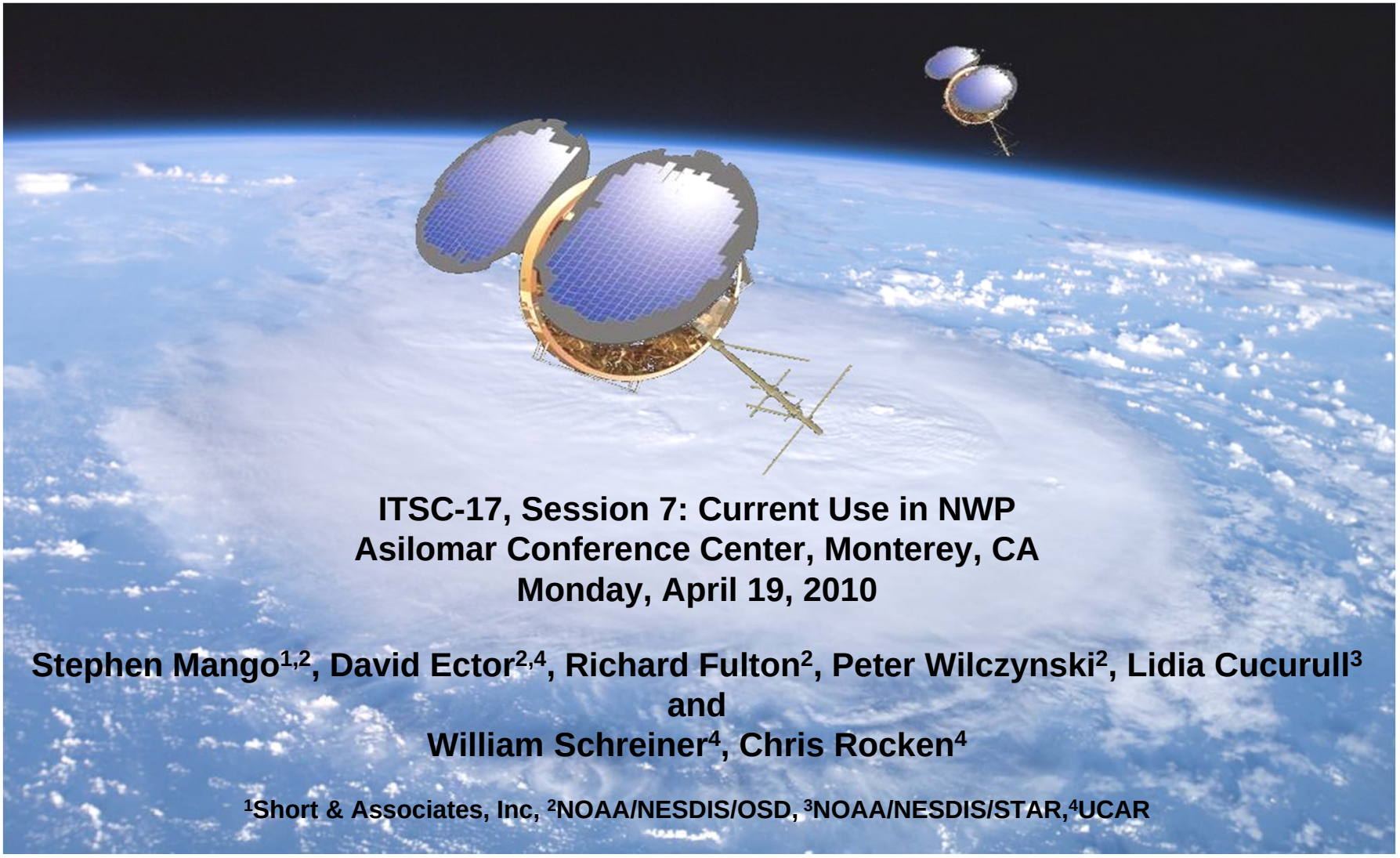
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Emerging and Evolving Opportunities for Achieving Global Soundings for NWP and Climate Using GNSS/GPS Radio Occultation Systems



ITSC-17, Session 7: Current Use in NWP
Asilomar Conference Center, Monterey, CA
Monday, April 19, 2010

Stephen Mango[1,2], David Ector[2,4], Richard Fulton[2], Peter Wilczynski[2], Lidia Cucurull[3] and William Schreiner[4], Chris Rocken[4]

[1]Short & Associates, Inc, [2]NOAA/NESDIS/OSD, [3]NOAA/NESDIS/STAR,[4]UCAR

OUTLINE

- Introduction / Basis

  COSMIC/FORMOSAT-3 GPS RO Constellation [Apr 2006 – Present]
  [6 GNSS RO S/C in LEO Orbits (alt = ~ 800 km., i = 72°)]

  Comparison of Traditional Cross-Track Sounders and GNSS RO Sounders

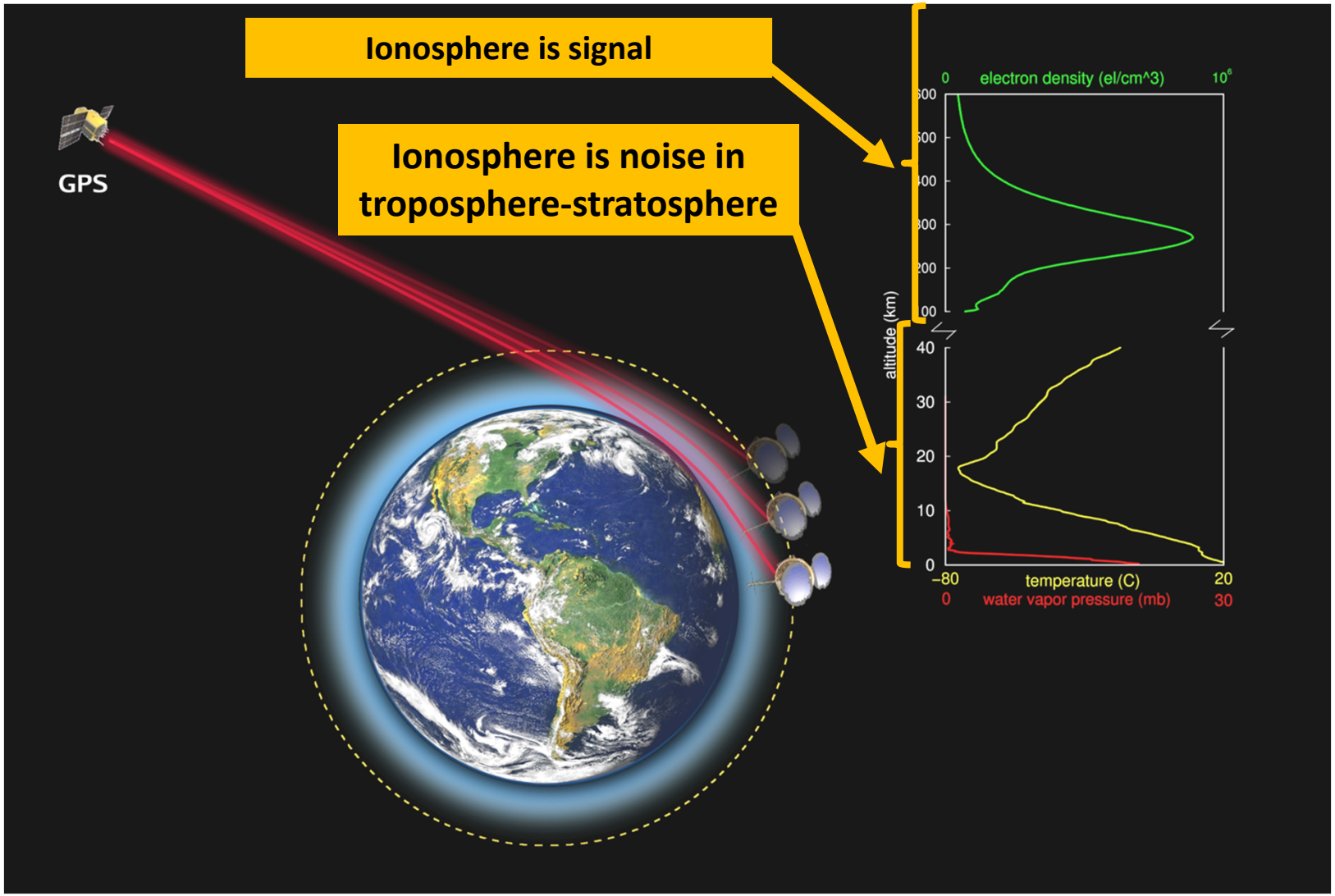
- Multiplicity of GNSS Signal Sources
  - GNSS Signal Source Constellation Systems
  - GNSS Signal Source Characteristics
  - Timelines for GNSS Signal Sources

- Multiplicity of Spacebased GNSS Radio Occultation Receivers
  - Some GNSS RO Capabilities, Coverage/Spatial Density,
  - Multiple GNSSRO Constellations

- COSMIC-2 Status

- Coverage utilizing Multiplicities of GNSS Sources and RO Receivers
  - Global and/or Regional

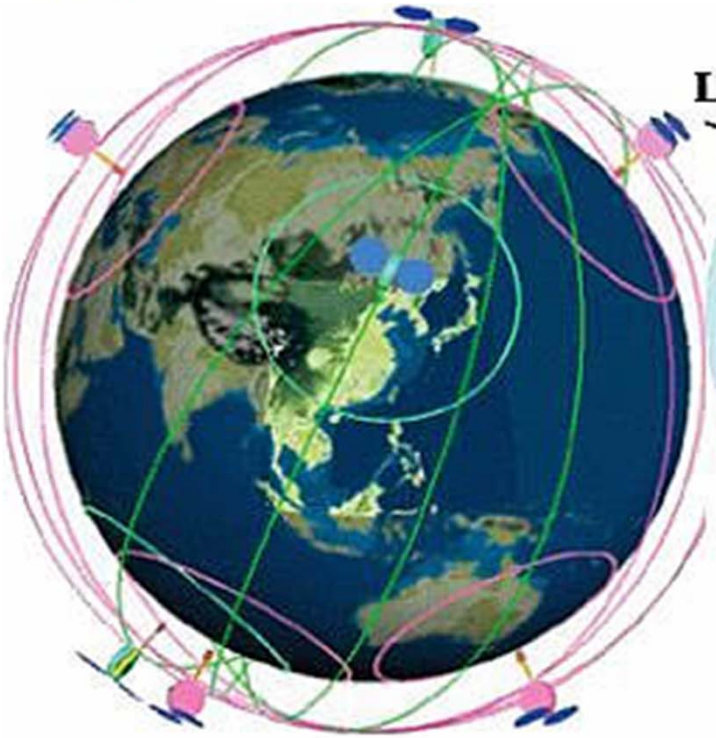
GPS Radio Occultations
[GPSRO]

