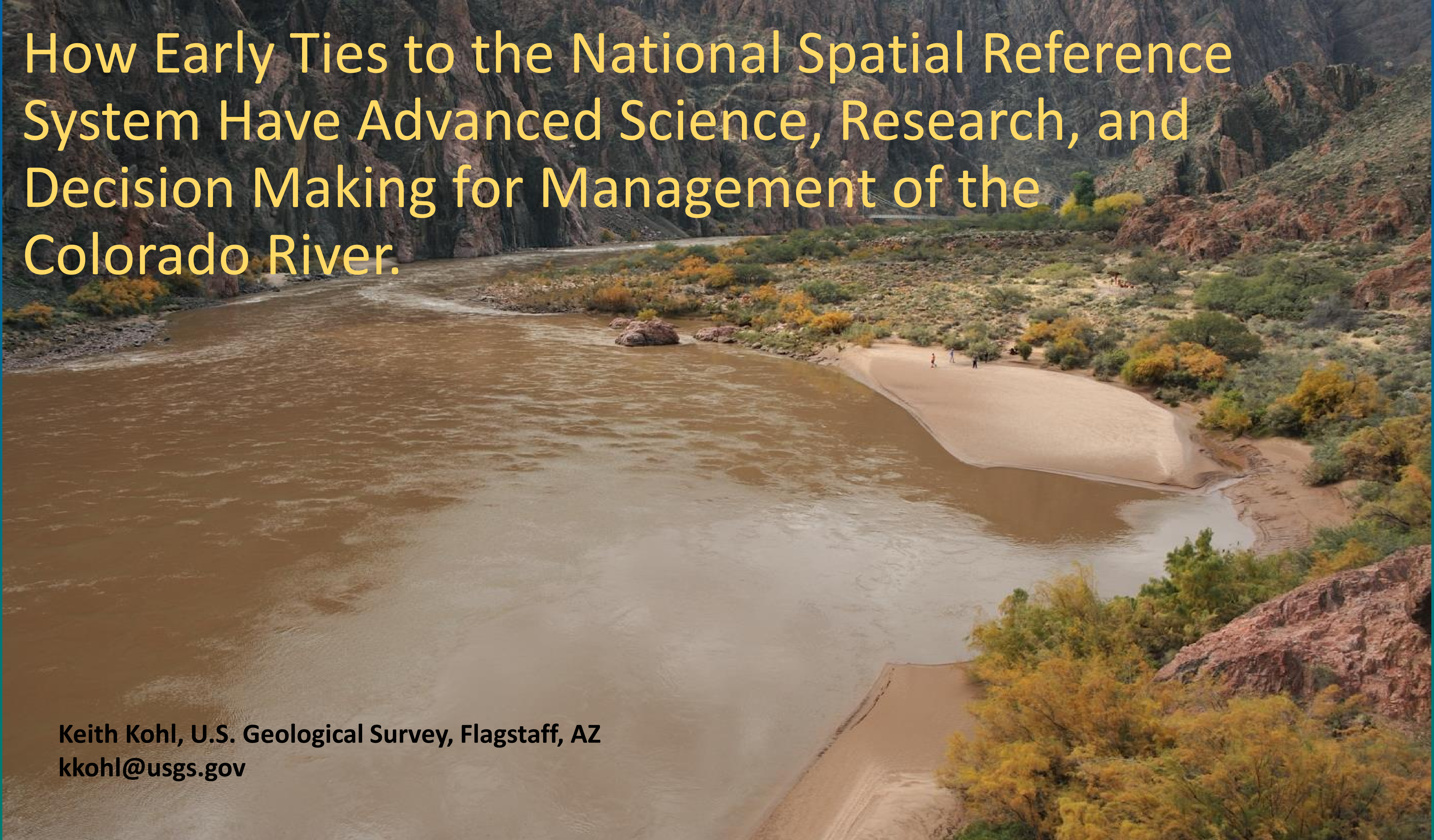


# How Early Ties to the National Spatial Reference System Have Advanced Science, Research, and Decision Making for Management of the Colorado River.

