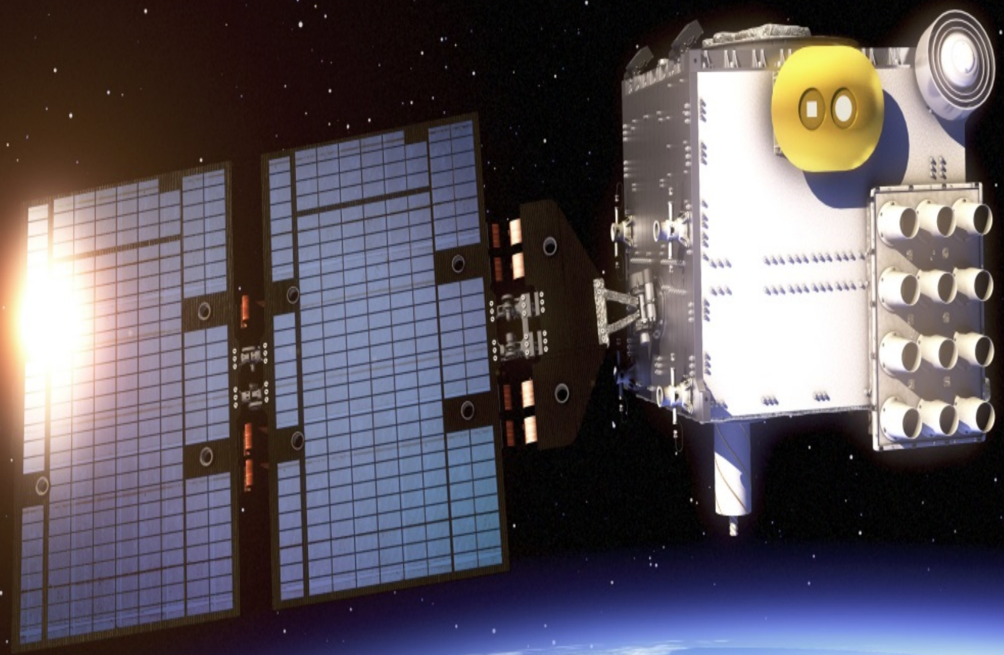
Ground GNSS Network Design and Operation to Support COSMIC-2



John J. Braun

on behalf of the COSMIC Scientific and Technical Team

(J. Castilleja, D. Hunt, J. Lin, B. Schreiner, S. Sokolovskiy, T. Van Hove, J. Weiss)

COSMIC Ground-IO Overview

- Real-time Computation of Clock and Satellite Orbits for GNSS Satellite Constellations (GPS and GLONASS) are required for C-2.
  - GNSS satellite clocks must be estimated in near real-time, and can not be extrapolated forward in time with sufficient accuracy for RO analysis.
  - GNSS clock estimation requires access to a global network of GNSS stations.
- RO retrievals from open loop tracking instruments, such as the TRIG instrument onboard C-2, require externally collected navigation data messages (NDM) for accurate and precise atmospheric profiles.
  - A subset of the global GNSS fiducial network can be used to collect a redundant stream of NDMs in real-time.

Existing Ground GNSS Network Implementation for COSMIC

- Current COSMIC GNSS station network utilizes data collected from four different sources (eumHrf, canHrf, igsHrf, and cosHrf)
  - » Data file durations are between 15 and 60 minutes in length.
  - » Access is primarily through ftp (canHrf collects realtime streams), from designated data archive centers.
  - » Satellite clocks are computed in 15 minute increments, with latencies that approach 40 minutes. Not suitable for C-2 requirements.
- The NDMs are collected from a non-redundant network of GNSS stations.
  - – The loss of connection to an individual NDM site leads to geographic holes in data coverage.
  - – The loss of NDMs in existing COSMIC processing leads to the occasional degradation of profiles.
  - – C-2 needs a more robust and reliable way to collect these messages.