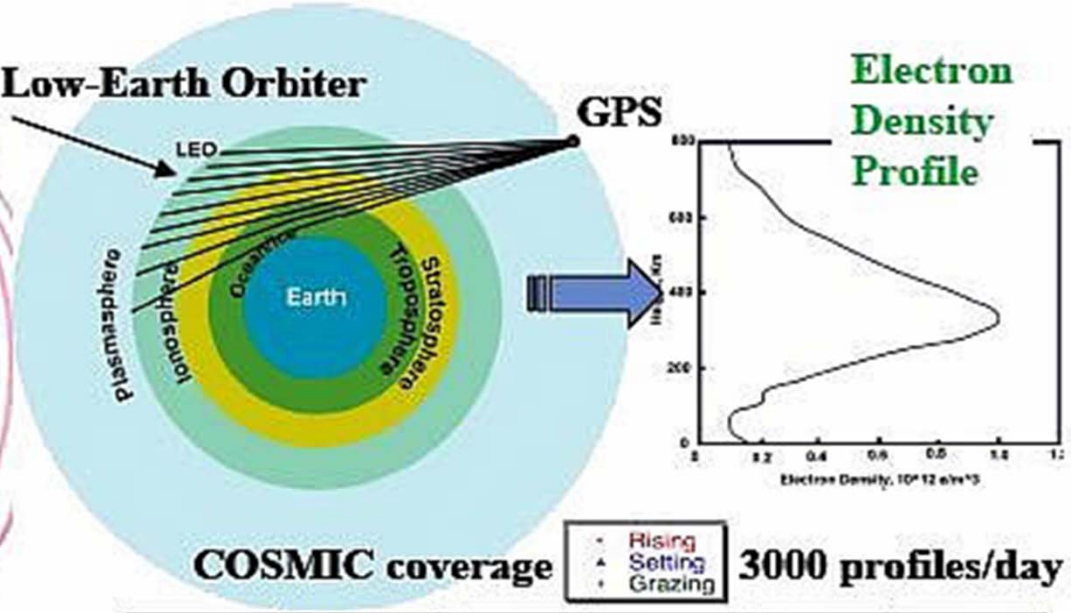


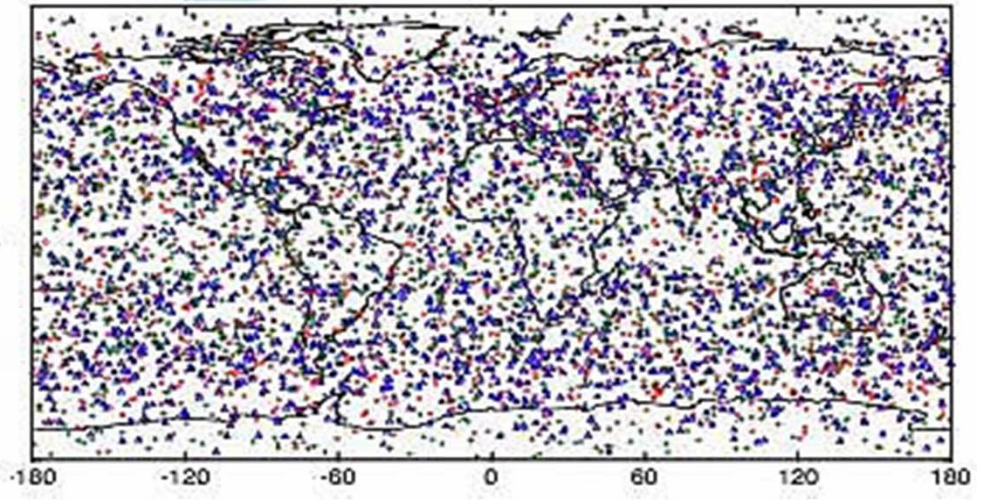
Environmental Data Records Provided by GPS RO

Atmospheric Temperature Profiles [T (h_s)]
Water Vapor Profiles [ρ(h_s)]
Pressure Profiles [P(h_s)]
Refractivity Profiles [N(h_s)]
Bending Angle Profiles [α(h_s)]
Electron Density Profiles [N_e(h_s)] & Total Electron Content [TEC]
Ionospheric Scintillation [S_4 & σ_φ]
Height of the top of the planetary boundary layer [PBL]
Height of the tropopause [$H_{trop\ max}$]

COSMIC / FORMOSAT-3





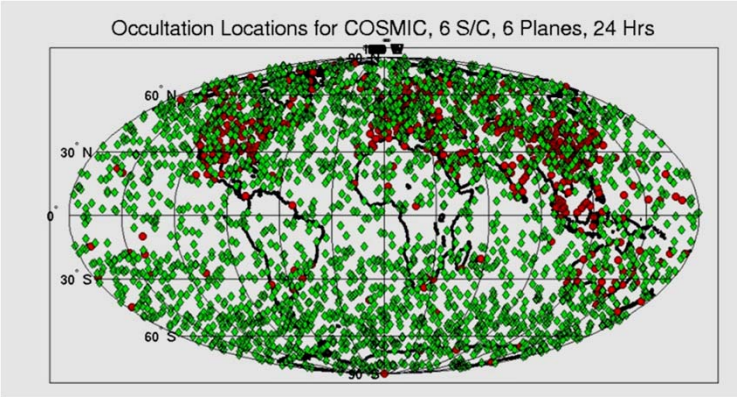


Six-satellite COSMIC constellation

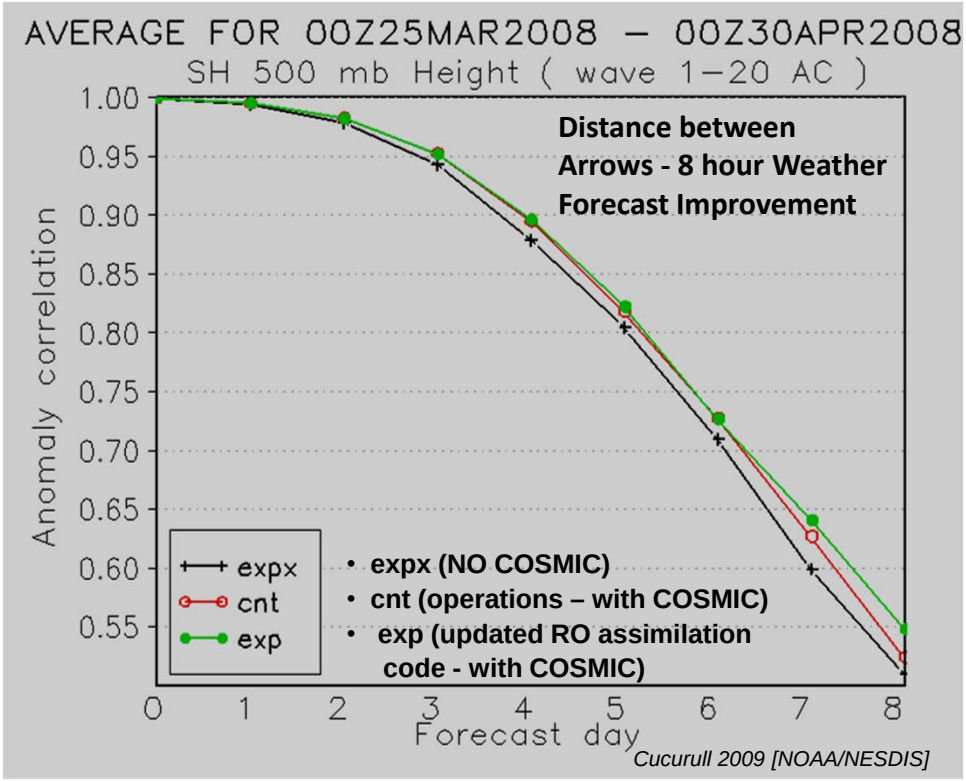
NSF NASA USAF NOAA NSPO ONR

Six (6) COSMIC GPS RO Satellites
Significant Impact on Weather Service Forecast Skill

- **Proven significant forecast accuracy improvement**
- **40-day experiments:**
  - **Black line - No COSMIC**
  - **Red line - COSMIC Initial Operations**
  - **Green line - Current COSMIC**



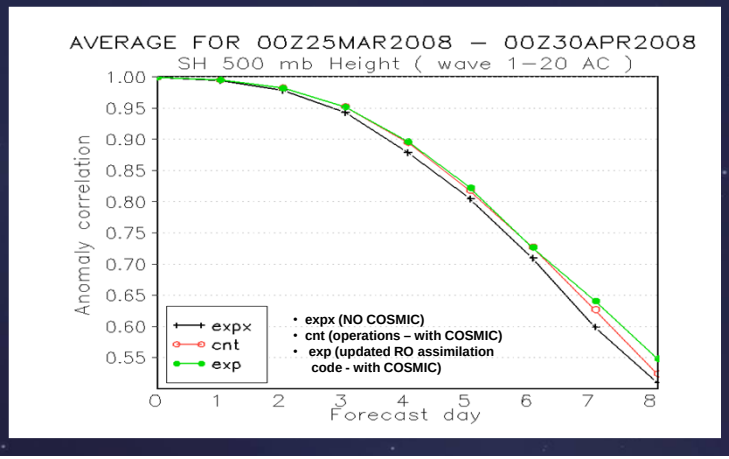
Daily - COSMIC vs Radiosondes



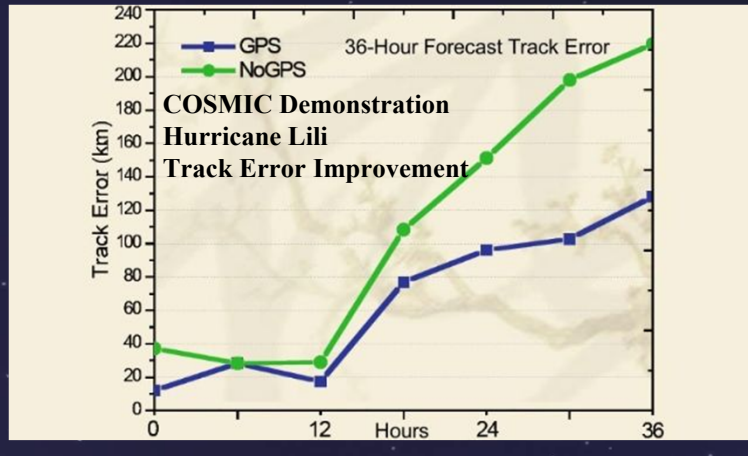
-COSMIC provides significant improvement in Weather forecast skill
8 hours improvement at Forecast Day 4 and
>15 hours improvement during Forecast Day 7
- Particularly significant improvement over the oceans and in Southern Hemisphere
- Analysis – COSMIC satellite loss causes significant NOAA forecast skill loss