**Keith Kohl, U.S. Geological Survey, Flagstaff, AZ**
**kkohl@usgs.gov**

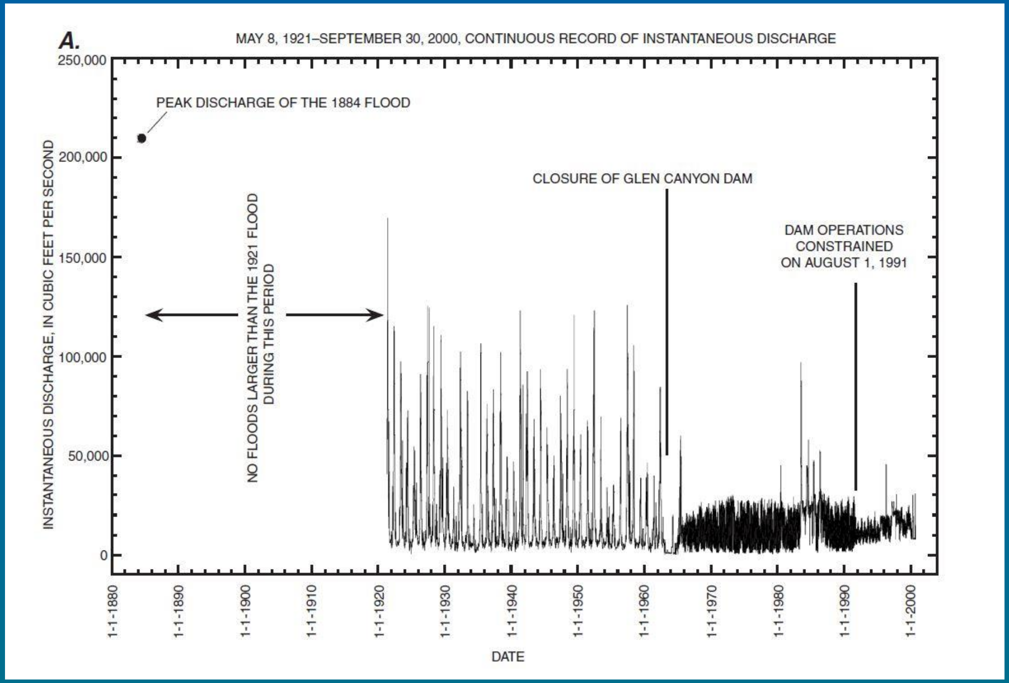
Sediment Conservation Goals:

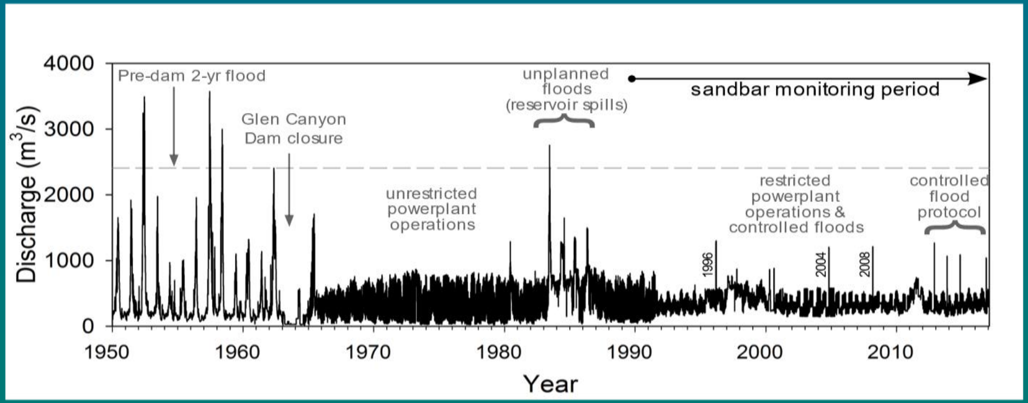
- Improve shoreline habitats, campsites, and campsite safety by building sandbars and filling gullies and rills through timely High-flow Events.
- Conserving the sediment as a resource by storing the sand above stages reached by typical Glen Canyon Dam operations
- Minimize the amount of sediment transported to and deposited in Lake Mead

Sediment Monitoring Methods:

1) Collect continuous sediment flux measurements at the end of each of 5 reaches to determine where and how much sediment has entered the system. Provides 15-minute records of suspended sediment concentrations.
2) Survey repeatable maps of channel morphology to compute volumes of sediment change within each reach. Provides cut/ fill maps of channel change at a ~5-year cycle.
3) Compare results of the 2 methods to compute a sediment budget where sediment input volumes are calculated to determine if High-Flow Event triggering criteria are reached. (500,000 metric tons of sediment input triggers HFE protocols)


**Figure 1.** Map of the Colorado River from Glen Canyon Dam to Lake Mead, Arizona, showing streamflow and sediment-monitoring stations (circles). The reaches used for this study are around the RM30, RM61, and RM87 gages.