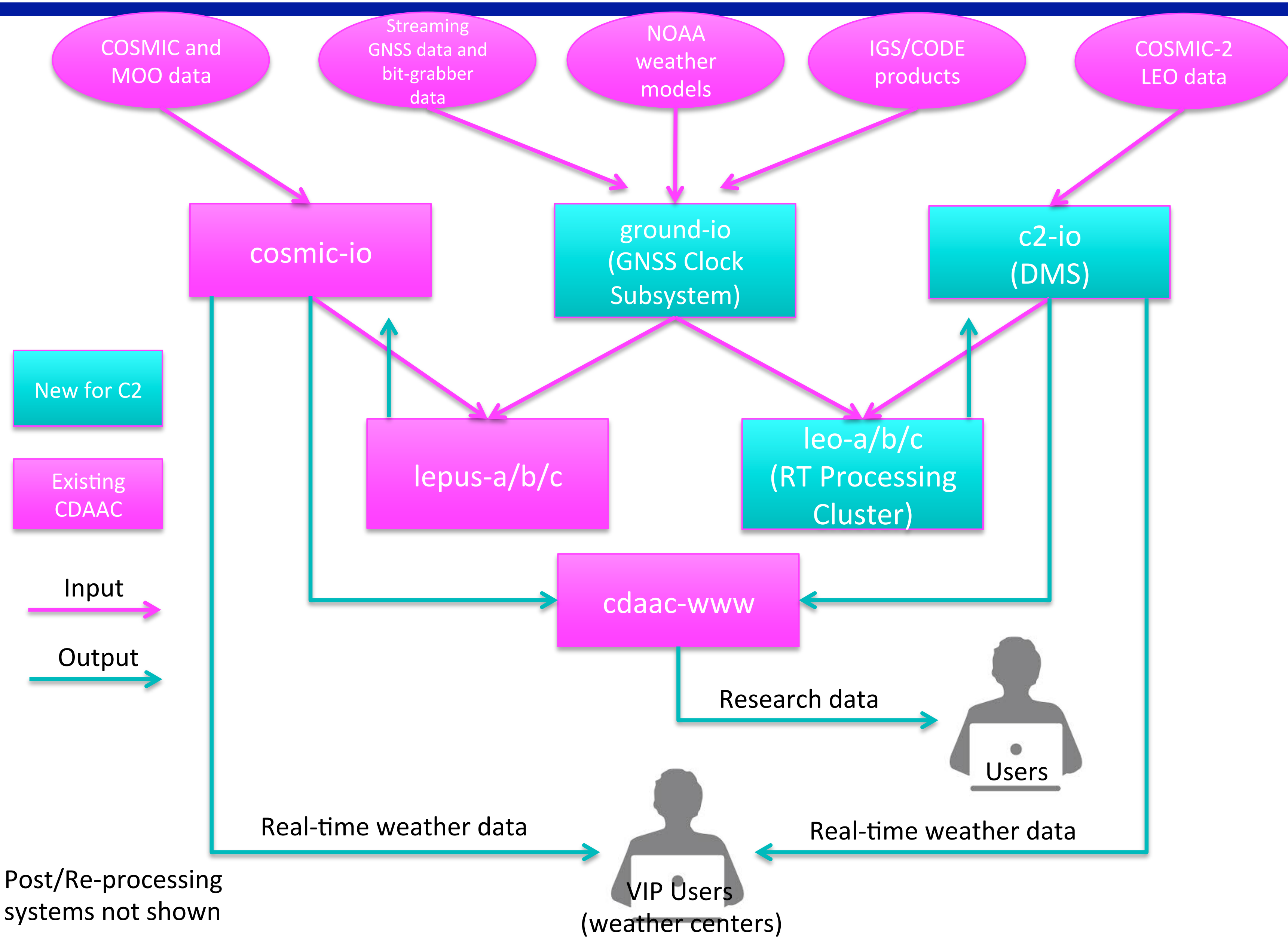
Network Reliability

- Distributed GNSS fiducial networks can be made highly redundant in two different ways.
  - » Create a minimum number of ground GNSS stations that are highly reliable and redundant (equipment, power, communications, etc).
  - » Utilize a network of high quality ground GNSS stations that have a significant degree of geographical overlap, thereby tolerating outages at any single station through a redundant observational system.
- Minimum network solution
  - » Exceptionally difficult to design an individual station that is 100% reliable.
  - » Requires hardened power, communications, GNSS equipment, etc.
  - » Does not account for “catastrophic” failures at a location. Lighting strikes, earthquakes, vandalism.
  - » Relies on on-site personnel to quickly resolve problems at a single site.
  - » Very expensive.
- Redundant network solution.
  - – Builds redundancy through a collective over sampling of the GNSS constellation.
  - – Allows for short-term failures at any single location without degradation of clock subsystem.
  - – Less reliant on a core set of sites for 100% uptime.
  - – Leverages existing IGS network model.
  - – Significantly cheaper.

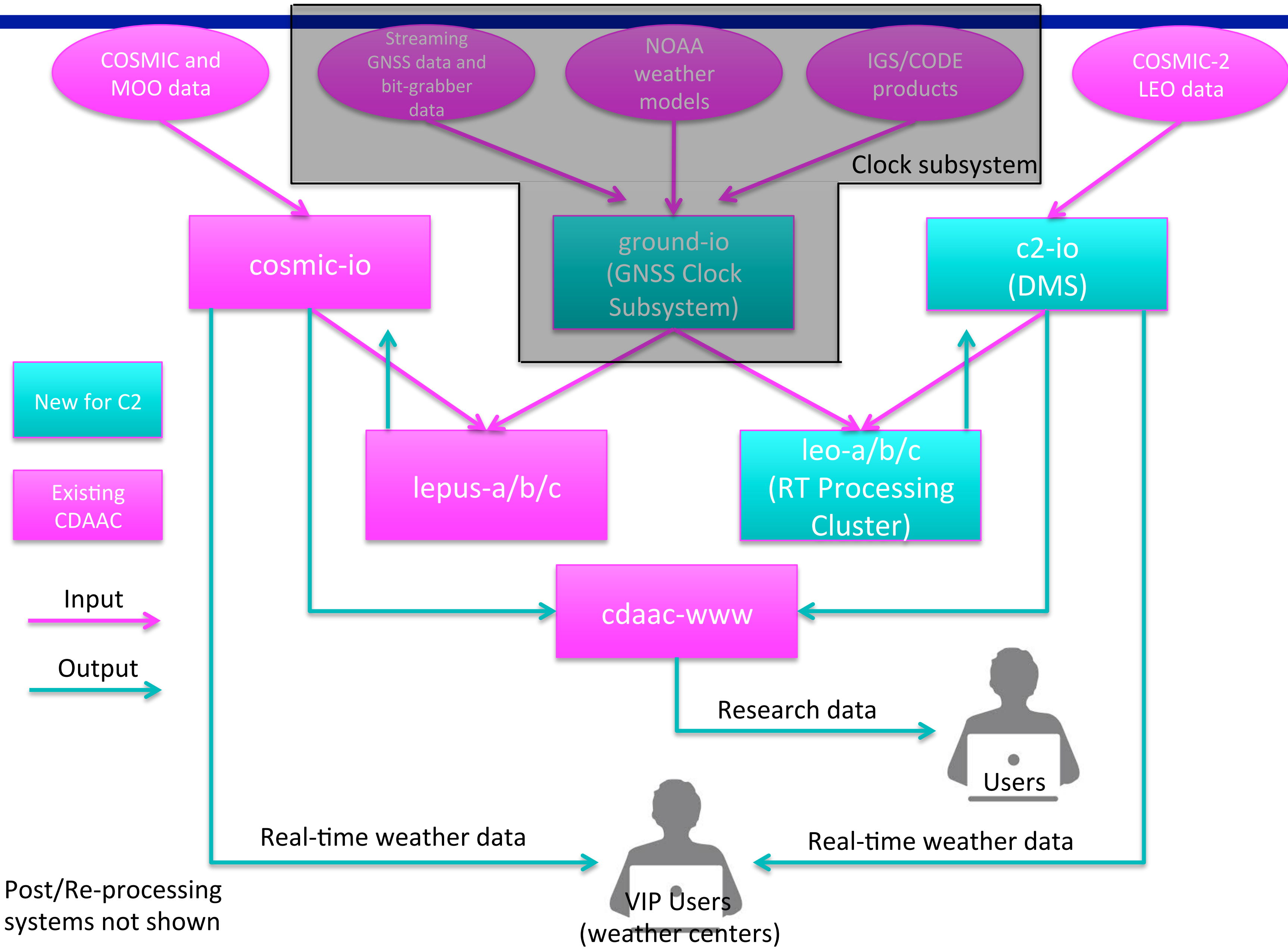
Proposed Ground Station Network and GNSS Clock Subsystem for C-2