GNSS RO
Application Area Examples

NWP



Storms / Severe Weather



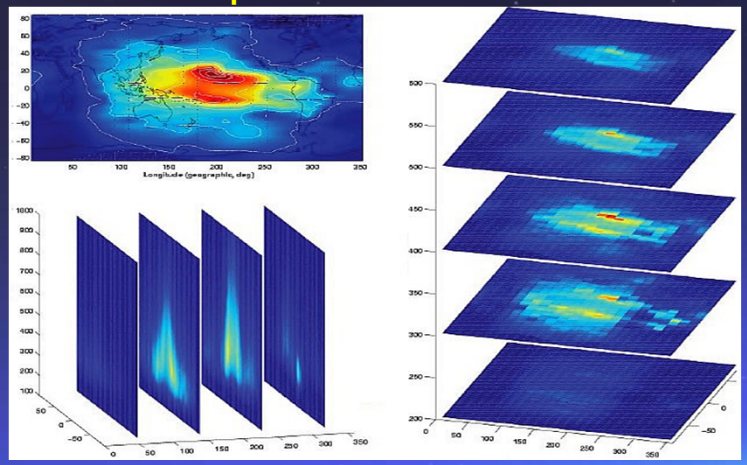
Climate

GNSS RO can measure:

- ENSO Signal
  (El Niño - Southern Oscillation – dominant tropospheric variability)
- Global QBO
  (Quasi-Biennial Oscillation - dominant signal in stratosphere)

From Bill Randel [UCAR]

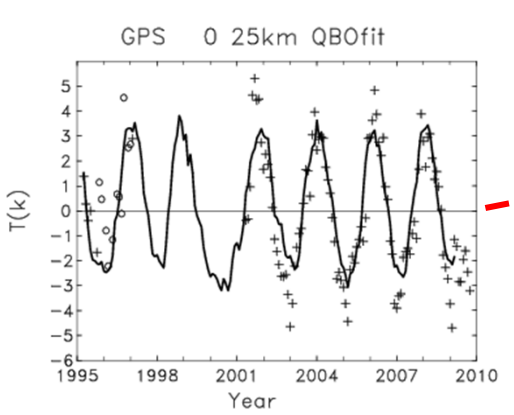
Space Weather

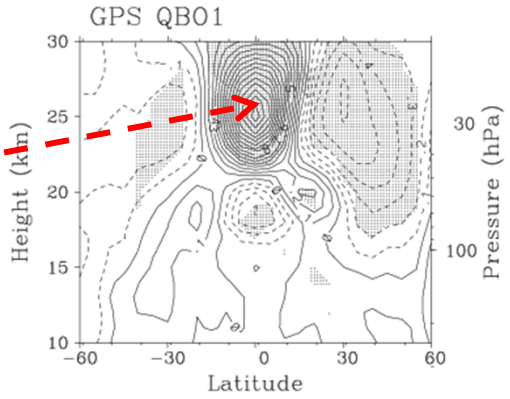


3-D Maps Global Electron Distribution From Electron Density Profiles Updated@ Few Minutes Combined Tomographically [from A. Mannucci, 2009]

COSMIC
Climate Signal Measurements

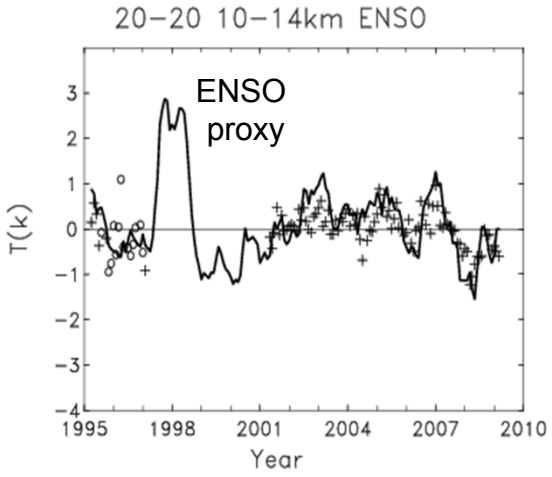
Global QBO Signal (Dominant Signal in Stratosphere)

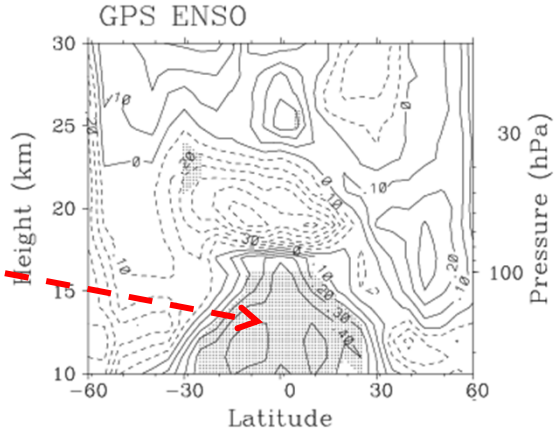




ENSO Signal (Dominant Tropospheric Variability)

Characteristic ENSO signature





From Bill Randel [NCAR] 2010

Comparison (1/2)

Traditional Cross-track Infrared/Microwave Sounders and GPS Radio Occultations [GPSRO] Sounders

Attribute	AIRS/AMSU IASI/AMSU CrIS/ATMS	GPSRO
Assimulation of Pre-Geophysical Product Data into NWP Models, i.e. Weather Forecasting	Yes (Calibrated Radiances or Retrieved Profiles)	Yes (Bending Angles or Refractivities)
Assimulation into Climate Prediction Models	Yes	Yes
All Weather Sounding Capability for Troposphere	No*	Yes[1]
Direct measurement of total mass of atmosphere at each altitude level	No	Yes
Determination of Atmospheric Temperature Profiles throughout Troposphere	Yes	Yes[2]
Determination of Atmospheric Moisture Profiles	Yes	Yes[2]
Accurate Determination of Tropopause [establishes important boundary condition for NWP]	No	Yes
Requires First Guess Sounding – affects accuracy & rate of convergence of an iterative process	Yes	No

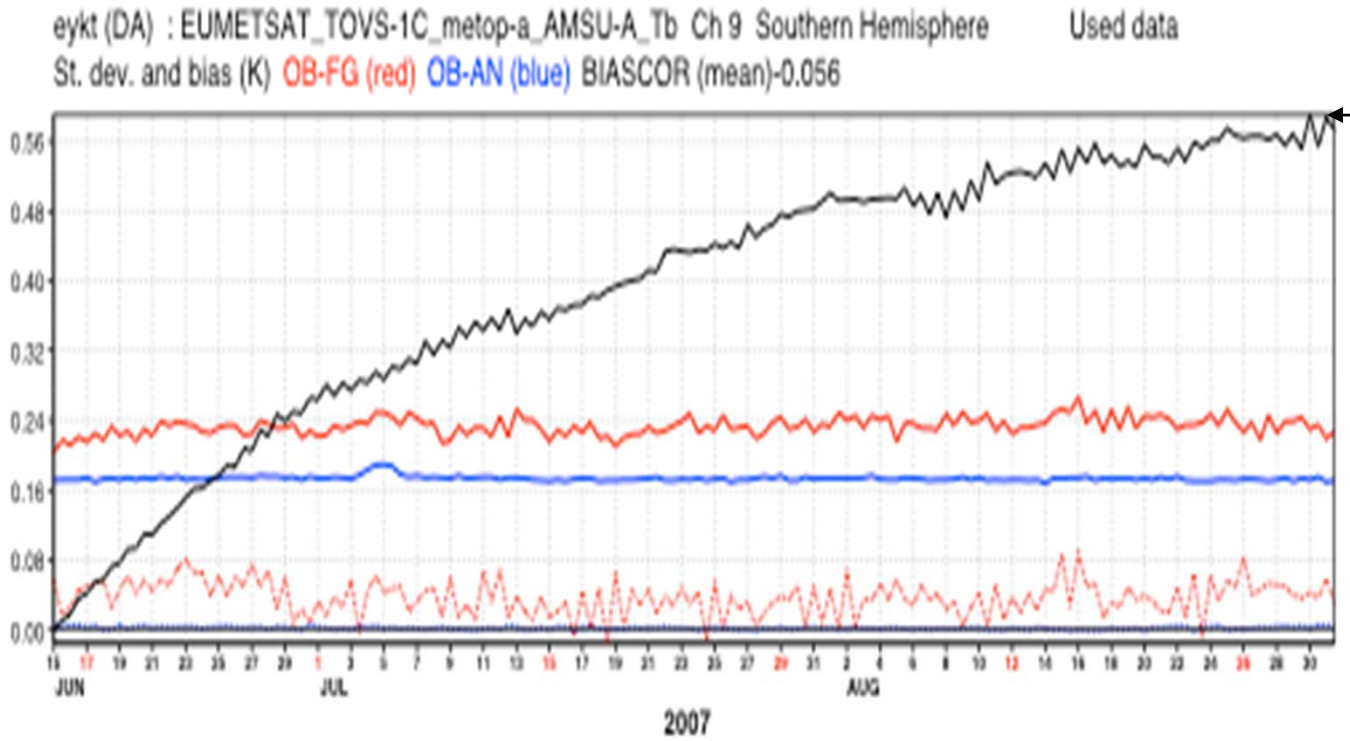
Footnotes: 1. Only minimally affected by clouds, aerosols and light precipitation, "Applications of COSMIC to Meteorology and Climate", R.A. Anthes, C. Rocken, Y.-H. Kuo
2. Separates temperature and moisture effects where T(layer) < 225 K or altitude h > ~ 8 km

