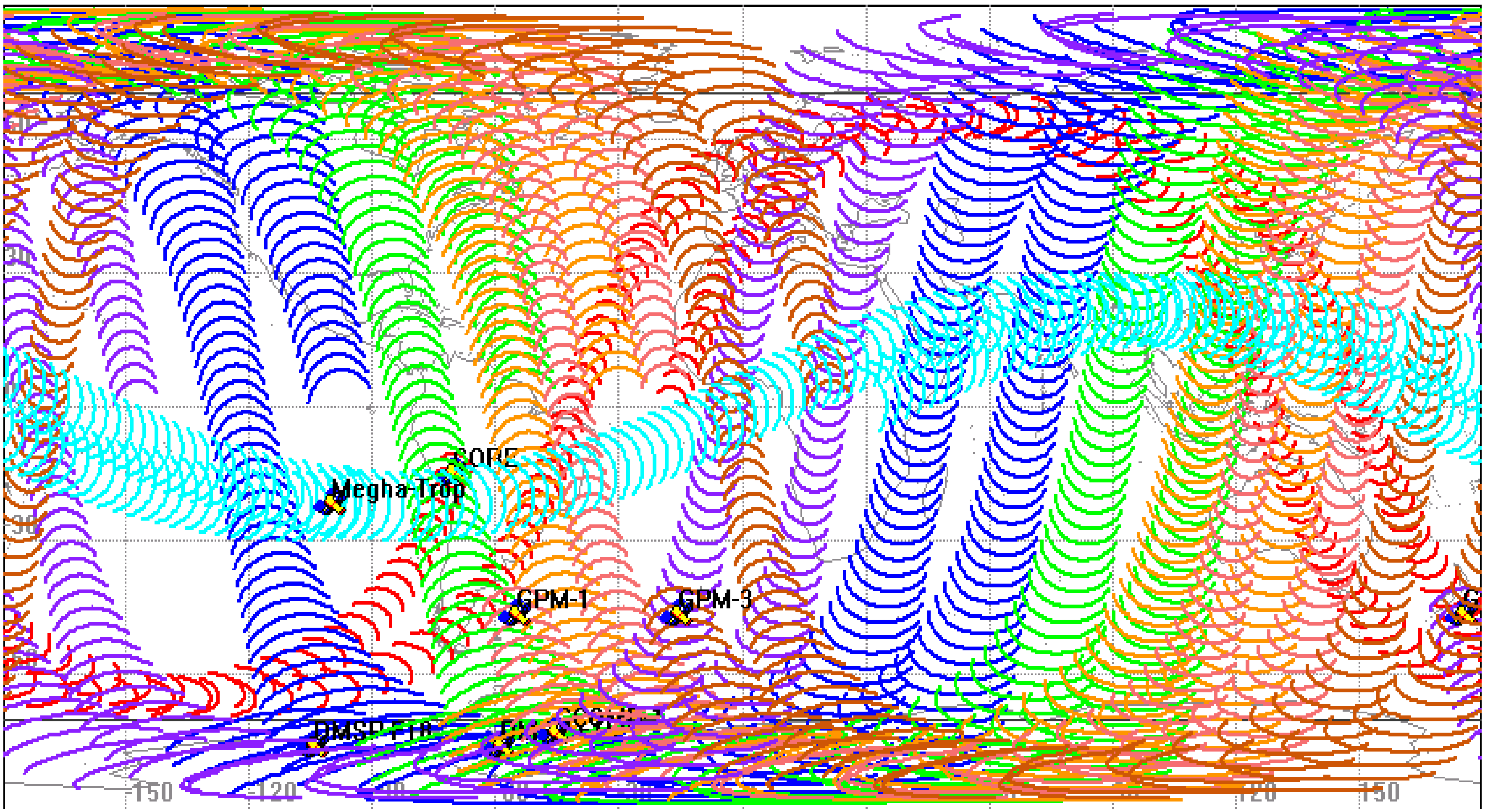
GPM Core, Four Co-ops, & Two 833-km Sun-Synch Drones



hours

GPM Era Coverage with 3 Sun-synchs

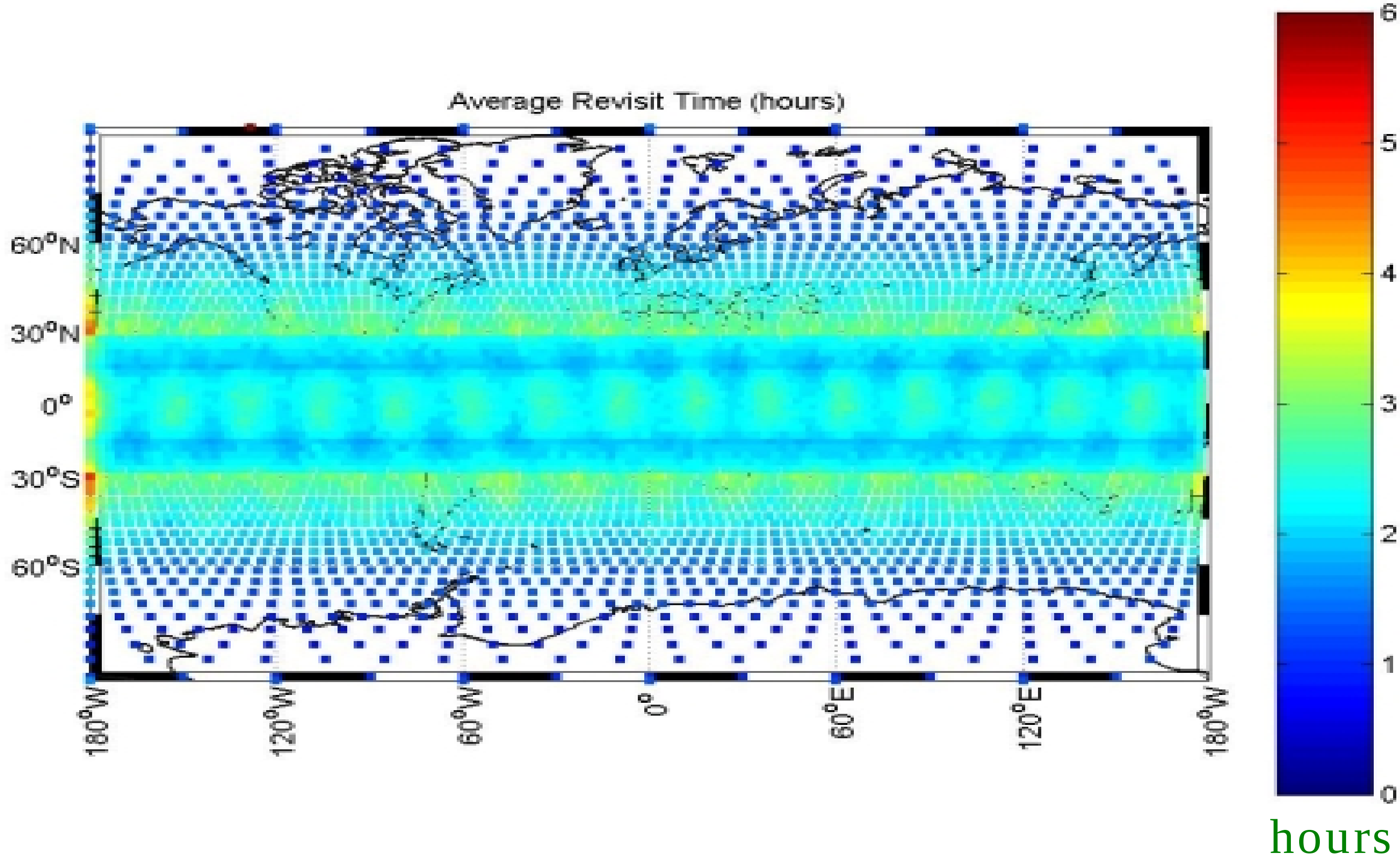
GPM Core, DMSP-F18, DMSP-F19, GCOM-B1, Megha-Tropiques,
& Three 600-km Sun-Synch Drones: GPM-1, GPM-2, GPM-3