- Utilize the internationally adopted NTRIP protocol to collect real time streams of data GNSS fiducial data
  - » Collection of raw data streams eliminates need for access through designated archive centers (ftp). This significantly reduces latency.
  - » Provides configurable length of data files (ie 5 minutes). This reduces latency and allows flexibility in design of clock subsystem.
- Partner with International GNSS Service (IGS) to become an official real time IGS data provider
  - » Leverages existing network of GNSS stations.
  - » Supports free and open access to data within the broader scientific community.
  - » Provides cost-effective way to obtain GNSS ground data to support C-2 operations.

CDAAC-2 DPC Architecture

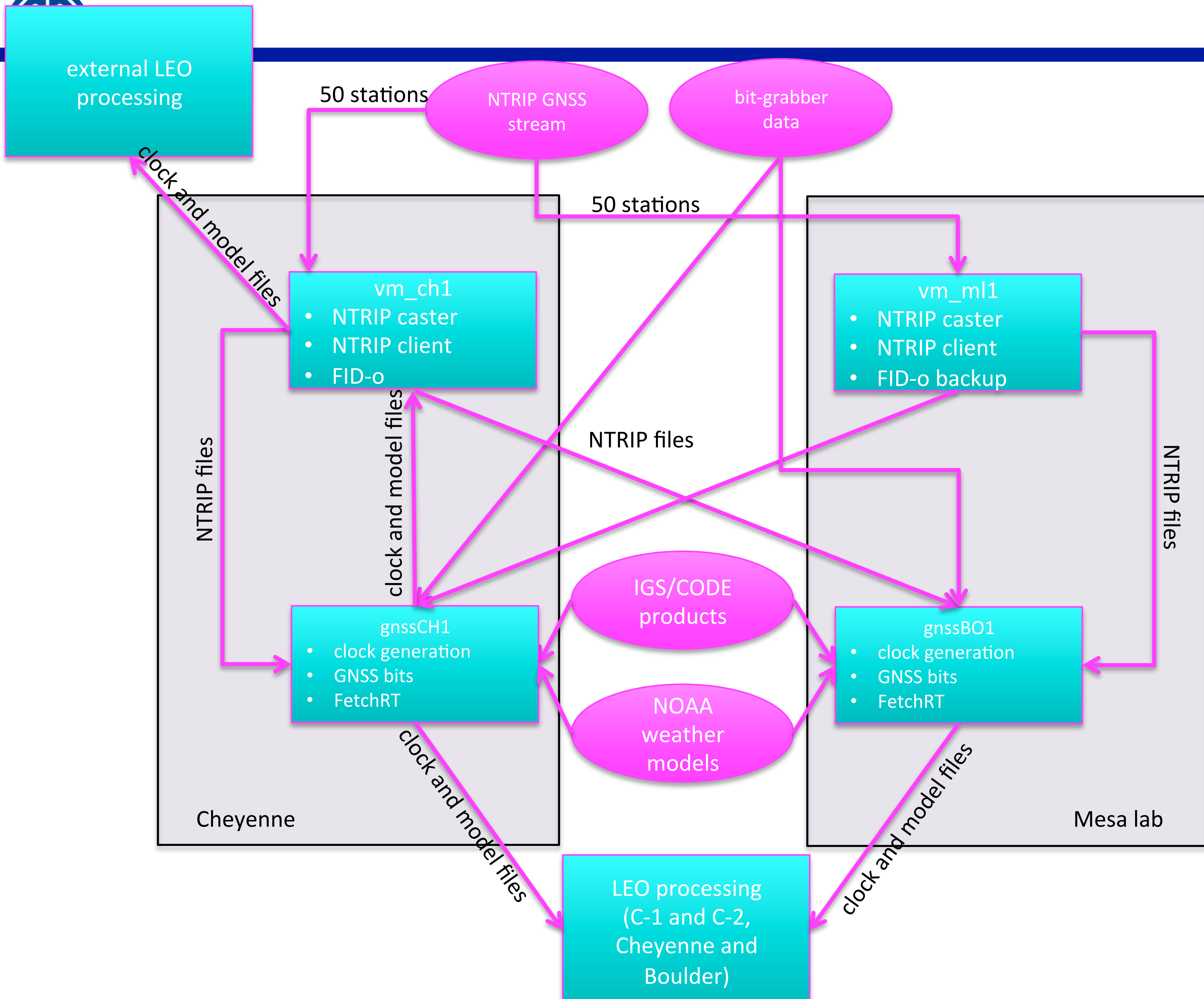


Clock subsystem



Post/Re-processing systems not shown

Clock subsystem details



GNSS Clock Subsystem Design

- Data Collection System
  - » NTRIPCaster software to collect and serve data to CDAAC-2 (CDAAC V5.0) processing system.
  - » Data collection and monitoring through BKG Ntrip Client (BNC) software.
  - » GNSS clock estimation using Bernese V5.2.
- Computing Hardware
  - » Dual String High Availability (HA) Linux system, similar to proposed RT processing cluster.
- Physical Location of Clock Subsystem
  - » NWSC – highly reliable offsite computing environment.
  - » Allows flexibility in distribution of clock subsystem products to downstream processing clusters.