Comparison (2/2)

Traditional Cross-track Infrared/Microwave Sounders and GPS Radio Occultations [GPSRO] Sounders

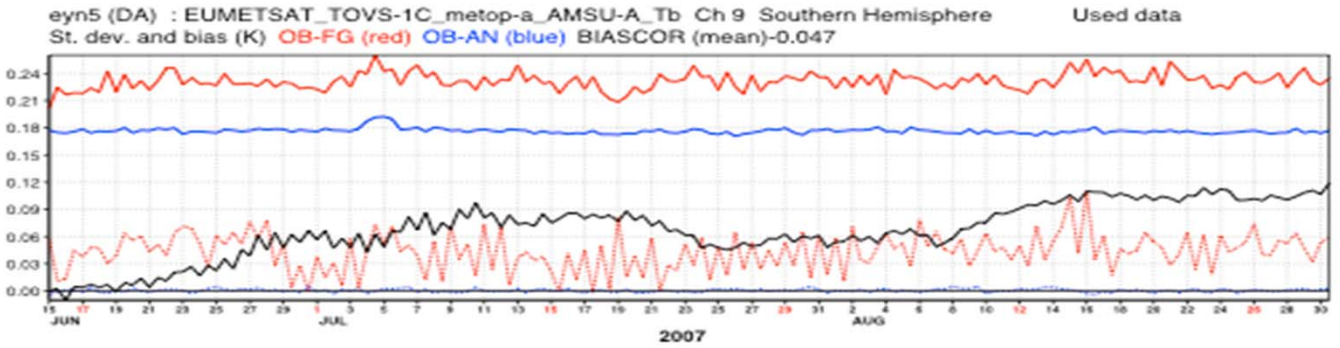
Attribute	AIRS/AMSU IASI/AMSU CrIS/ATMS	GPSRO
High Accuracy Profiling throughout Troposphere for weather & climate forecasting	Yes – High	Yes - Higher
Vertical (Altitude) Resolution throughout Troposphere	High	Higher
Horizontal Resolution for NWP throughout Troposphere	Moderate	Low –Along Track High – Cross Track
Requires radiosondes, vicarious calibrators or other external sources for calibration/validation	Yes	No Self Calibrating
Instrument Drift over lifetime of sensor (s)	Usual and Customary & Can present calibration issues	Not a calibration issue, due to rationing technique
Satellite-to-Satellite Bias – Requires correction	Yes*	No
Can profile Ionosphere [e.g. electron density]	No	Yes

Bias Correction AMSU-A Ch 9 – with and without COSMIC (ECMWF)



Without COSMIC

GPS RO "Anchors" the model



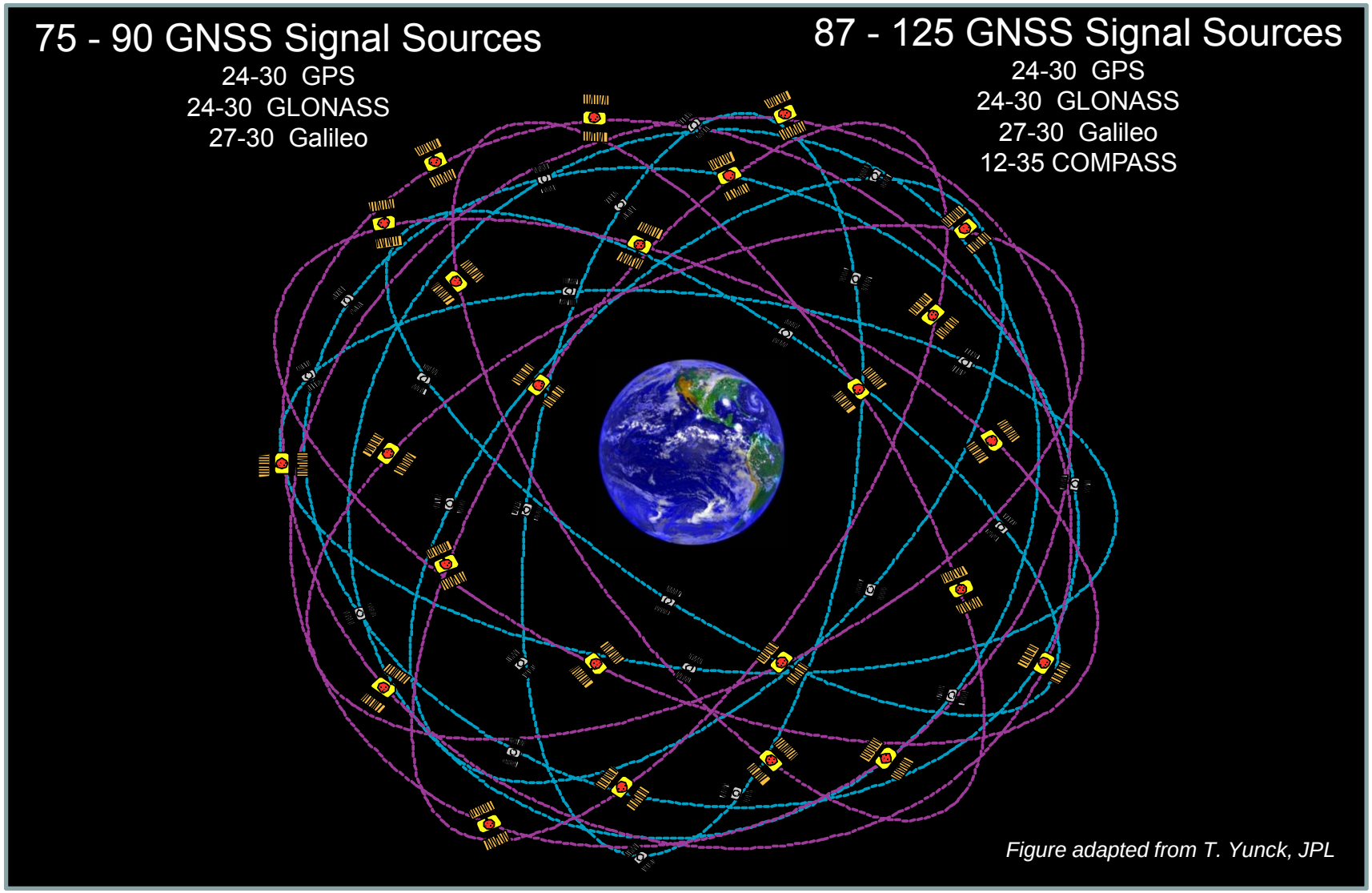
With COSMIC

Healy et al

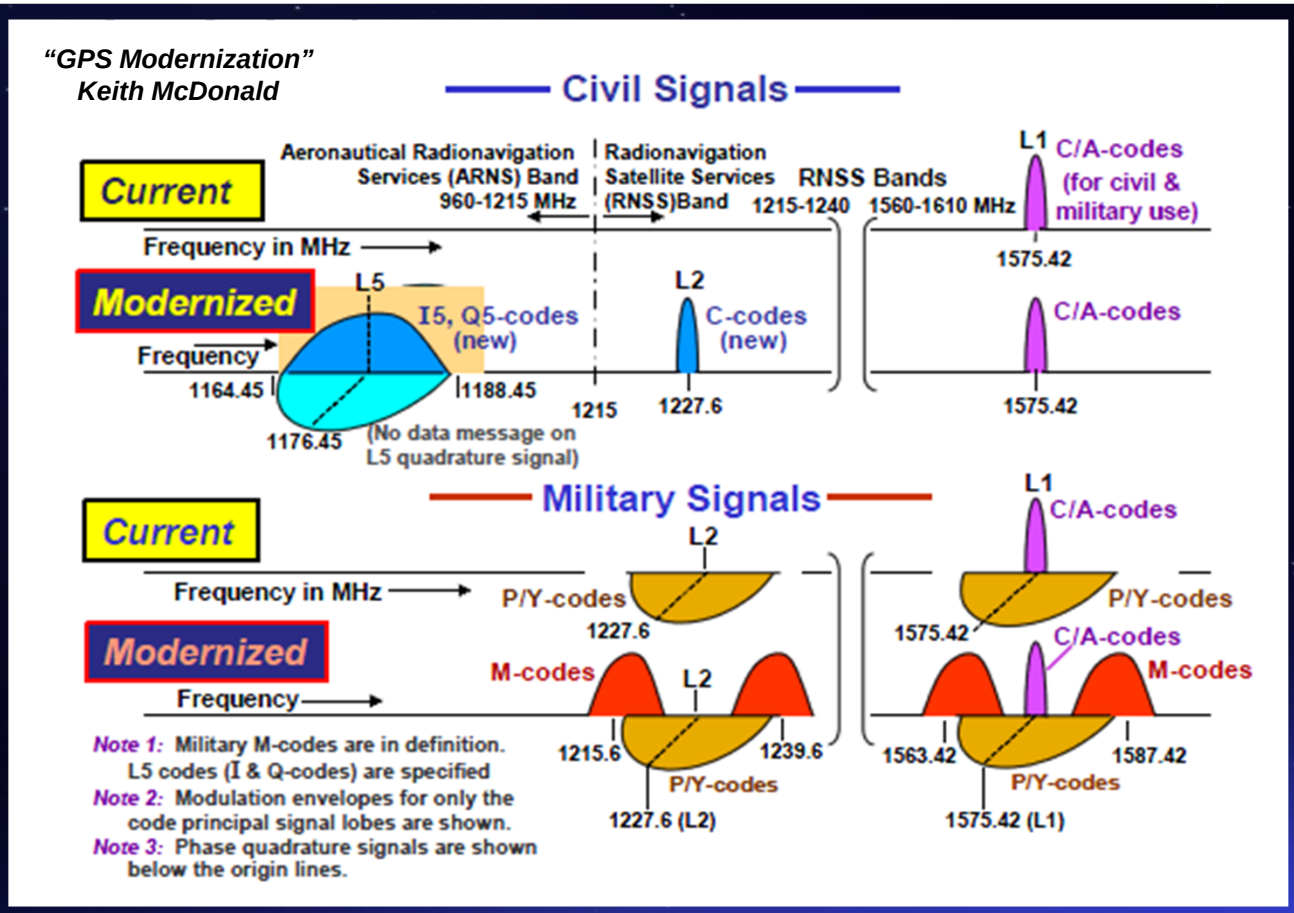
Multiplicity of GNSS Signal Sources
GNSS Signal Source Constellation Systems