3-hour Ground Trace

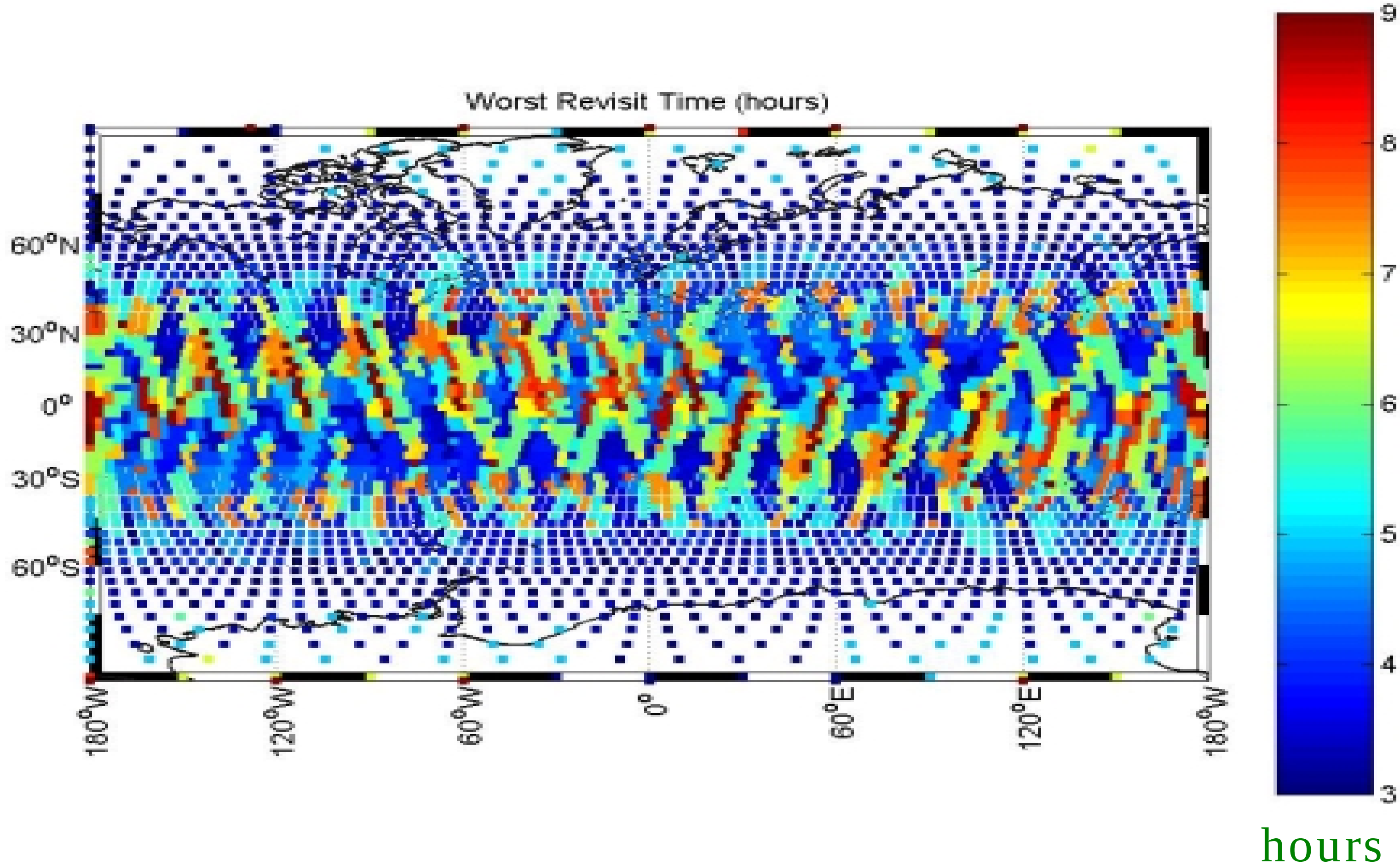
7-Day Average Revisit Time

GPM Core, Four Co-ops, & Three 600-km Sun-Synch Drones



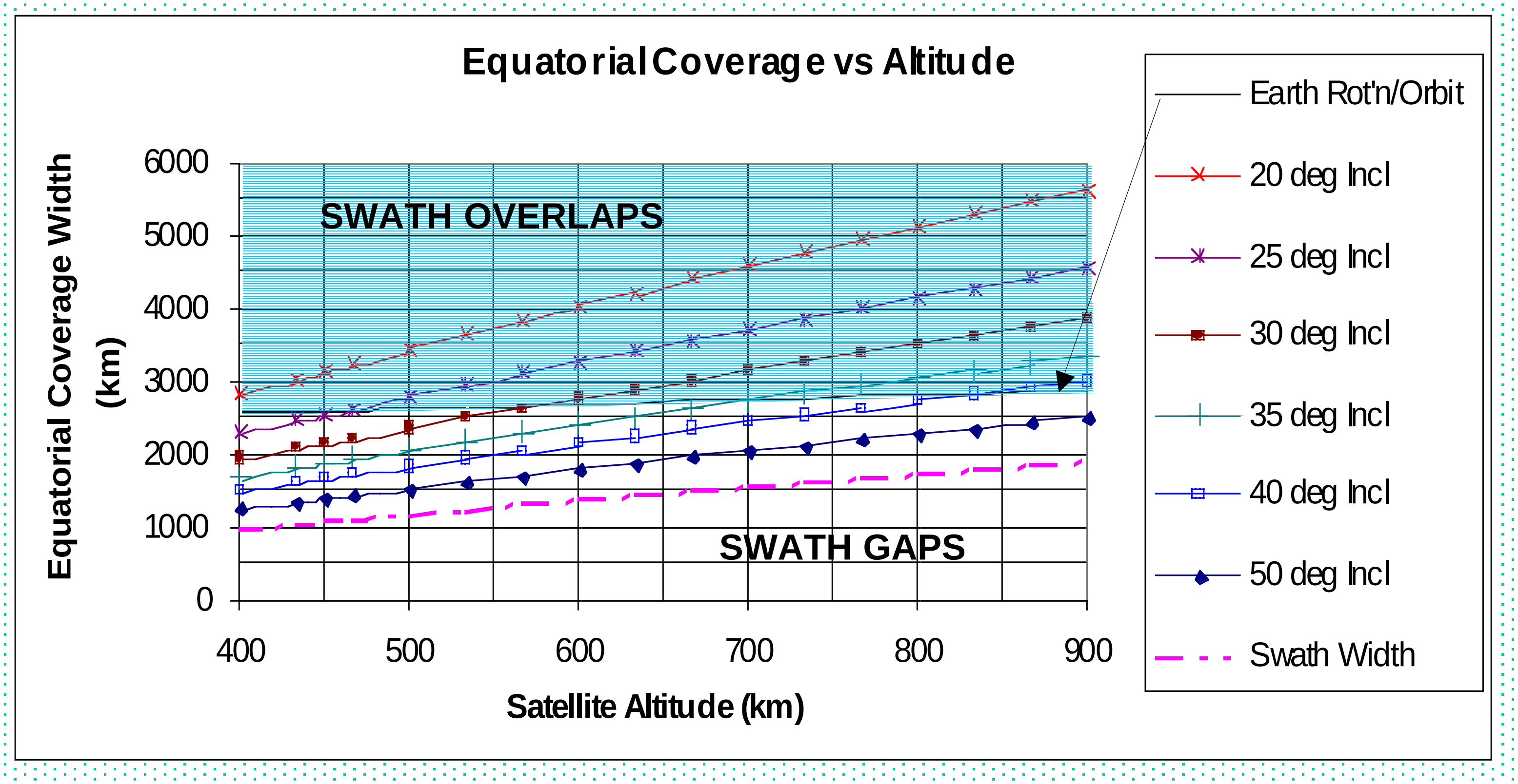
1-Day Worst Case Revisit Time

GPM Core, Four Co-ops, & Three 600-km Sun-Synch Drones



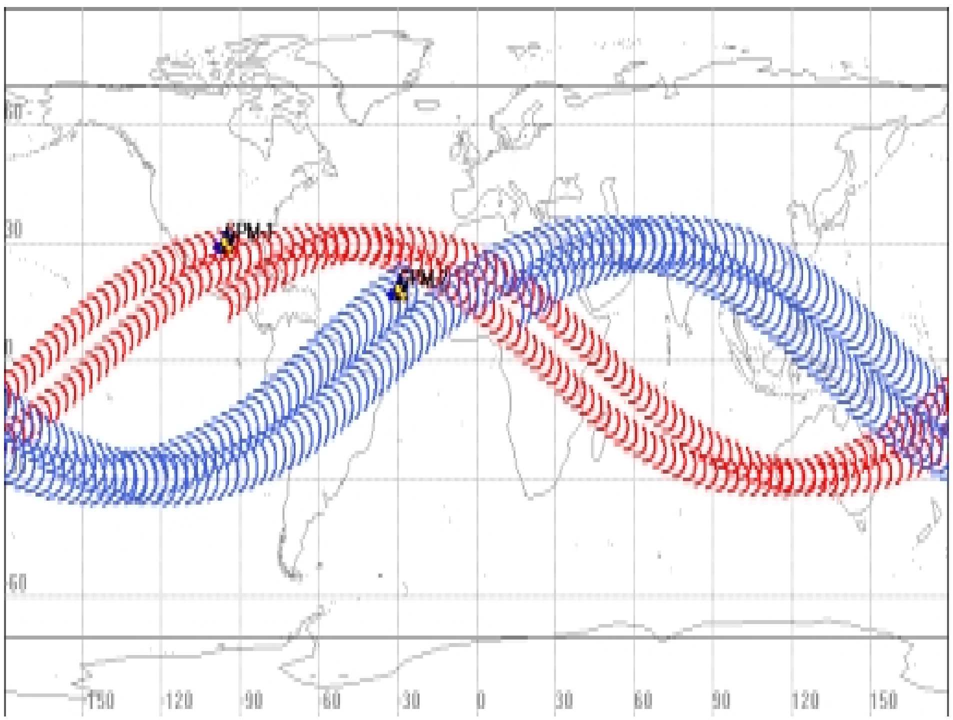
Completing Coverage with Non-Sun-Synchronous Lower Inclination Drones