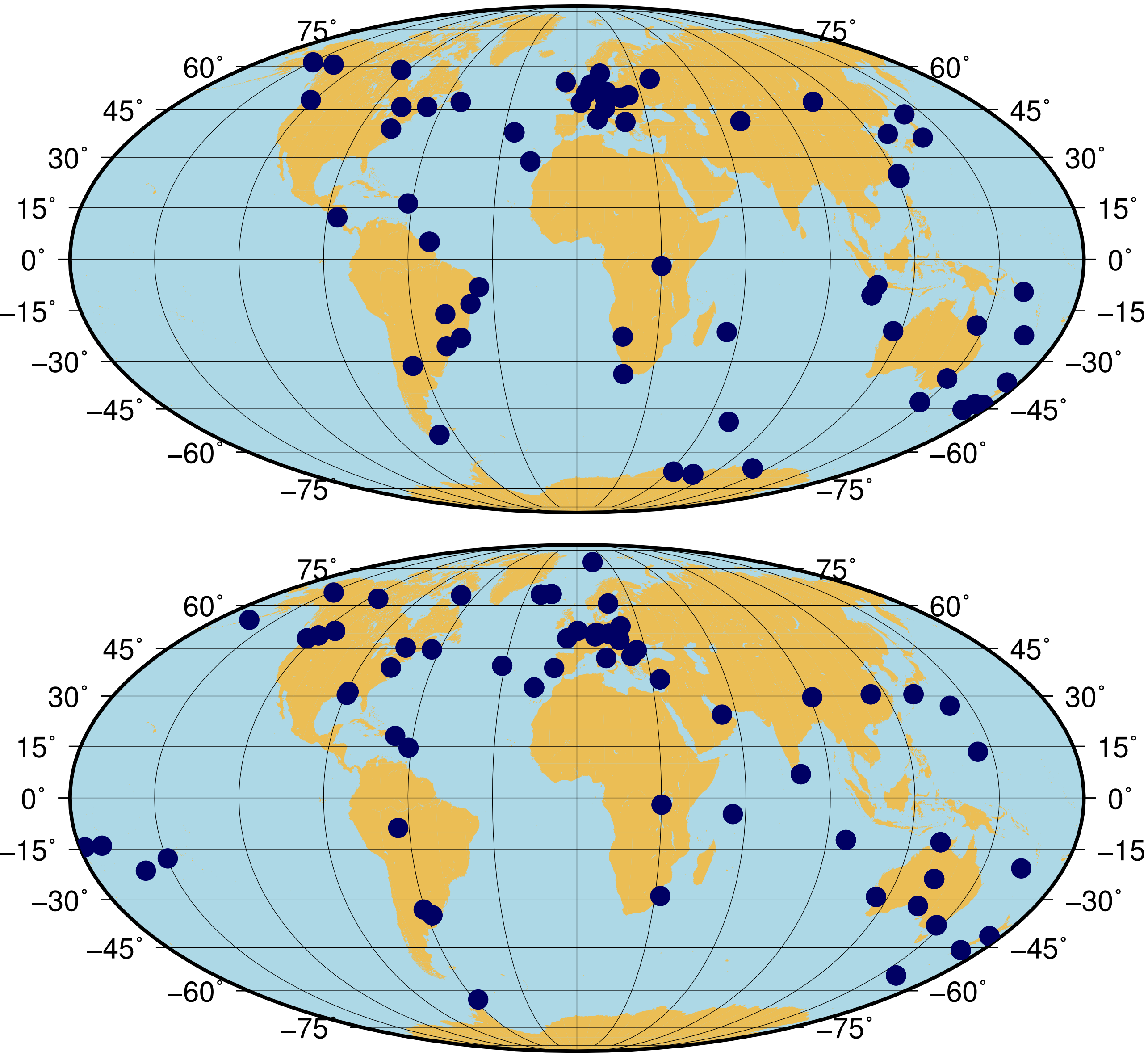
CDAAC + NTRIP Integration

- Create NTRIPCaster at UCAR.
  - » Provides a mechanism to make most direct connection to global GNSS network.
  - » Allows redistribution of data to other users (ie Taiwan).
  - » Provides a backup service to existing real-time IGS providers.
- Install/Operate BKG NTRIP Client (BNC)
  - » Automated client configuration, simplifies configuration and modification of network.
  - » Utilizes existing software (teqc) for data quality and epoch loss monitoring.
  - » Develop scripts to automate client configuration, perform simple monitoring as well as automatic restart of data streams that become stale.
- Implement GNSS Clock Subsystem for RO processing
  - Utilize Bernese V5.2 software within CDAAC computing architecture.
  - GPS and GLONASS clock estimation.
  - Specification of analysis window intervals as well as fiducial network will provide method to meet C-2 data latency and quality requirements.
  - Clock and orbit subsystem can be modularized and separated from other elements of RT processing system. Reduces computing burden on RT processing cluster. Allows a single clock subsystem to be used for multiple missions.