System	Status	Constellation Configuration/Performance
GPS [USA]	31 Satellites actively broadcasting plus 2 Satellites Spares (retired from active service but kept in orbit as spares)	30 Satellites for Complete Constellation (MEO Orbits) 6 Orbital Planes (was 3 Orbital Planes originally), 55^{o} Inclination 4 Operational Satellites + 1 Spare per orbit (equally spaced) [was 7 + 1 orig.] Ascending Nodes separated by 60^{o} in Right Ascension or longitude Altitude ~ 20,200 km (12,552 mi., 10,900 nm) Orbital Period ~ 11 ^{hrs}58^{min}; 2 orbits in 1 sidereal day [23.9344696 hrs] (repeats same ground track @ day)
GLONASS [Russian Fed]	19 Satellites in orbit [all 2nd Generation: GLONASS-M, aka Uragan-M types] [16 operational, 3 under maintenance (1 may be decommissioned); FDMA type] 18 Satellites required for complete coverage of Russian Federation 24 " " " " " worldwide Third Generation Satellites planned to start in 2009 [CDMA] Plan to conduct 2 launches of 3 Satellites @ or 6 Satellites (within next ~2 yrs), Launch plan Sept 2010–2 GLONASS-M(FDMA) + 1 GLONASS-K(CDMA), # of Satellites to be increased to 30 by 2011	To be 24 Satellites (MEO Orbits) 3 Orbital Planes, 64.8^{o} Inclination Planes have latitude displacement of 15^{o} 7 Operational Satellites +1 Spare per orbit (equally spaced) Ascending Nodes separated by 120^{o} longitude Altitude ~ 19,100 km (11,868 mi., 10,307 nm) Orbital Period ~ 11 ^{hrs}15^{min}; 64 orbits in 30 days Performance: 1. SP [Standard Precision] Mode: Hor. 5-10 m.; Ver.15 m.; Speed ~10 cm/sec; Timing 200 nsec 1. HP [High Precision] Mode: ???
Galileo [EU]	Presently in test bed phase GIOVE [Galileo In-Orbit Validation Element] GIOVE-A (built by Surrey Sat. Tech. Ltd-SSTL) Launched 12/28/2005 GIOVE-B (built by Astrium and Thales Alenia Space) Launched 4/27/2008 GIOVE-A2 (built by SSTL) was to be ready for Launch 2nd half of 2008 GIOVE to be followed by 4 IOV Galileo satellites (much closer to final design) IOV will have the minimum needed 4 Satellites for a demo/validation 2 IOV Satellites to be launched in Nov 2010 (as of 10-13-2009) 2 IOV " " " " Early 2011 (as of 10-13-2009) Remaining 28 Satellites of Galileo – EU & ESA to select builder by late 2009 11 Companies bidding - Nov2009; Contract Award for 22 satellites Dec 2009 – Competing Teams incl. OHB Systems/Surrey Sat Tech. & EADS Astrium Thales Alenia Space Award to Surrey Sat Tech. & EADS Astrium Operational Galileo planned: (16 sats:4 IOV & 12 FOC) to be deployed by end of 2013; Remaining 10 sats post-2014	To be 30 Satellites (MEO Orbits) [Walker 27/3/1] 3 Orbital Planes, 56^{o} Inclination 9 Operational Satellites+1 Active Spare per orbit Ascending Nodes separated by 120^{o} longitude Altitude ~ 23,100 km (14,351 mi., 12,463 nm) Orbital Period ~ 14 ^{hrs}5^{min}; 17 orbits in 10 days Satellite Lifetime ~ 12 years Performance: Accuracy – Hor. And Vert. - meters Better positioning at high lats. than GPS& GLONASS
Compass [China]	Completed experimental phase, Beidou-1, 4 satellites Operational System will be called Beidou-2 Launched 1st operational Beidou-2 into MEO – Apr 2007,2nd into GEO, Apr 2009 Plans to launch 10 more operational in next 2 years after first Plan to have regional coverage of China by 2011-2012 [12 sats, = 5 GEO, 3 IGSO, 4 MEO] Plan to have complete coverage of globe by 2020 [35 sats]	Global Service to be 35 Satellites (5 GEO-geostationary plus 3 Inclined geosynchronous [IGSO] plus 27 MEO) MEO Orbits, 6 Orbital Planes ?, 55.5^{o} Inclination Altitude (Perigee) ~ 21,500 km (13,359 mi., 11,602 nm), Eccentricity=0.00068 Orbital Period ~ 12 ^{hrs}53^{min} (773.4 min); XX orbits in YY days Global Service Accuracy: 10m position, 20nsec timing, 0.2 m/s speed Regional Services Accuracy [Wide Area Differential Service] 1 m position

GPS/GLONASS/Galileo/COMPASS Constellations in Full Operational Capability



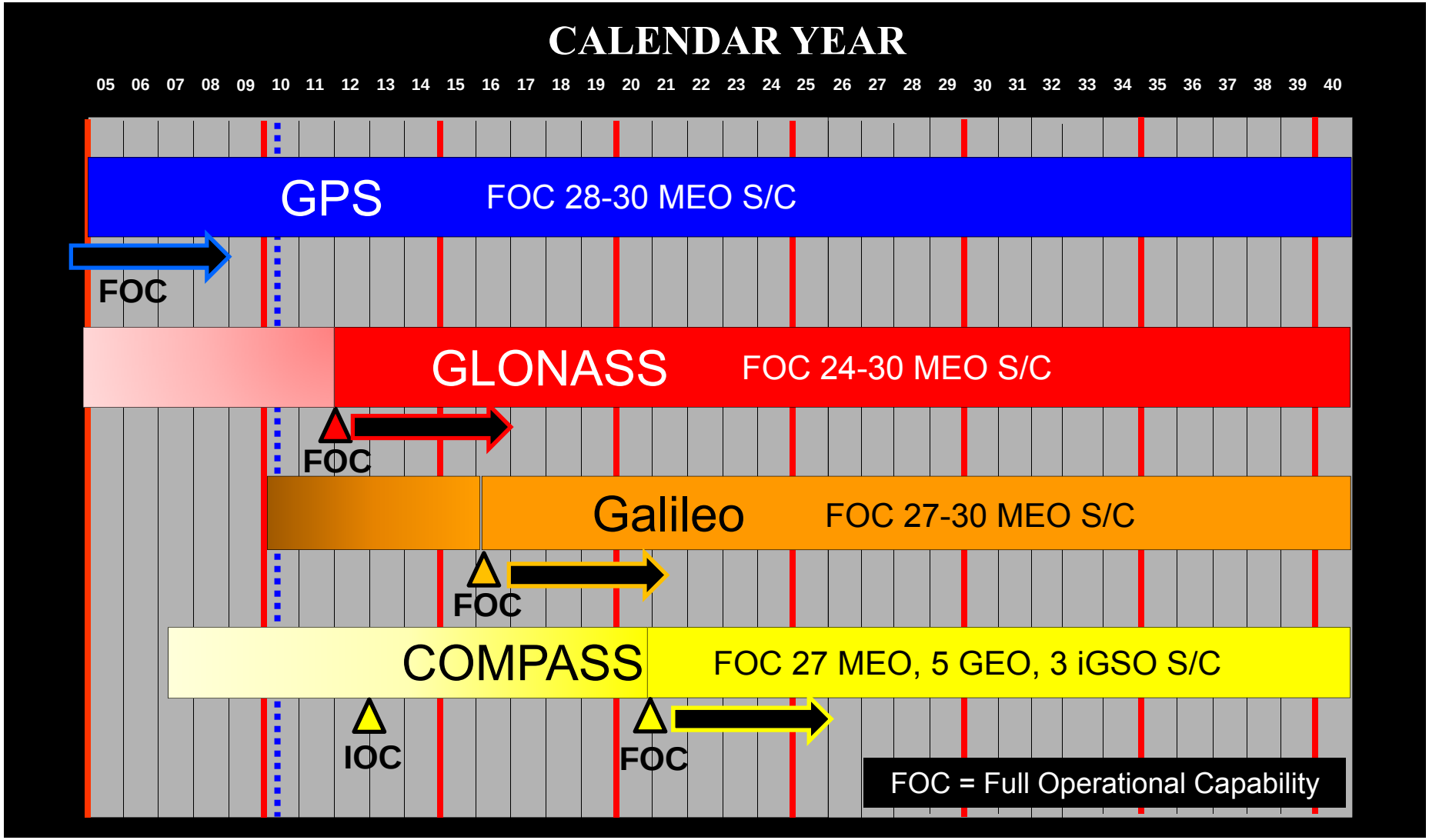
GNSS RO
Signal Source Characteristics



Opportunities with Challenges exist for GNSS System Operational Timelines
Opportunities with Challenges exist for GNSS Signal Compatibilities & Interoperability