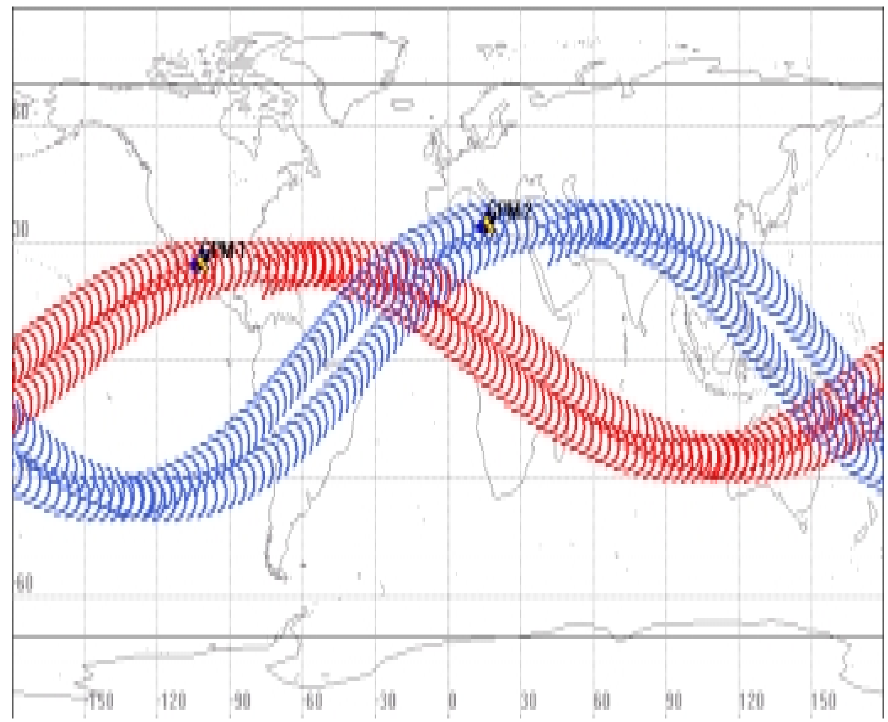
- *Lower inclination orbits can place all coverage between +/- 90 latitude*
- *Effective coverage scheme requires satellite swath widths to be consistent with Earth's rotation*



Equatorial Fill Examples

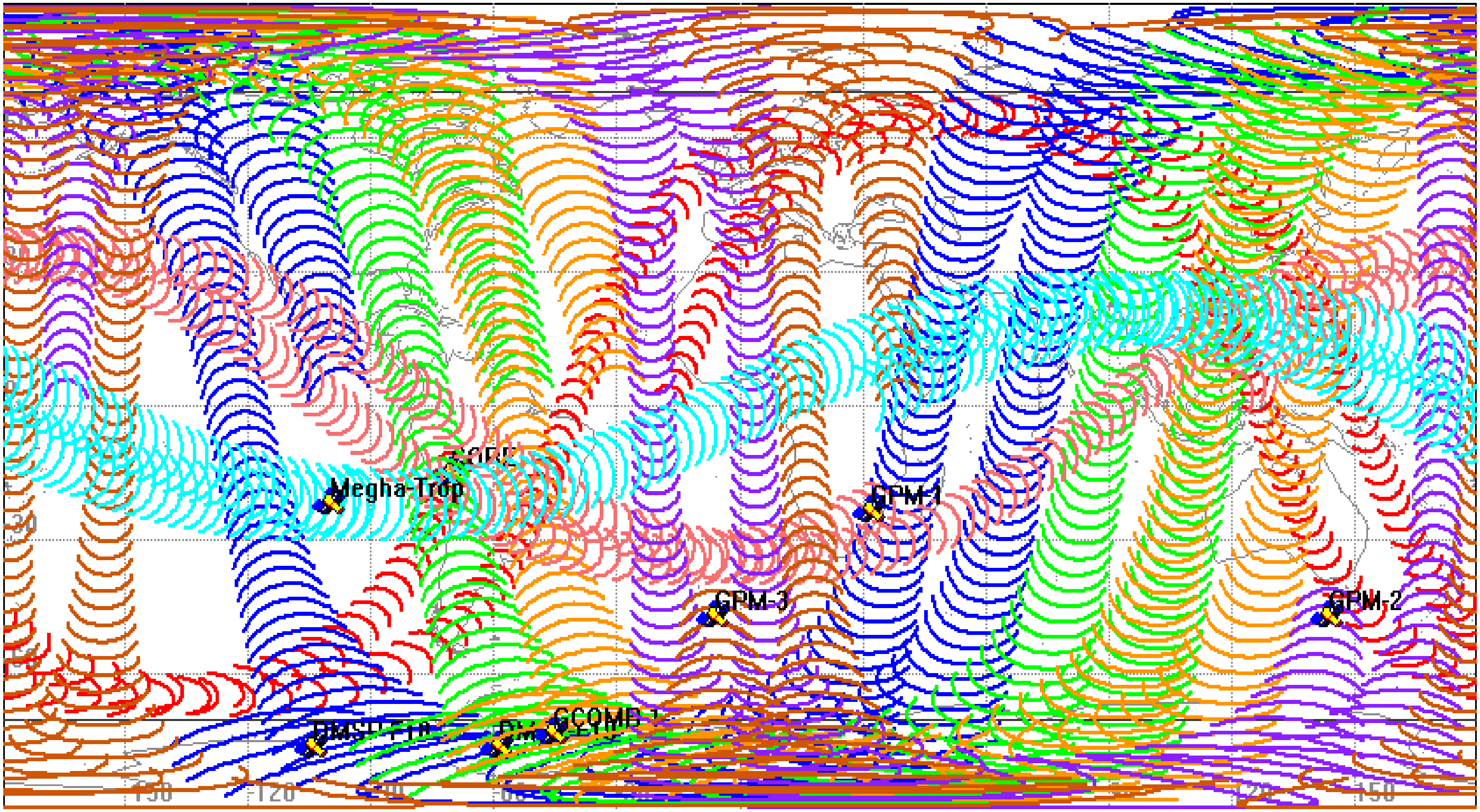
Same Inclination: 30 450 & 700 km Altitude	Same Altitude: 600-km 25 & 35 Inclination