A.
MAY 8, 1921–SEPTEMBER 30, 2000, CONTINUOUS RECORD OF INSTANTANEOUS DISCHARGE
PEAK DISCHARGE OF THE 1884 FLOOD
NO FLOODS LARGER THAN THE 1921 FLOOD DURING THIS PERIOD
CLOSURE OF GLEN CANYON DAM
DAM OPERATIONS CONSTRAINED ON AUGUST 1, 1991
INSTANTANEOUS DISCHARGE, IN CUBIC FEET PER SECOND
250,000
200,000
150,000
100,000
50,000
0
1-1-1880
1-1-1890
1-1-1900
1-1-1910
1-1-1920
1-1-1930
1-1-1940
1-1-1950
1-1-1960
1-1-1970
1-1-1980
1-1-1990
1-1-2000
DATE


4000
3000
2000
1000
0
Discharge ($m^3$/s)
Pre-dam 2-yr flood
Glen Canyon Dam closure
unplanned floods (reservoir spills)
sandbar monitoring period
unrestricted powerplant operations
restricted powerplant operations & controlled floods
controlled flood protocol
1996
2004
2008
1950
1960
1970
1980
1990
2000
2010
Year

# Method 1: Suspended sediment flux measurements

**Multifrequency acoustical measurements**

**Calibrated pump samples**
**Equal-Discharge-Increment**
**Equal-Width-Increment**
**Velocity-weighted-average Point-sample Array**

Provides:
Continuous high quality sediment transport data, at the end of each reach, & in real time!
Determines sediment inflow and outflow for each reach.

However:
Uncertainty in continuous flux measurements (+/- 5%) quickly approaches the 500,000 metric ton triggering criteria

# Method 2: Repeat measurements of bed morphology:

**Multibeam Sonar, Topographic surveying, Underwater camera for substrate calibration**

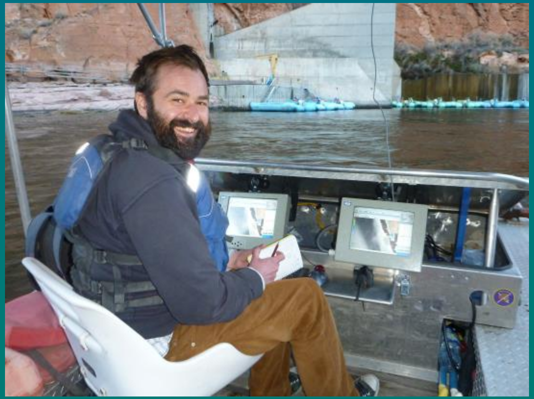
**Digital imagery, LiDAR (Aerial, boat and tripod-mounted)**

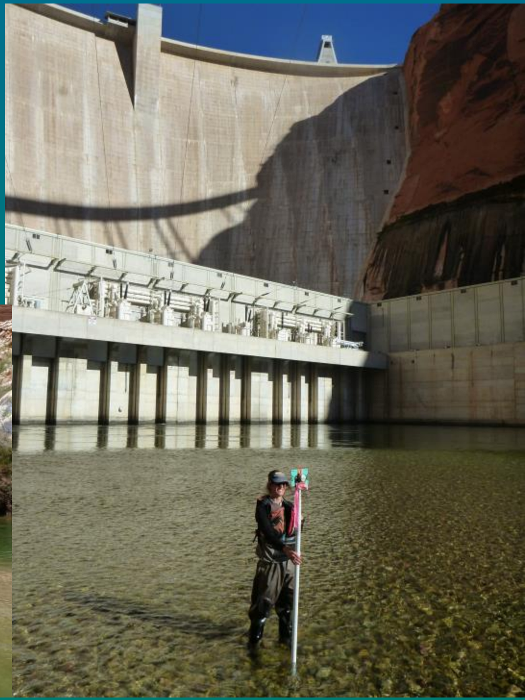
Provides:

- A 25cm resolution map of riverbed elevations
- Delineations of sand, sand-gravel, cobble, bedrock , and vegetation substrate through filtered backscatter
- A “time-zero” to constrain flux measurements and reset associated error propagations
- An independent method to compute sediment evacuation or deposition within each reach