Ground-IO Physical Infrastructure

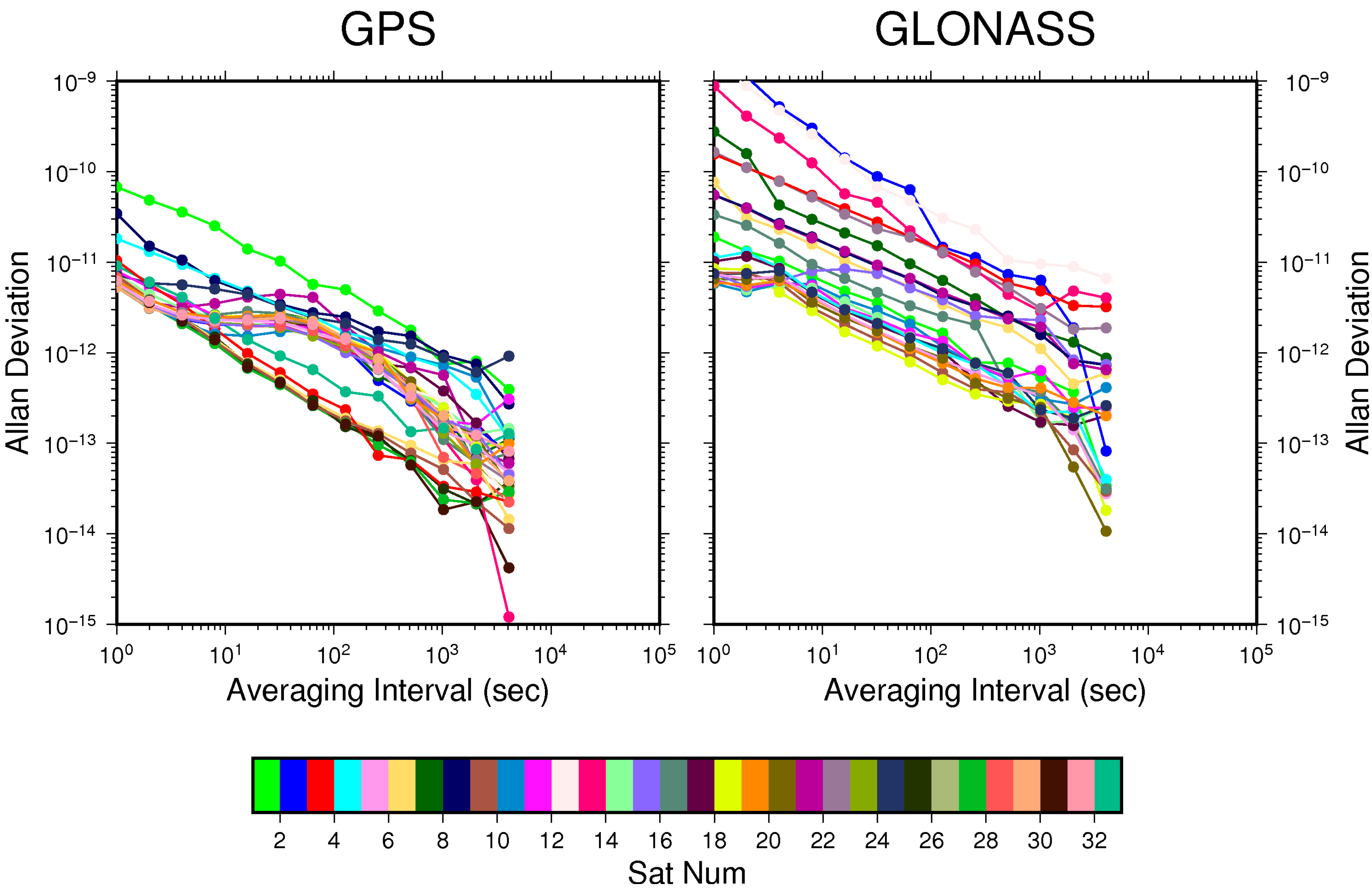
- Ground-IO HA Linux Cluster will be at NCAR Wyoming Supercomputing (NWSC) Center.
- NWSC has 24/7 support, redundant power and communications.
- Mirror site will be at NCAR ML
- NWSC is connected via a high-speed fiber optic network to rest of UCAR facilities in Boulder.

Global GNSS Ground Station Network



- Geographically separate processing sub-systems will allow division of network into clusters.
- NTRIP generated files will be pushed between processing centers.
- Ground network is divided in a manner that maximizes geographic separation.