GPM Era Coverage with 3 Inclined

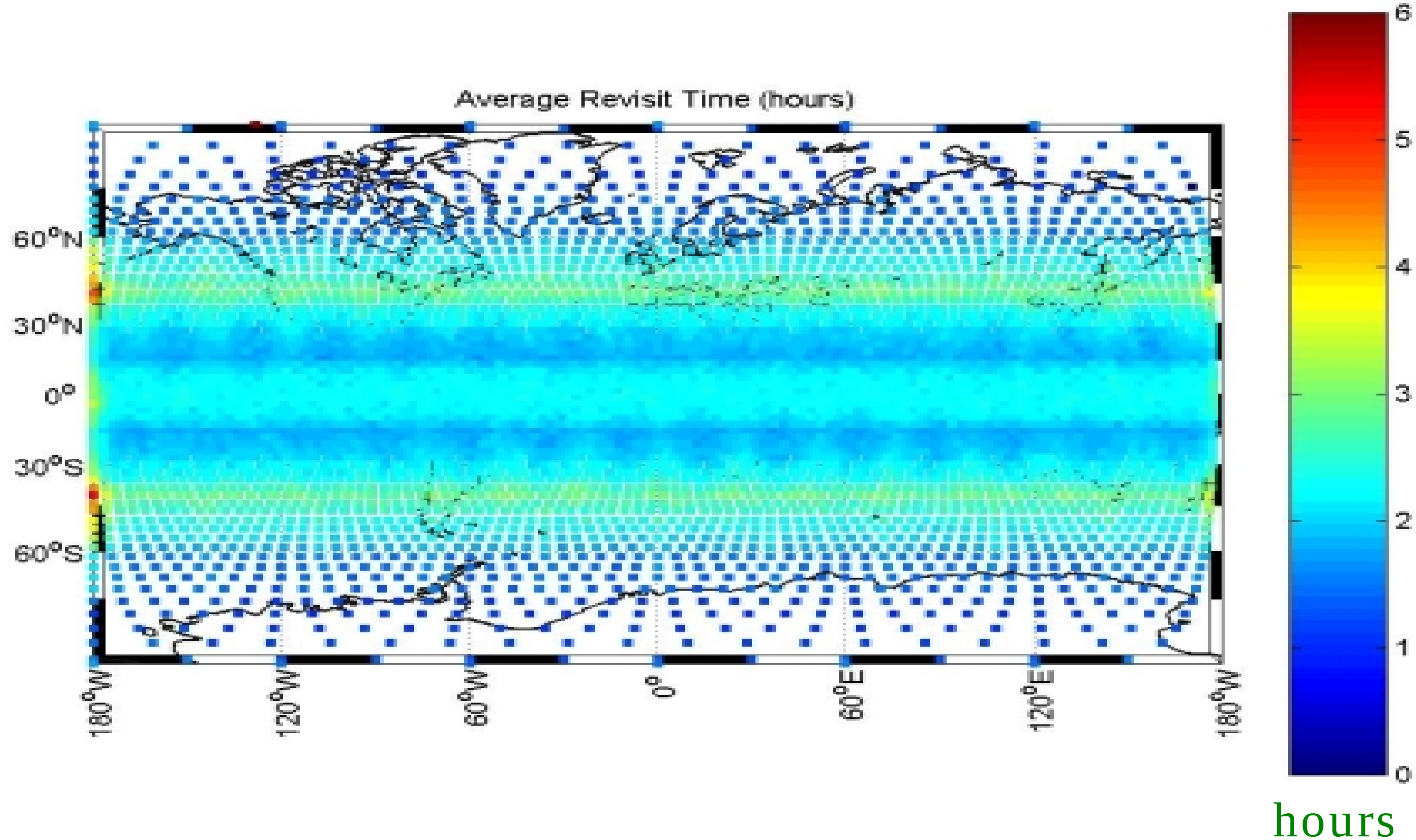
GPM Core, DMSP-F18, DMSP-F19, GCOM-B1, Megha-Tropiques, & Three 600-km Drones @ 34 , 84 , 90