Timelines

GNSS Signal Source Constellation Systems



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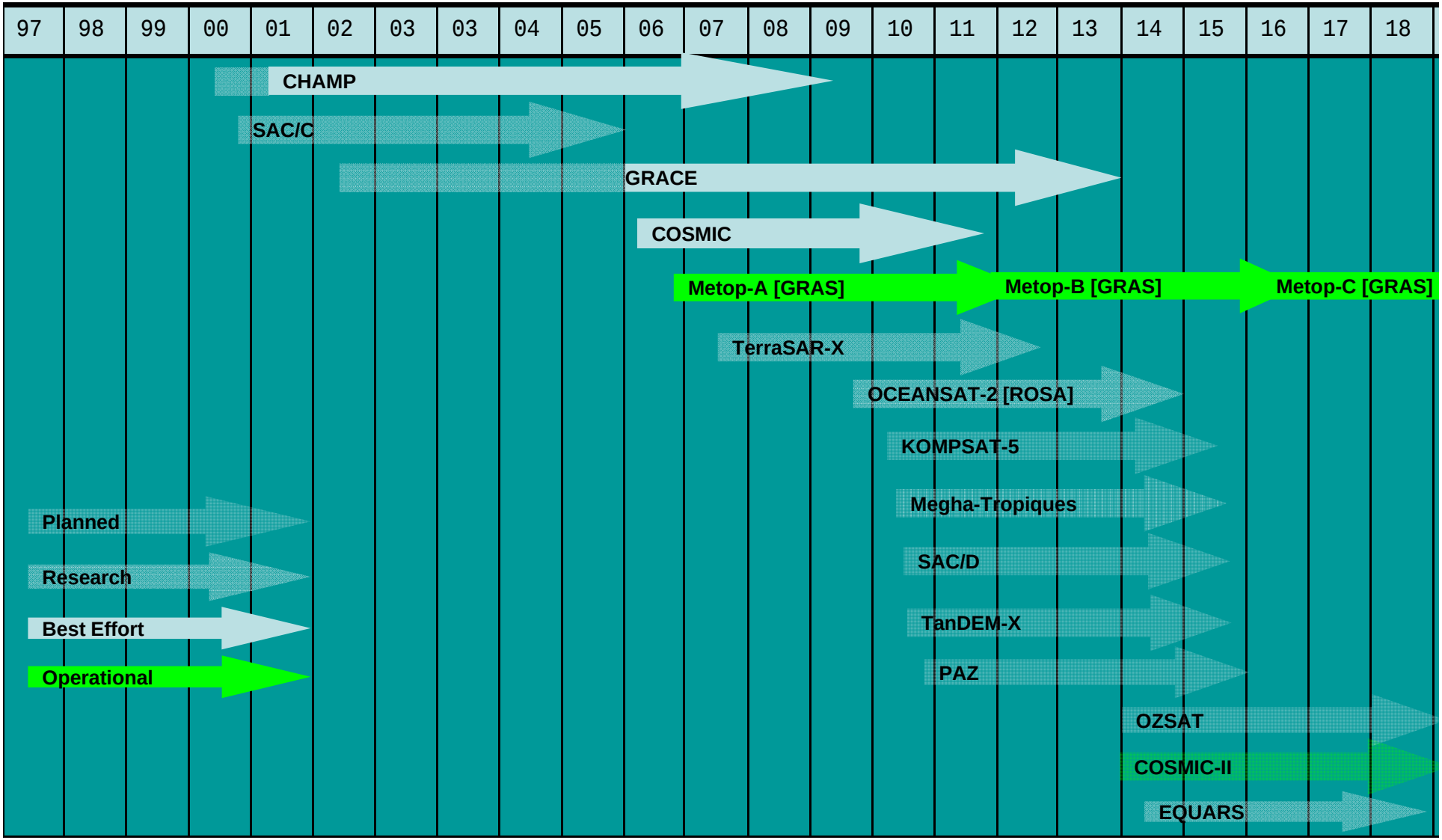
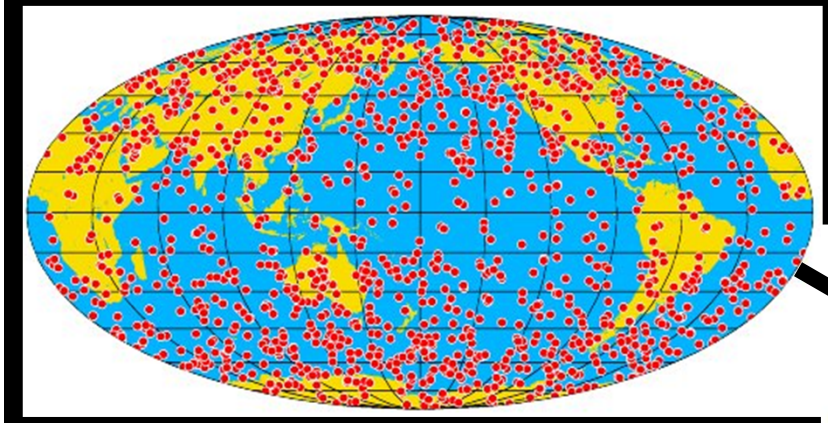
GNSS RO Actual / Possible Missions

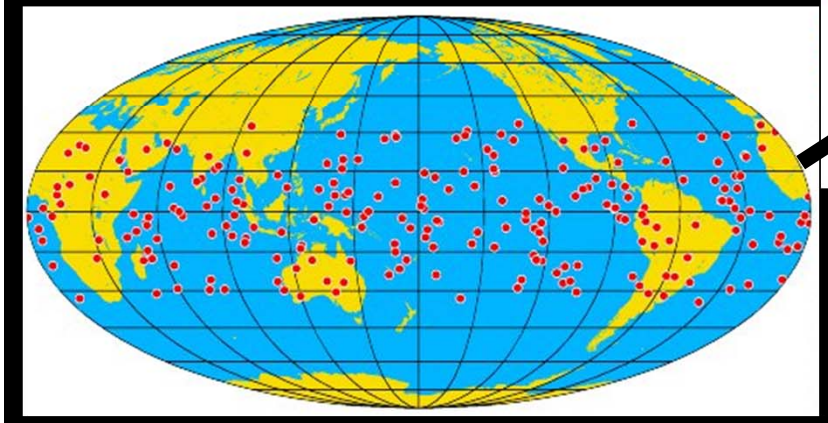


Multiple GPSRO Constellations

COSMIC [USA-Taiwan] + EQUARS [Brazil, Japan]

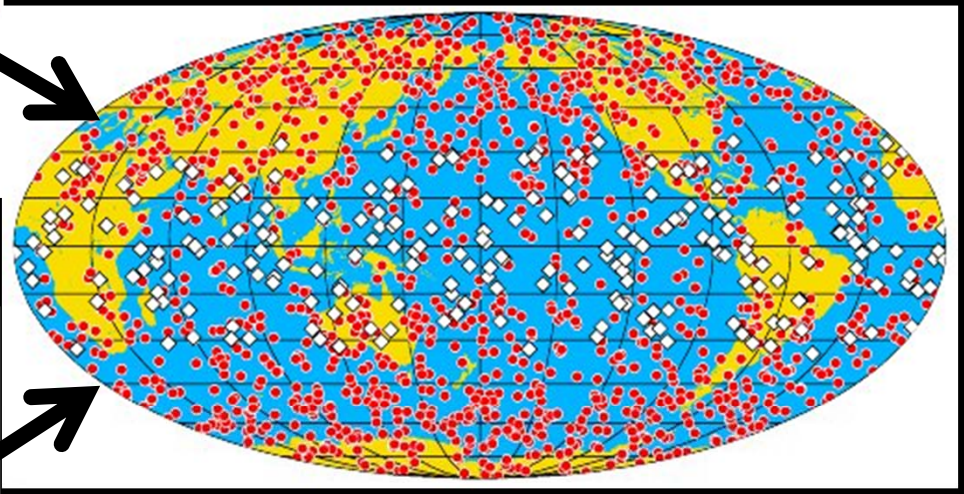


COSMIC [6 S/C; i=72º] (24 hrs.)



EQUARS [6 S/C, i=20º] (24 hrs.)

COSMIC + EQUARS (24 hrs.)



Equatorial Atmosphere Research Satellite = EQUARS

From Takahashi et al. [INPE]

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

GPS / GNSS RO

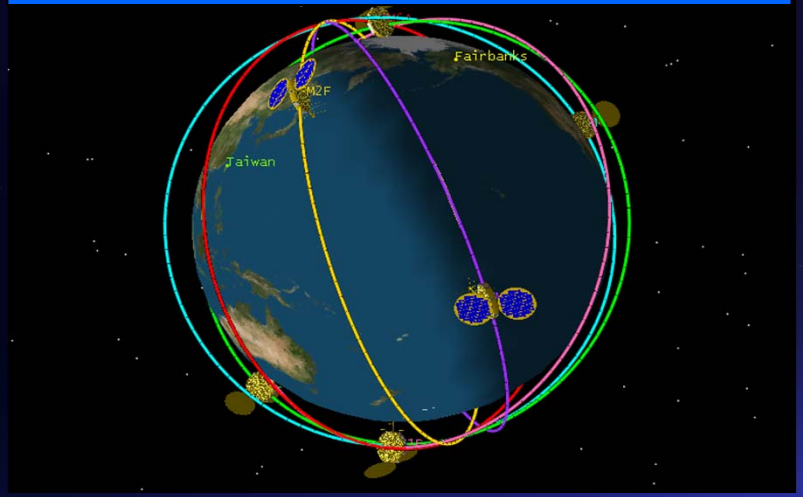
Global Positioning System /Global Navigation Satellite Systems
Radio Occultations Sensors

COSMIC = Constellation Observing System for

- Meteorology ⇒ Weather, NWP mission
- Ionosphere ⇒ Space Weather/Environment mission
- and Climate ⇒ Climate mission