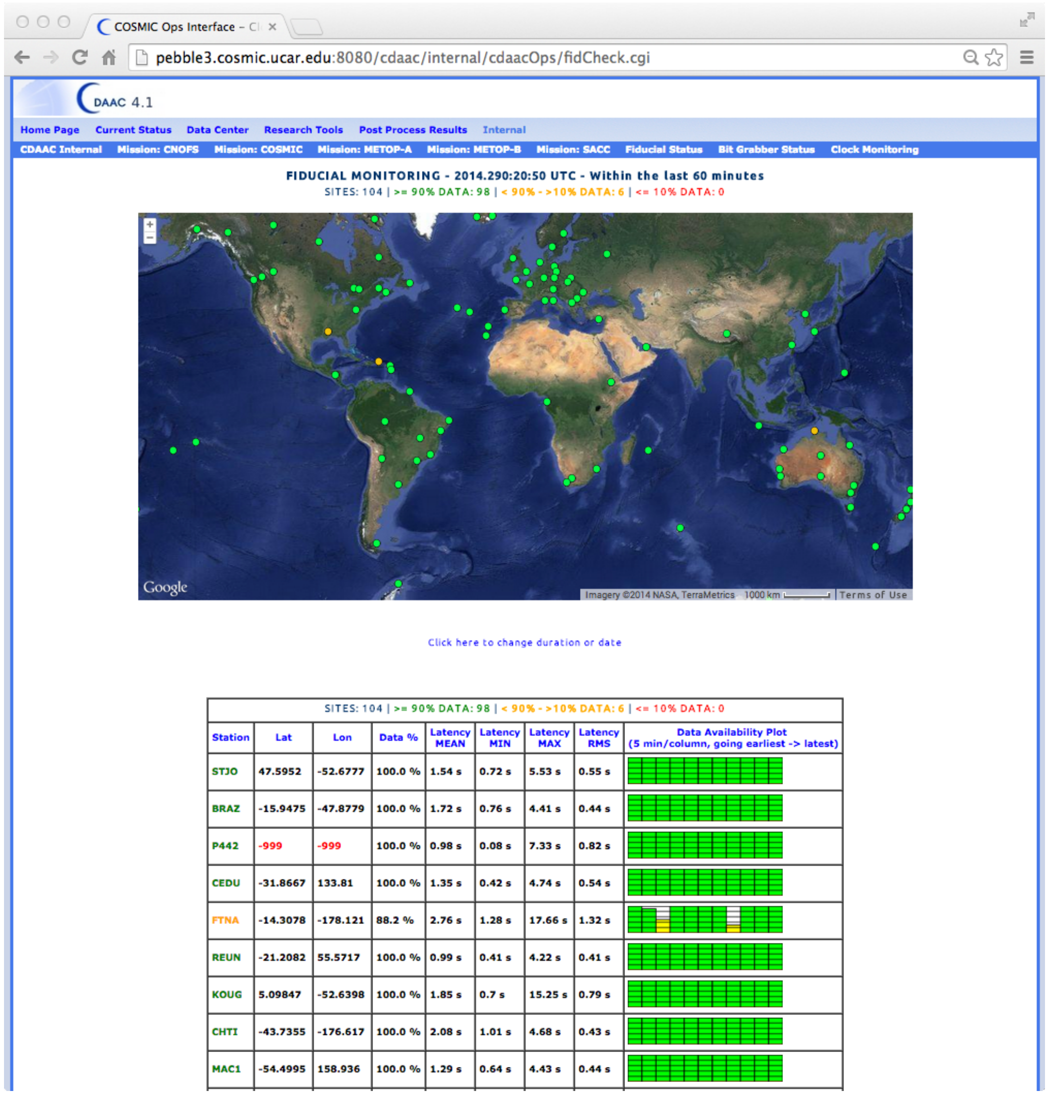
GNSS Allan Deviation



Clock and Orbit Integrity Monitoring

- Real-time clock and orbit products will be monitored for integrity using alternative GNSS ground stations for "truthing"
  - » Will use clock and orbit products from C-2 for real-time kinematic precise point positioning (PPP) and troposphere estimation to insure nominal behavior of products.
  - » Will use a global network to ensure full monitoring of GPS and GLONASS constellations.
  - » Overall clock stability will be monitored through evaluation of allan variation of GNSS constellation.
- Post-Processing validation
  - » C-2 clock subsystem will be validated against post-processed IGS clock products to assess overall clock product quality with established data products.