3-hour Ground Trace

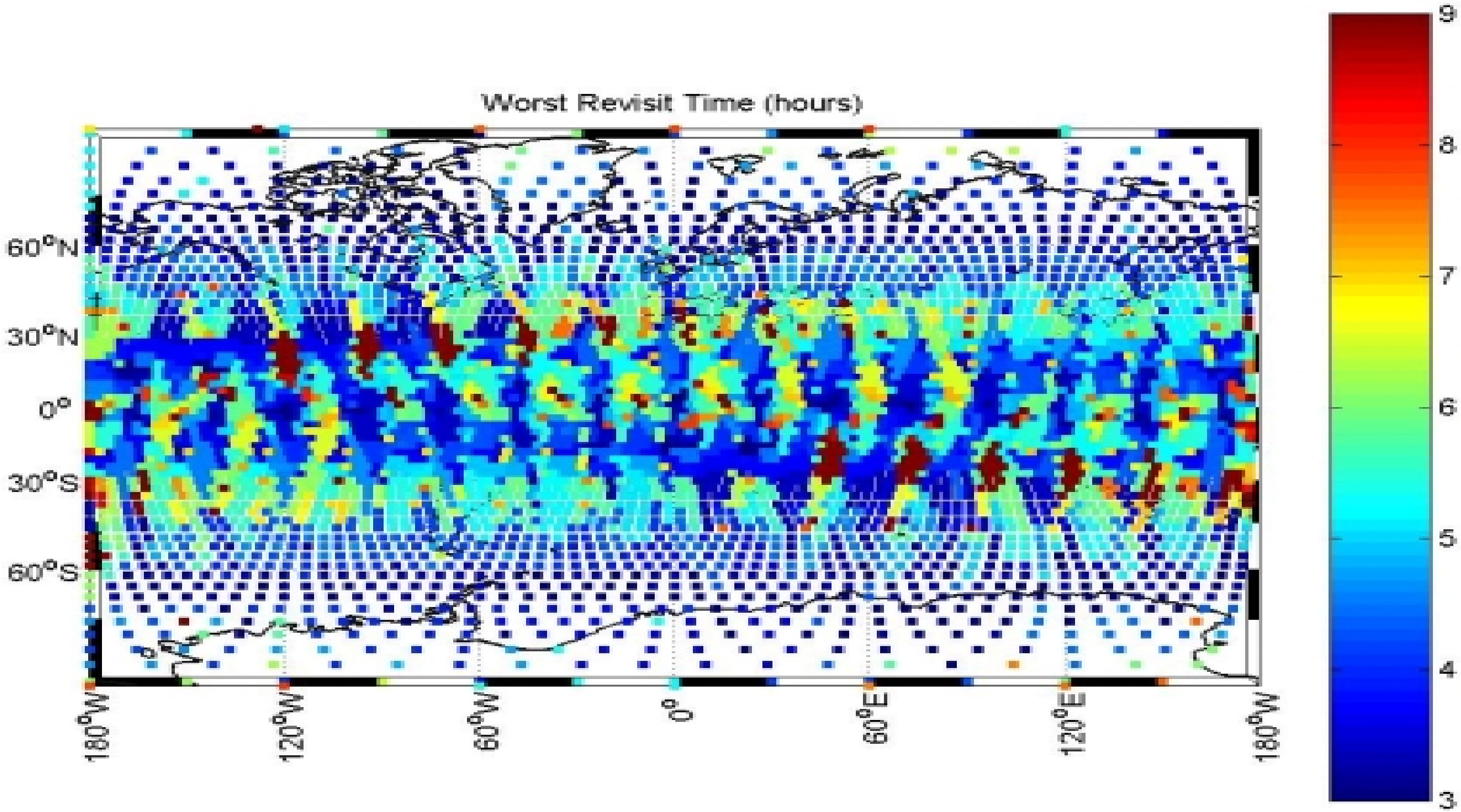
7-Day Average Revisit Time

GPM Core, Four Co-ops, & Three 600-km Drones @ 34 , 84 , 90



1-Day Worst Case Revisit Time

GPM Core, Four Co-ops, & Three 600-km Drones @ 34 , 84 , 90

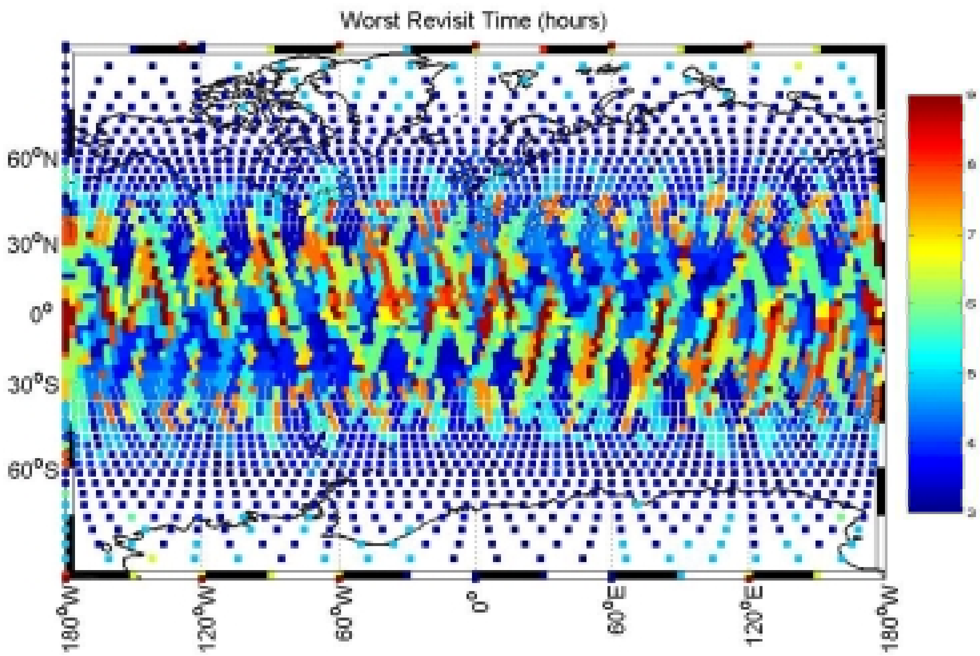


hours

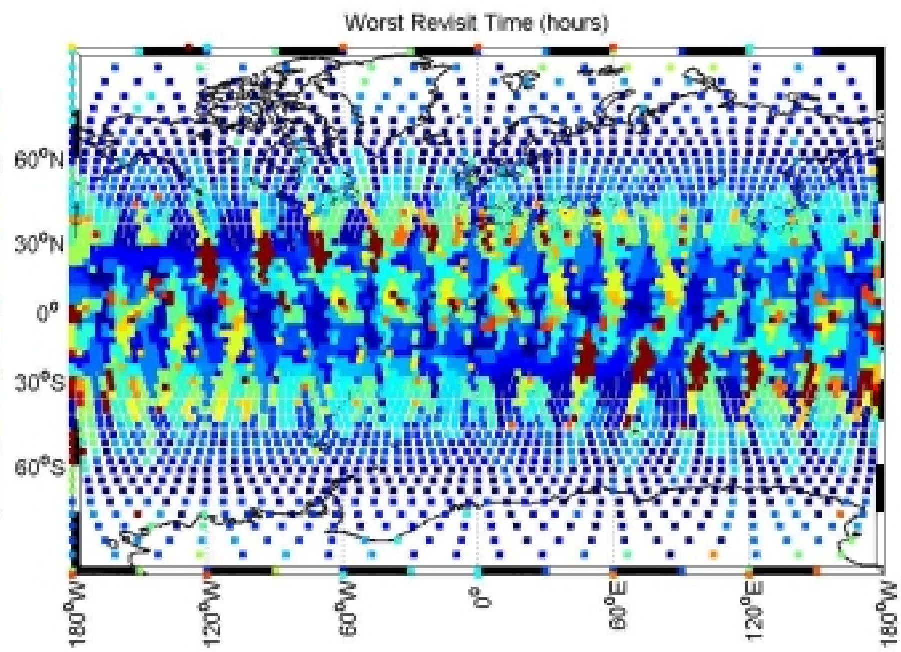
1-Day Worst Case Revisit Time

GPM Core, Four Co-ops, & Three 600-km Drones