COSMIC/Formosat-3

Existing Research, Proof-of-Concept System



6 Micro Satellites
Each with GPS Radio Occultations Sensor System

COSMIC-2

Future Operational System

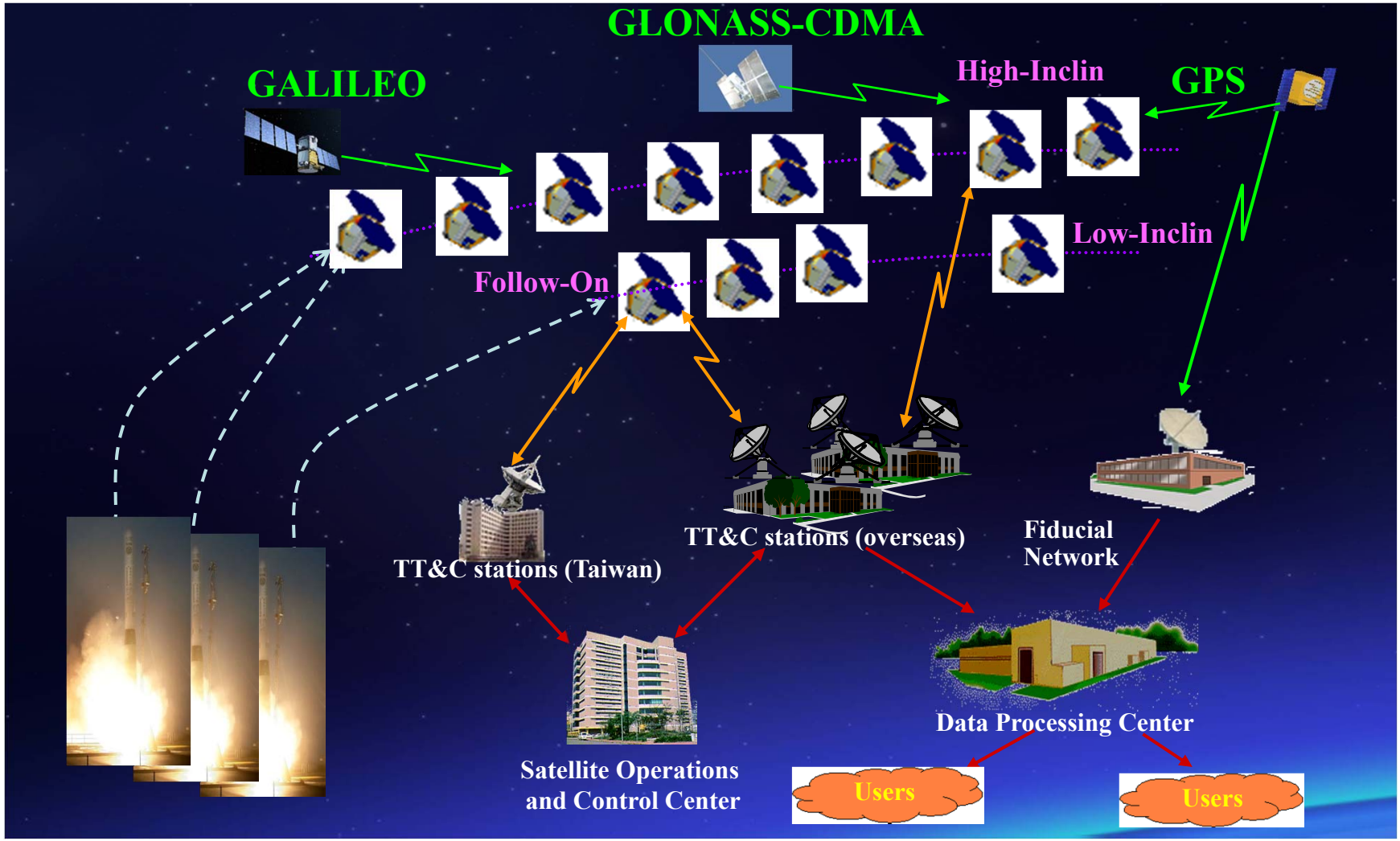
In Formulation

"Funded New Start [NOAA]"

≥ 12 Micro Satellites
Each with GPS Radio Occultations Sensor System

" A Multi-Mission, Multi-SmallSat System "

COSMIC-2 GNSS RO
Notional Architecture [USA-Taiwan]



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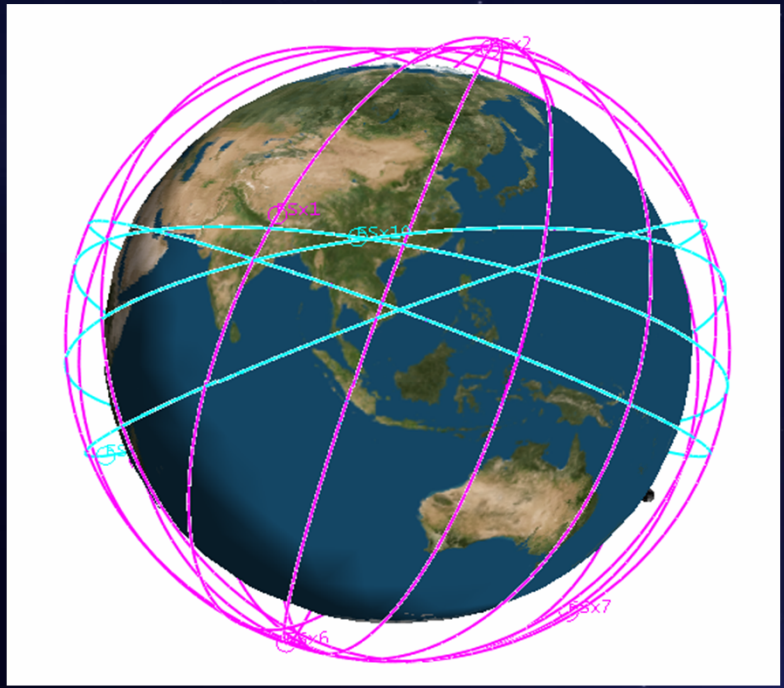
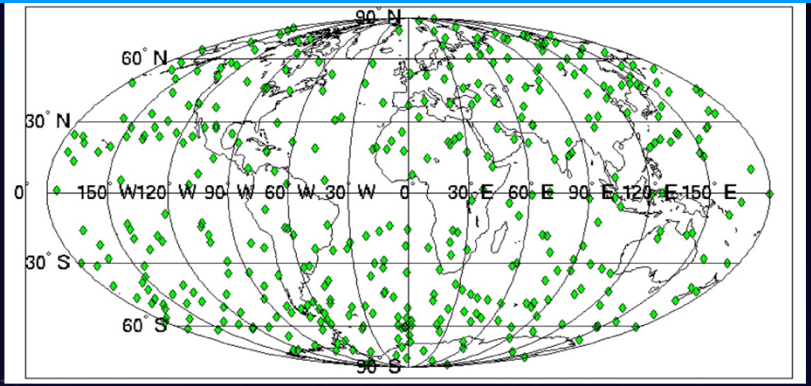
COSMIC-1 and COSMIC-2 Coverage

COSMIC/Formosat-3 aka COSMIC-1 – GPS Only RO, COSMIC-2 GPS/Galileo/GLONASS RO

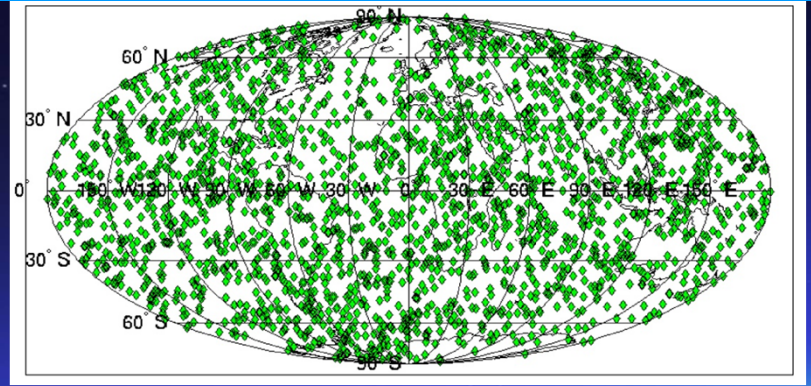


8 high-inclination-angle S/C
+ 4 low-inclination-angle S/C
Data are distributed
more homogeneously