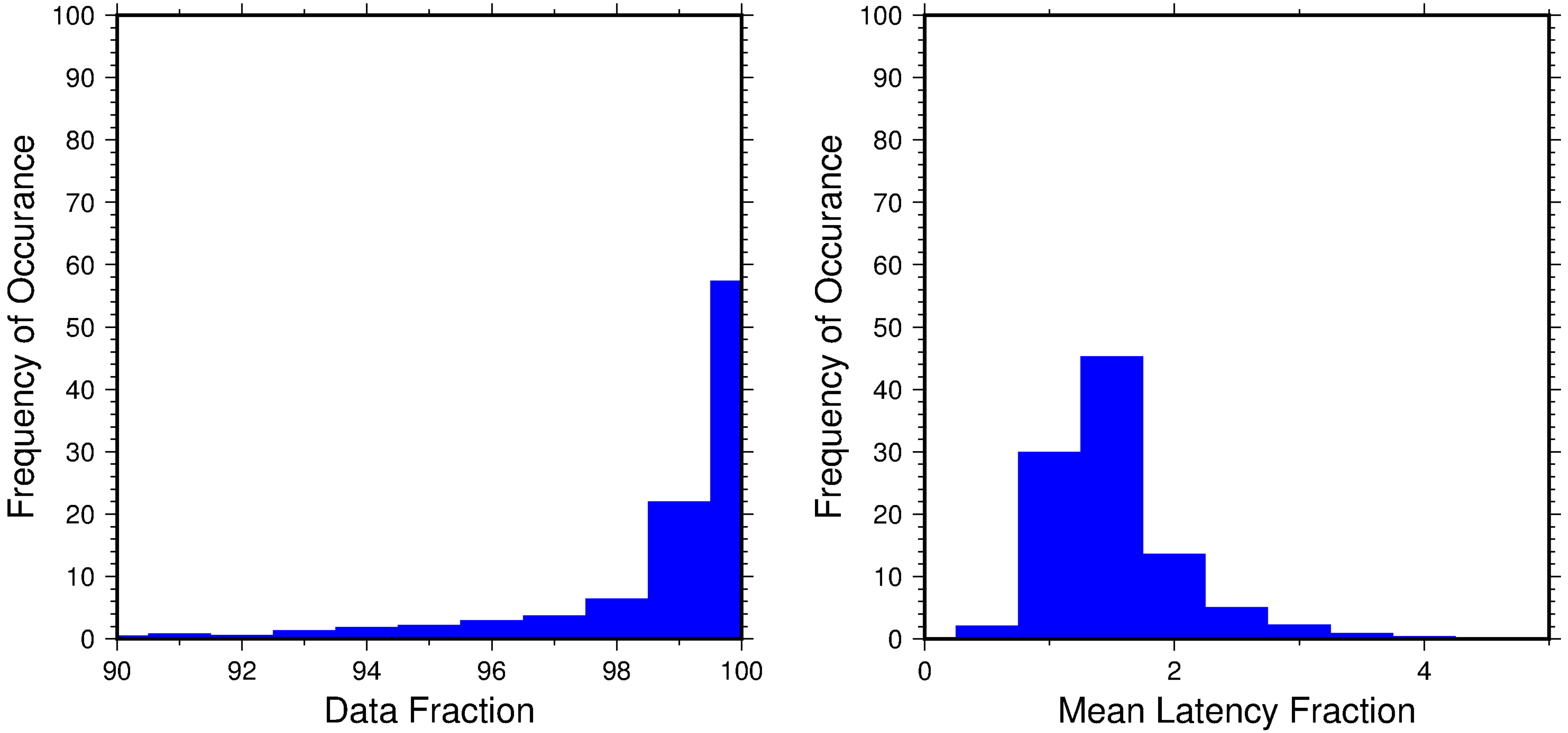
GNSS Station Monitoring Page



Station	Lat	Lon	Data %	Latency MEAN	Latency MIN	Latency MAX	Latency RMS	Data Availability Plot (5 min/column, going earliest -> latest)
STJO	47.5952	-52.6777	100.0 %	1.54 s	0.72 s	5.53 s	0.55 s	
BRAZ	-15.9475	-47.8779	100.0 %	1.72 s	0.76 s	4.41 s	0.44 s	
P442	-999	-999	100.0 %	0.98 s	0.08 s	7.33 s	0.82 s	
CEDU	-31.8667	133.81	100.0 %	1.35 s	0.42 s	4.74 s	0.54 s	
FTNA	-14.3078	-178.121	88.2 %	2.76 s	1.28 s	17.66 s	1.32 s	
REUN	-21.2082	55.5717	100.0 %	0.99 s	0.41 s	4.22 s	0.41 s	
KOUG	5.09847	-52.6398	100.0 %	1.85 s	0.7 s	15.25 s	0.79 s	
CHTI	-43.7355	-176.617	100.0 %	2.08 s	1.01 s	4.68 s	0.43 s	
MAC1	-54.4995	158.936	100.0 %	1.29 s	0.64 s	4.43 s	0.44 s	

- Monitoring of the GNSS ground network will be incorporated into C-2 operations.
  - Data latency
  - Percentage collected
  - Outages
  - Data quality

Nominal NTRIP – Caster Data Collection



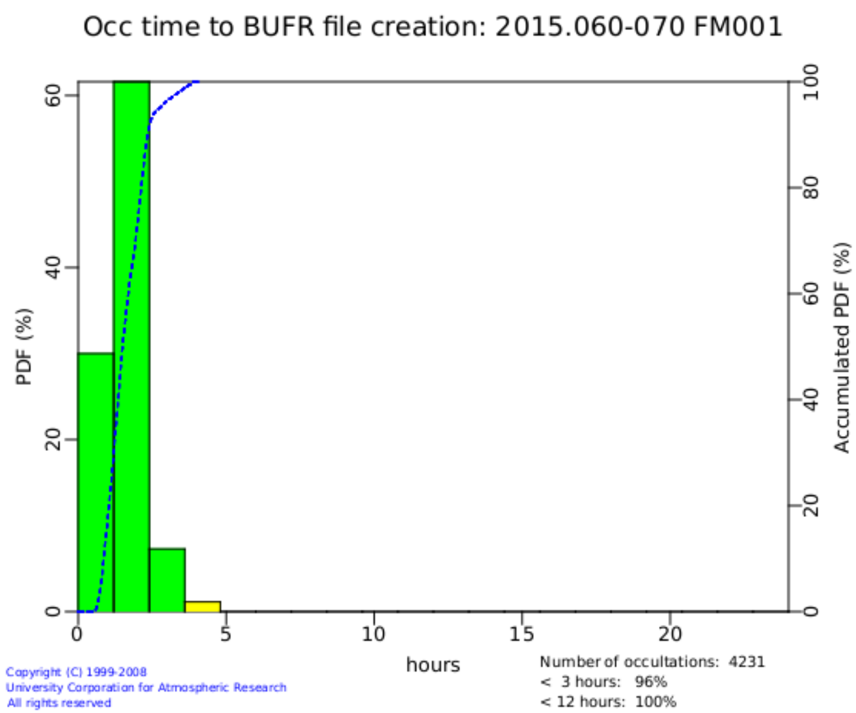
Data collected between 2015.001-100 are better than 98% complete.

Latency is generally less than 2 seconds.

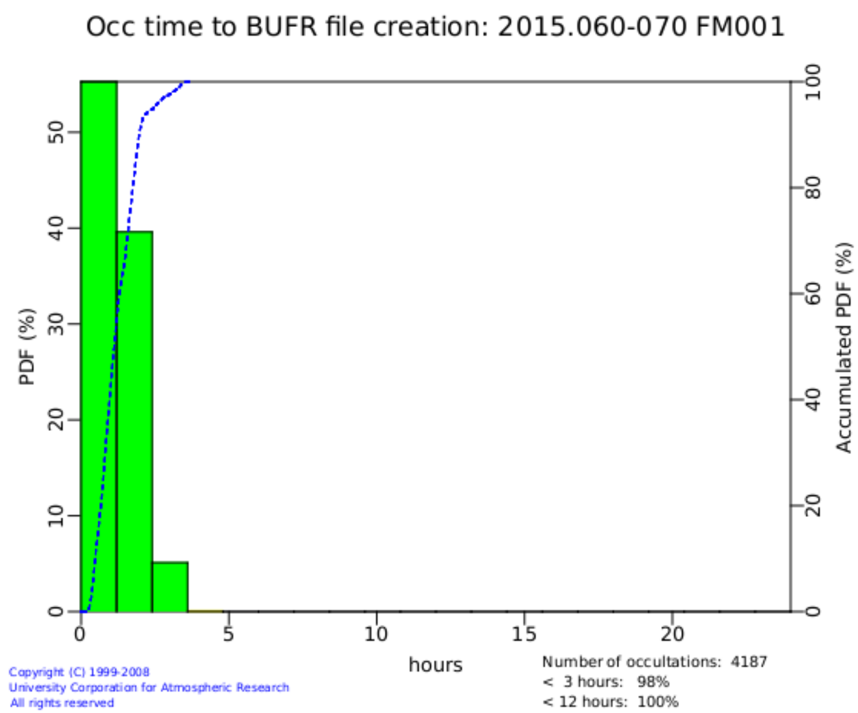
Recall that network is designed to be “double strength” to ensure product generation wit