600-km Sun-Synchronous



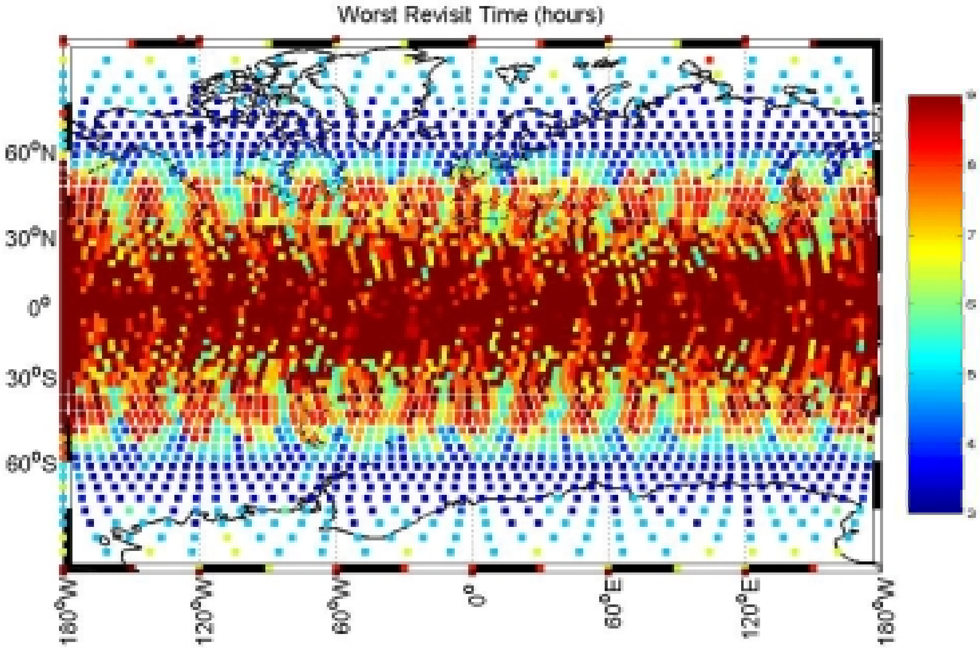
600-km Inclined - 34 , 84 , 90



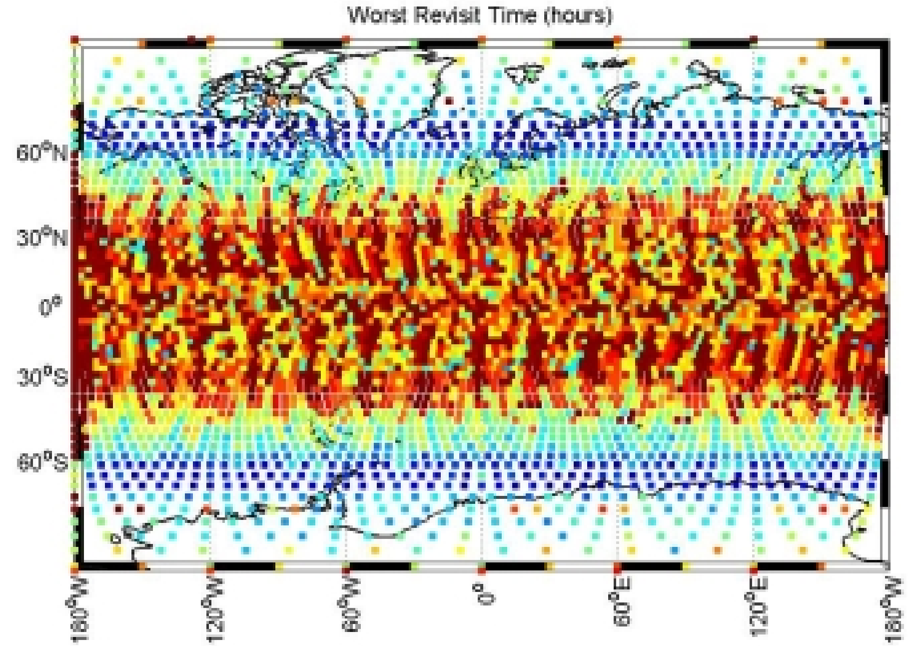
7-Day Worst Case Revisit Time

GPM Core, Four Co-ops, & Three 600-km Drones

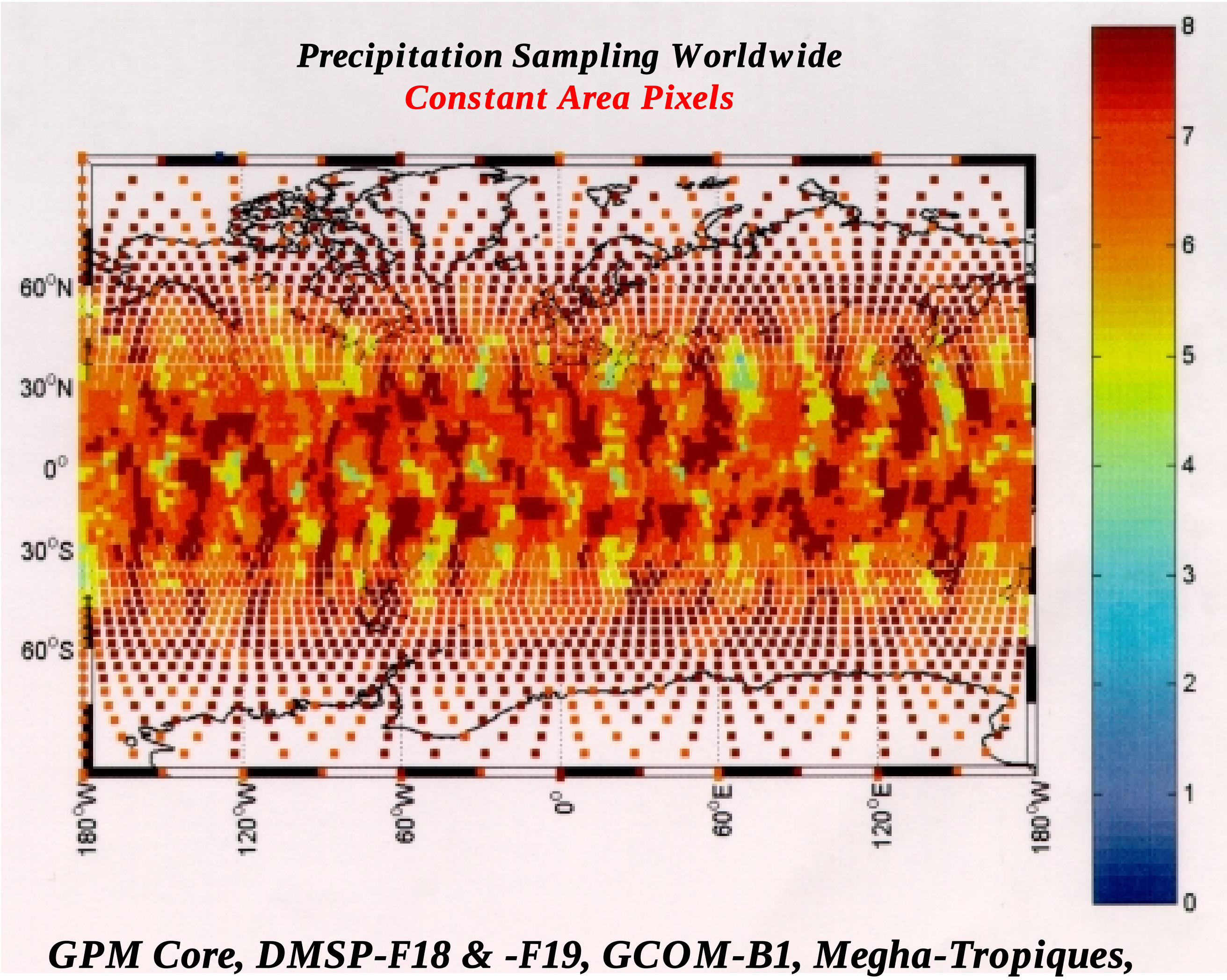
600-km Sun-Synchronous



600-km Inclined - 34 , 84 , 90

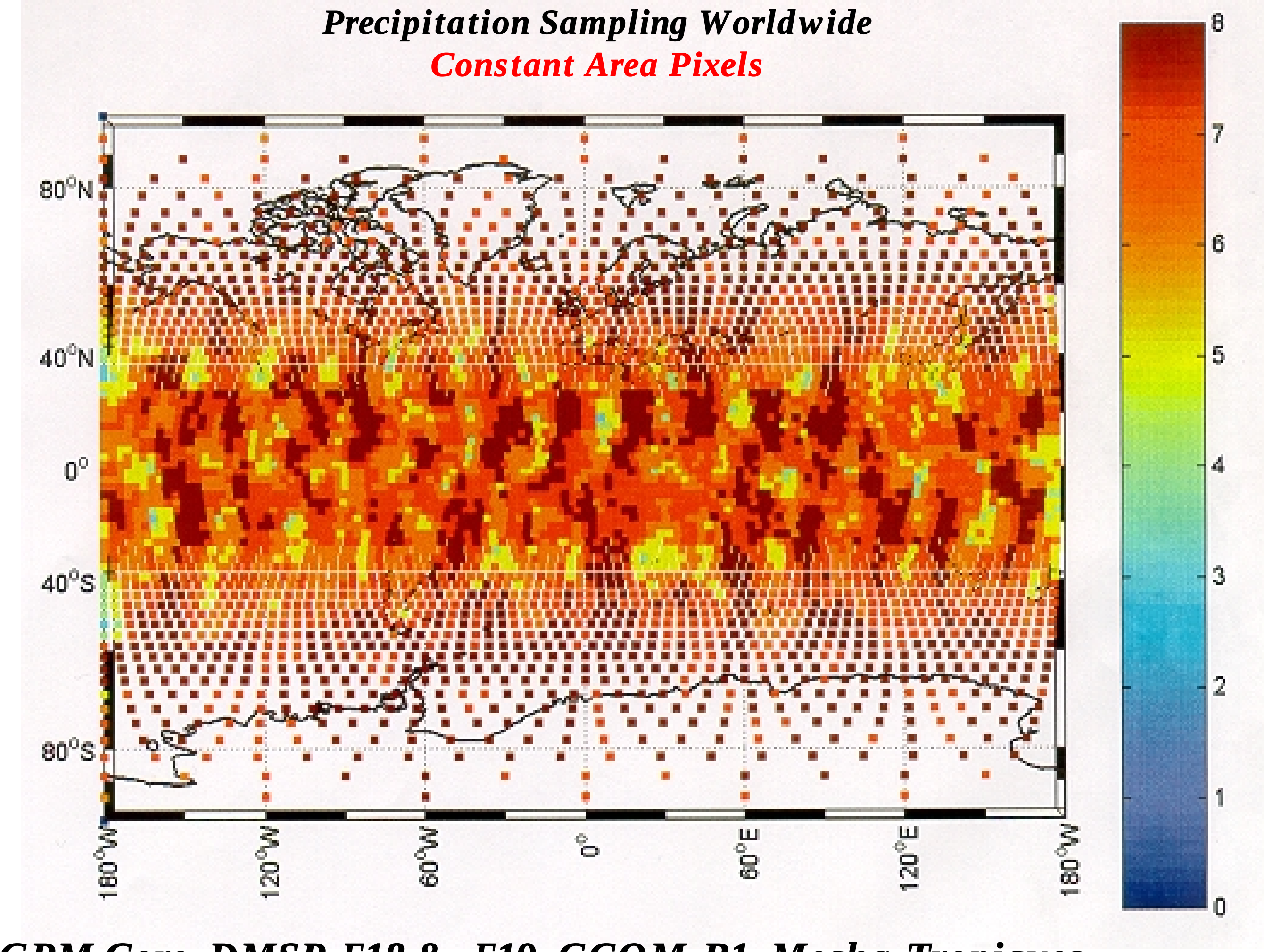