COSMIC / FORMOSAT-3 Occultations–3 Hrs Coverage

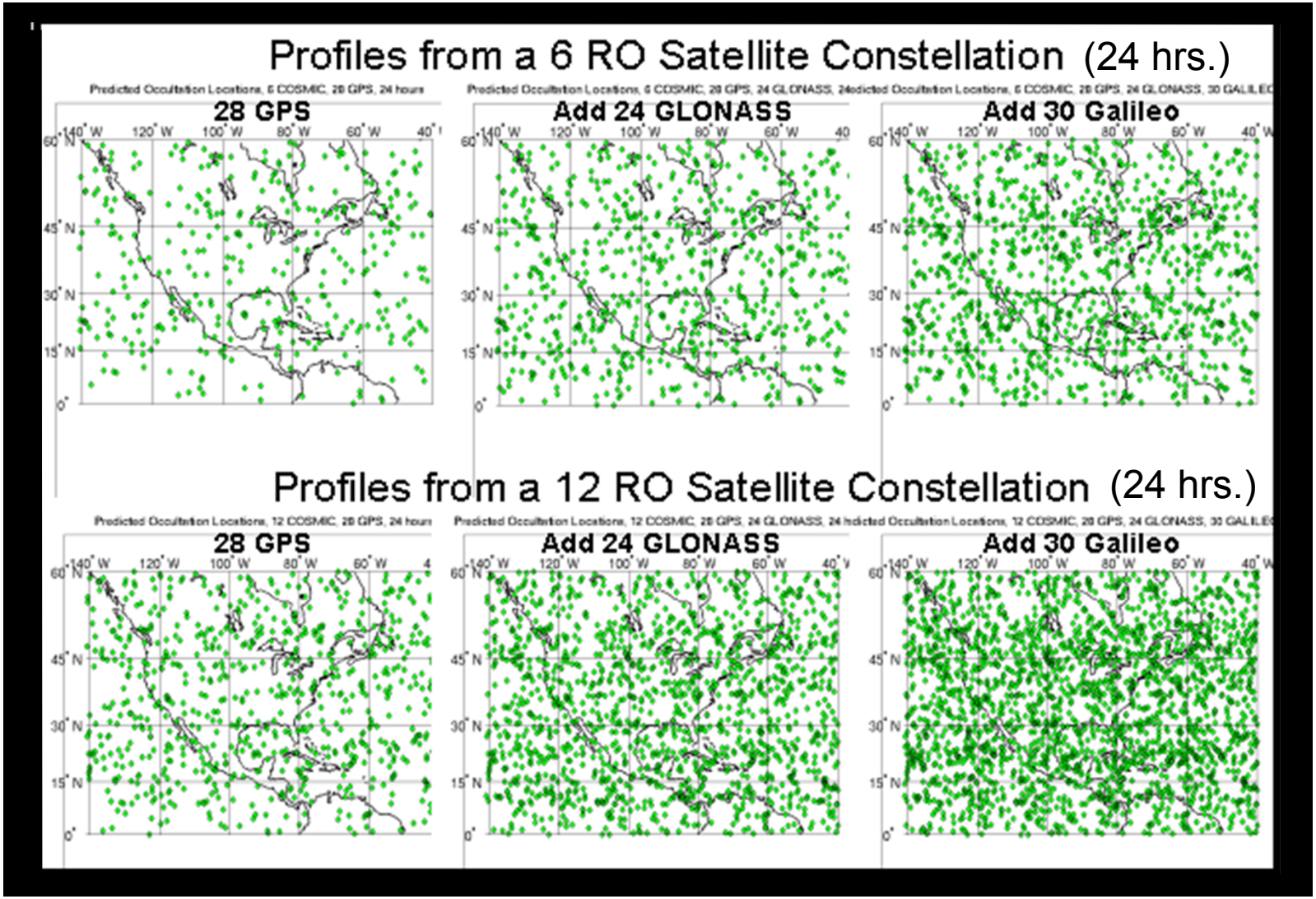


COSMIC-2 Occultations – 3 Hrs Coverage



Spatial Density of Soundings

Multiple GNSS Signal Sources & 6 & 12 GNSS RO S/C

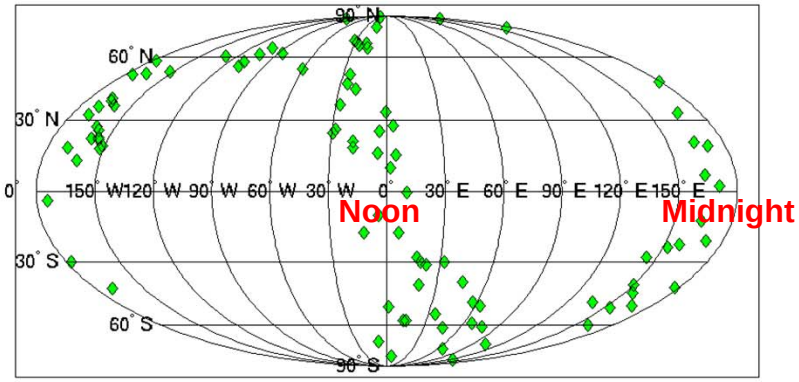


Propagated at UCAR

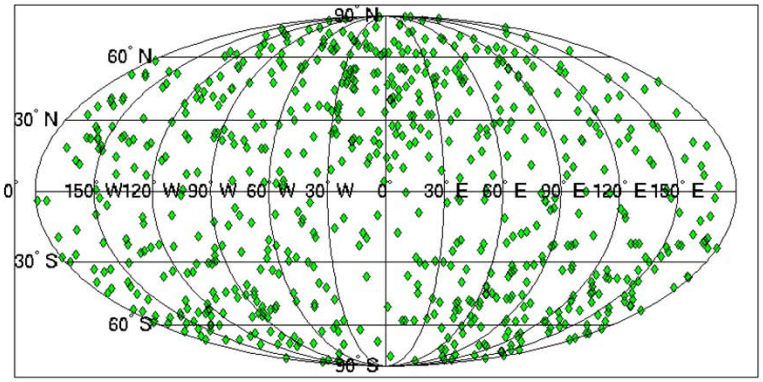
Local Time Coverage

(4 hrs.)

Sun-Fixed Occultations, 1 S/C, Inc 72 deg, GPS, 4 hours

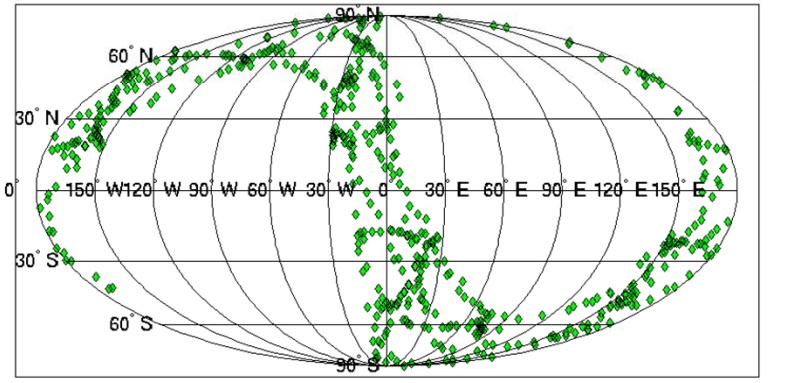


Sun-Fixed Occultations, 8 S/C in 8 Planes, Inc 72 deg, GPS, 4 hours

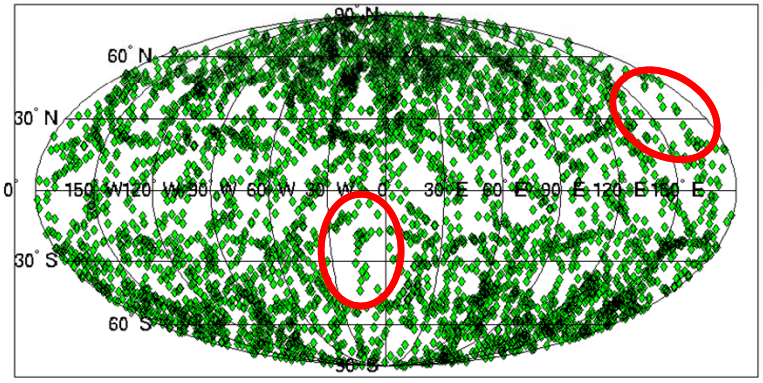


(24 hrs.)

Sun-Fixed Occultations, 1 S/C, Inc 72 deg, GPS, 24 hours



Sun-Fixed Occultations, 8 S/C in 8 Planes, Inc 72 deg, GPS, 24 hours

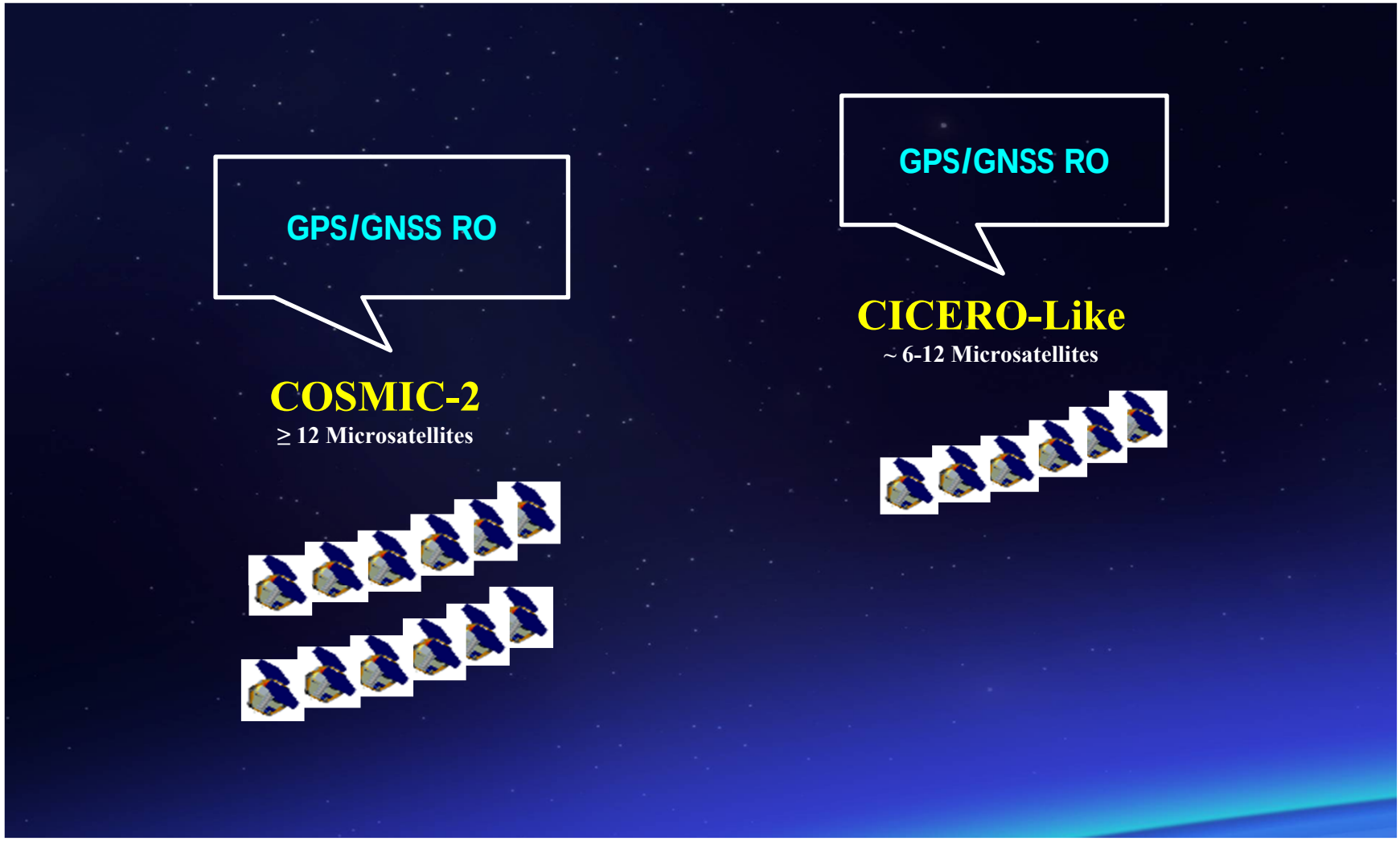


Multiplicity/Spatial Density of Soundings

Multiple GNSS Signal Sources – Multiple GNSS RO S/C

# GNSS RO S/C	GNSS Signal Sources	# Soundings Daily Total	Average Horiz. Spacing [km]	# Soundings Daily Average In 500 km x 500 km Box
6	GPS	3,112	404.8	1.5
6	GPS+GLO	5,959	292.6	2.9
6	GPS+GLO+GAL	9,307	234.1	4.6
12	GPS	6,267	285.3	3.1
12	GPS+GLO	11,954	206.6	5.9
12	GPS+GLO+GAL	18,645	165.4	9.1
24	GPS	12,506	201.9	6.1
24	GPS+GLO	23,905	146.1	11.7
24	GPS+GLO+GAL	37,320	116.9	18.3
48	GPS	25,012	142.8	12.3
48	GPS+GLO	47,761	103.3	23.4
48	GPS+GLO+GAL	74,536	82.7	36.5

NWP/Climate/SWx Sensors Continuity Notion
Phase [2011-2020]



Thank You So Much
For Your Attention …