However,

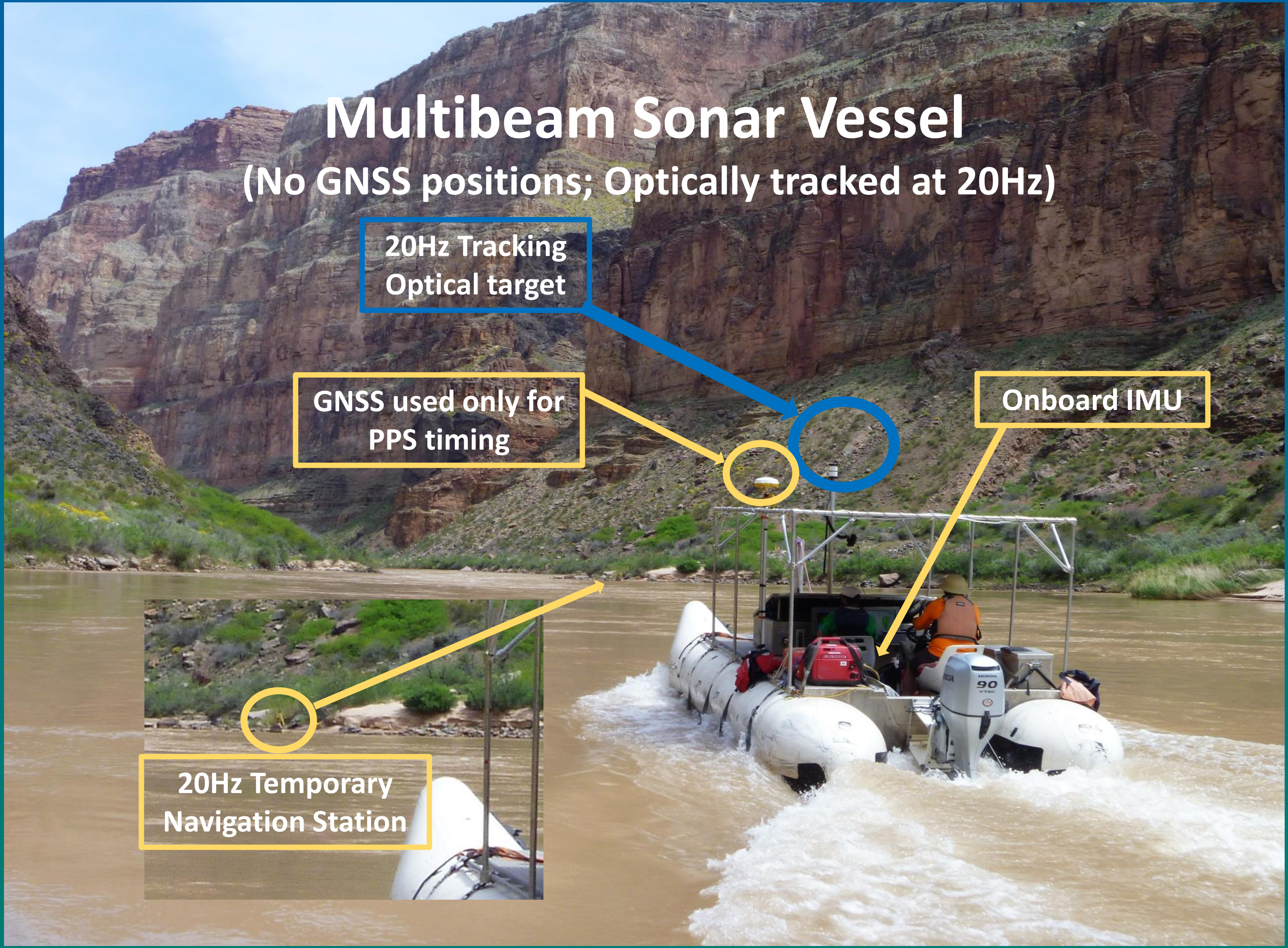
Repeat maps require the ~5-year cycle before each of the reaches are to be resurveyed.