Number of 3-Hour Intervals Sampled in One Day



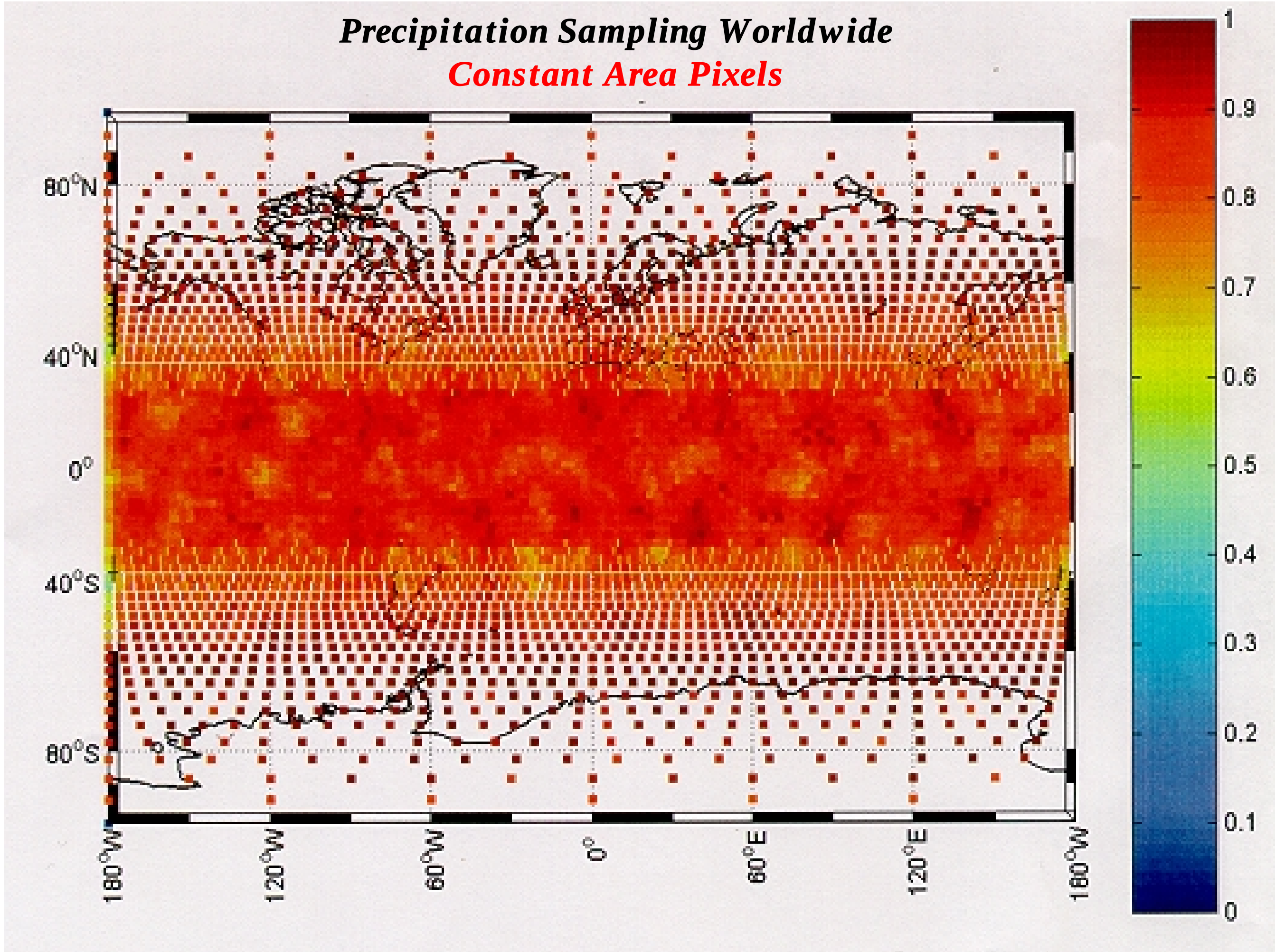
GPM Core, DMSP-F18 & -F19, GCOM-B1, Megha-Tropiques, & Three 600-km Drones @ 34 , 84 , 90   Inclination

Number of 3-Hour Intervals Sampled in One Day – Different Day



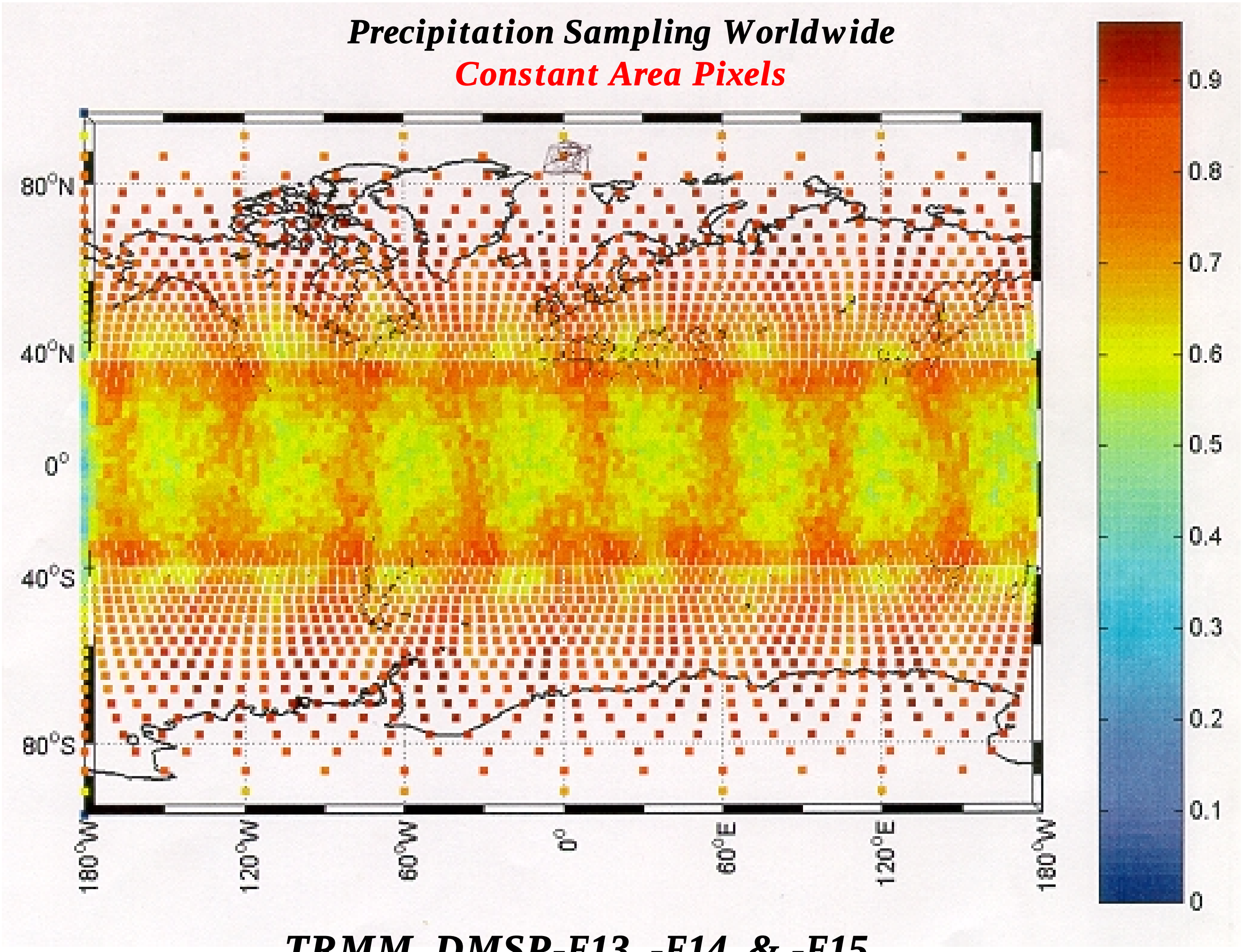
GPM Core, DMSP-F18 & -F19, GCOM-B1, Megha-Tropiques, & Three 600-km Drones @ 34 , 84 , 90 Inclination