Impact of Updated Clock Processing on Latency

Current Clock Subsystem
C-1 CDAAC



Streaming Clock Subsystem
C-2 CDAAC



GPS and GLONASS NDM Bits

GPS Navigation Message	GLONASS Navigation Message
300 bit length	85 bit length
50 bit per second stream	50 bit per second stream
Updated on ~2 hour interval	Updated on ~30 minute interval

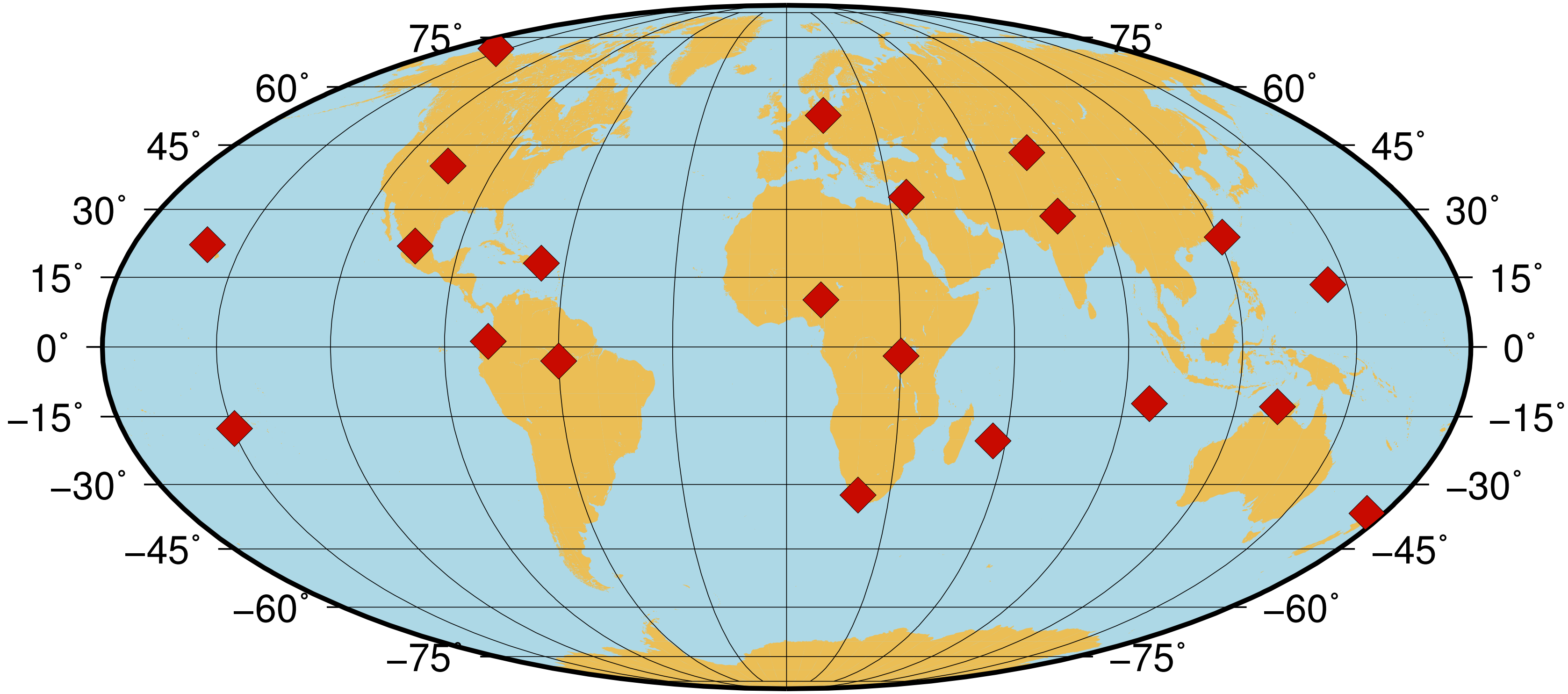
- COSMIC-1 GPS Bit Grabber Network
  - » Boulder, Taiwan, New Zealand, Brazil, Germany, South Africa
  - » Original network used specially designed “bit grabbers”
  - » Now transitioning to commercial grade GPS survey equipment (Trimble and Septentrio)
- Planned COSMIC-2 Bit Grabber Network
  - » C-1 sites, plus up to 10 additional C-2 sites.
  - » Will also solicit collection of NDM through IGS station operators.
  - » GLONASS NDM Bits for L1C and L2C via TBD Network (IGS-IP, other, ..)
    - – To be streamed in RAW receiver format or in RTCM format (to be investigated)
    - – Will require UCAR dedicated sites and/or coordination with international agencies

Commercially Available Receivers Capable of Collecting NDMs

- Septentrio
  - GPS and GLONASS navigation messages available through both stream and receiver logged files.
  - Septentrio Binary Format (SBF) is well documented format.

- Javad Positioning Systems (JPS)
  - GPS and GLONASS available.
  - Well represented within IGS network.
- Trimble
  - Available through RT17 and RT27 streaming data formats.
  - Already using in existing CDAAC operations.
  - Proprietary RT27 and RT17 formats, although NDM can be extracted using CDAAC software and/or teqc.

Redundant Navigation Data Message (NDM) Network



- Initial distribution of GNSS stations for C-2 NDM collection.
- Stations will also be used for clock and orbit determination.
- Data collection will be via real time stream. Will also have file download for NDM recovery.
- Station list comprised of C-1 NDM sites, new C-2 NDM sites, and contributing sites.
- Will allow for majority voting and redundant NDM collection

Summary and Conclusions

Ground GNSS Analysis for COSMIC-2

- Requirements for mission require a re-engineering of current clock/ orbit analysis.
- GLONASS also provides an additional new set of products.
- Based on collection of data via NTRIP protocols.
- Ground GNSS network will be designed as super redundant
- UCAR will deploy approximately 10 GNSS stations to support C-2 real time analysis.
- Will also collect NDM messages from ground stations

Areas for development

- Transition from demonstration to operations will be challenging
- Will begin diversify NTRIP sources in coming months.
- Data monitoring and integrity analysis is a major area of development.