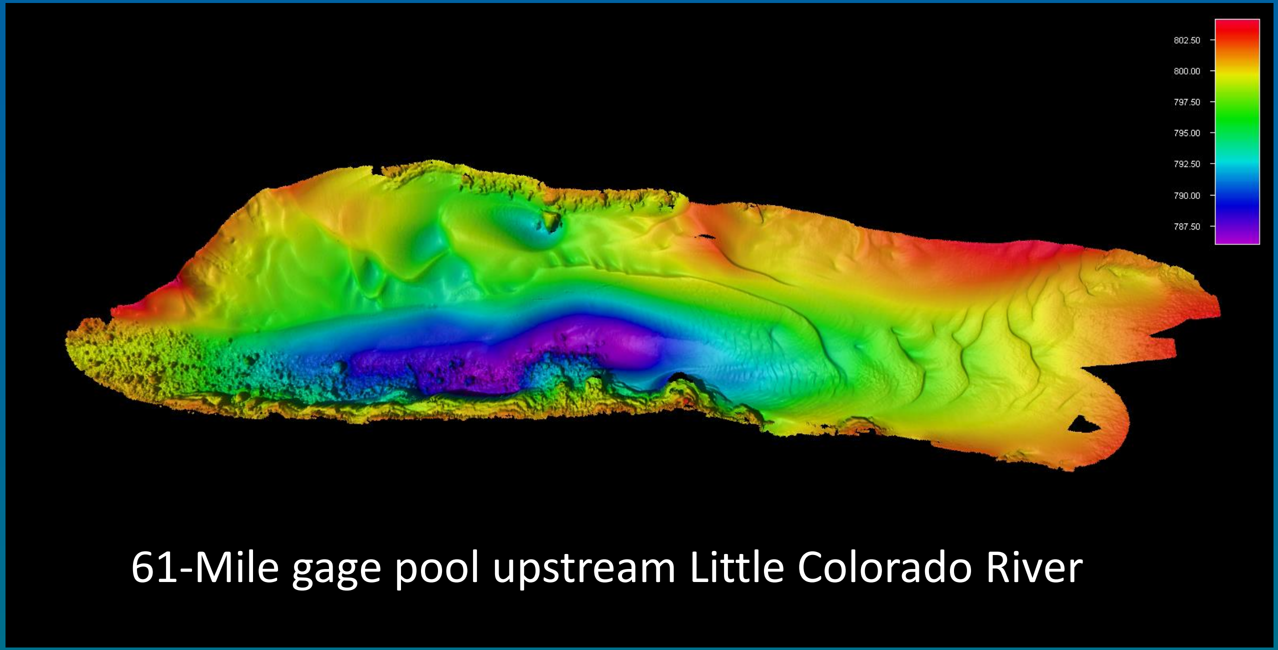


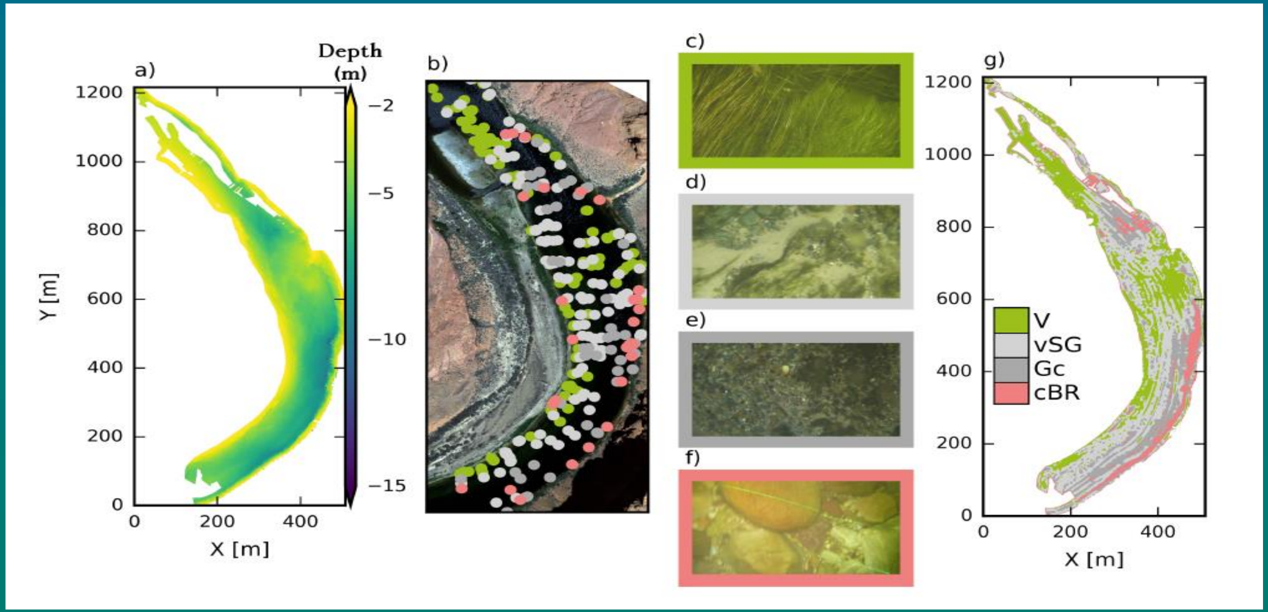
# Multibeam Sonar