GPM Era - Percentage of 3-Hour Intervals Sampled in 7-Day Period



GPM Core, DMSP-F18 & -F19, GCOM-B1, Megha-Tropiques, & Three 600-km Drones @ 34 , 84 , 90 Inclination

EOS Era - Percentage of 3-Hour Intervals Sampled in 7-Day Period

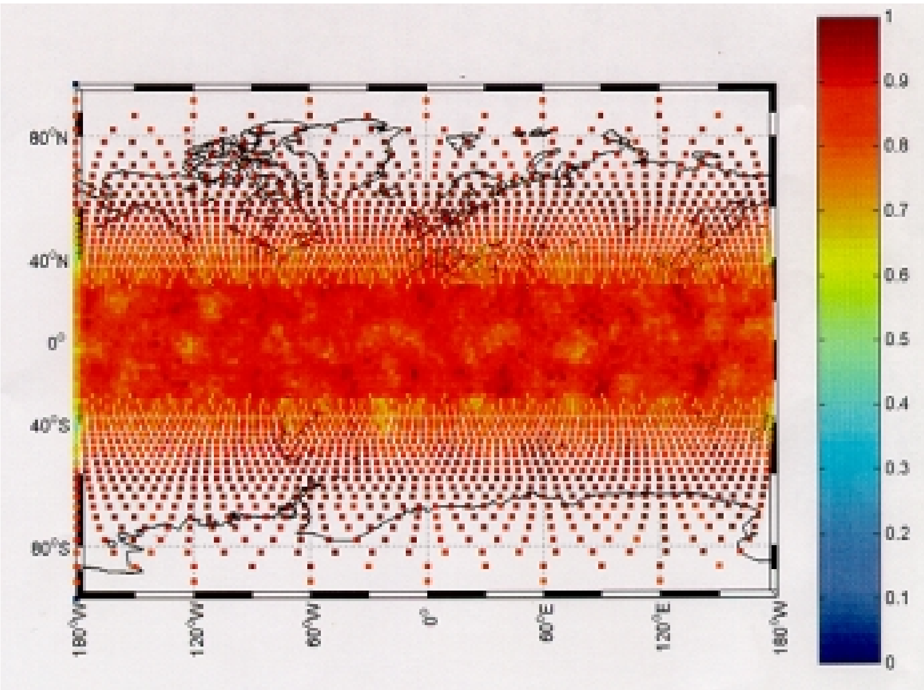


TRMM, DMSP-F13, -F14, & -F15, Aqua, & ADEOS-II

Percentage of 3-Hour Intervals Sampled in 7-Day Period

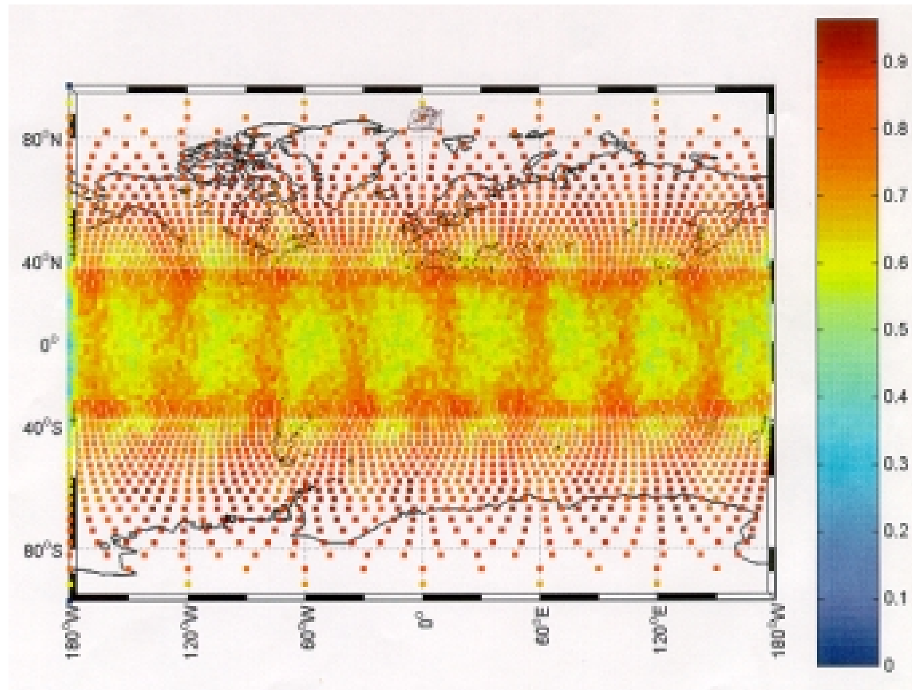
Precipitation Sampling Worldwide: Constant Area Pixels

GPM Era



GPM Core, DMSP-F18 & -F19, GCOM-B1, Megha-Tropiques, & Three 600-km Drones @ 34 , 84 , 90 Inclination

EOS Era



TRMM, DMSP-F13, -F14, & -F15, Aqua, & ADEOS-II

Fleet Optimizing Issues

- *What should be optimized?*
  - *Coverage?* *Major Precip Regions?*
  - *Sample interval?* *Hits per time bin?*
  - *Average?* *Worst case?*
  - *Over what period?* *To what percent?*
- *What weighting function(s), if any, should be applied?*
- *Is diurnal aliasing of concern?*
- *Does rain sample's value change with sample interval?*
- *What are characteristic increments of short sample intervals, e.g., due to clustering from multiple satellite coverage?*
- *What are constraints on Drone satellites?*
  - *Ground footprint & Radiometer aperture?*
  - *Scan mode and Scan swath width?*
  - *Launch & & Shared or multiple launch?*
  - *Inclination & Altitude?*

Conclusions

1. GPM must proceed as mission of opportunity with interested partners -- not requiring orthodox constellation of identical Drone satellites.
2. Non-heterogeneous orbits of Co-op satellites will produce “gap blinking” which precludes “perfect” sampling and coverage strategy.
3. Fleet approach will be used in which optimization scheme selects Drone orbits -- noting there are various optimization strategies -- also noting launch considerations may constrain preferred strategy.
4. “Gap blinking” is most serious if drones are placed in sun-synchronous orbits.
5. Non-sun-synchronous orbits are more effective for achieving consistent coverage.
6. Autonomous orbit control would eliminate coverage deterioration.