Vessel

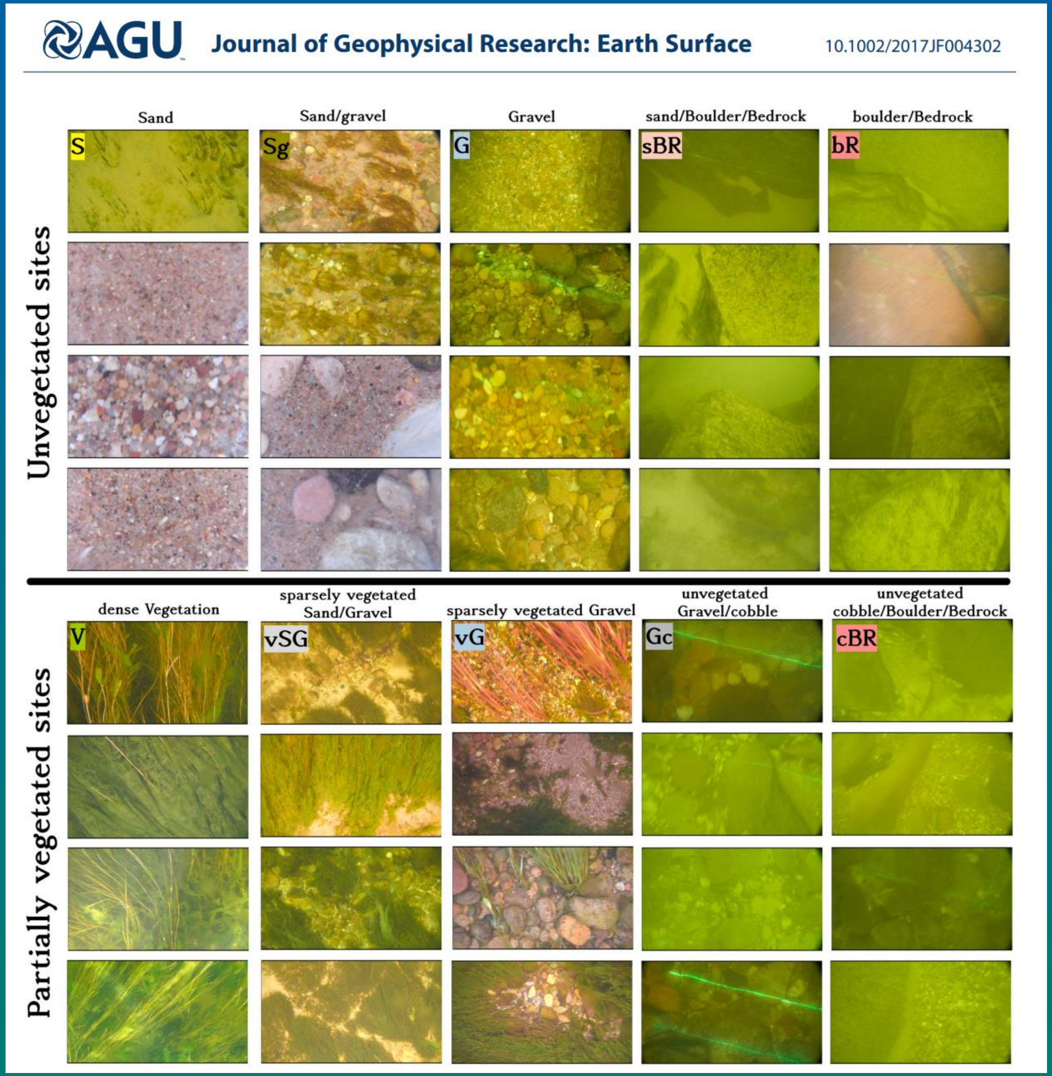
## (No GNSS positions; Optically tracked at 20Hz)

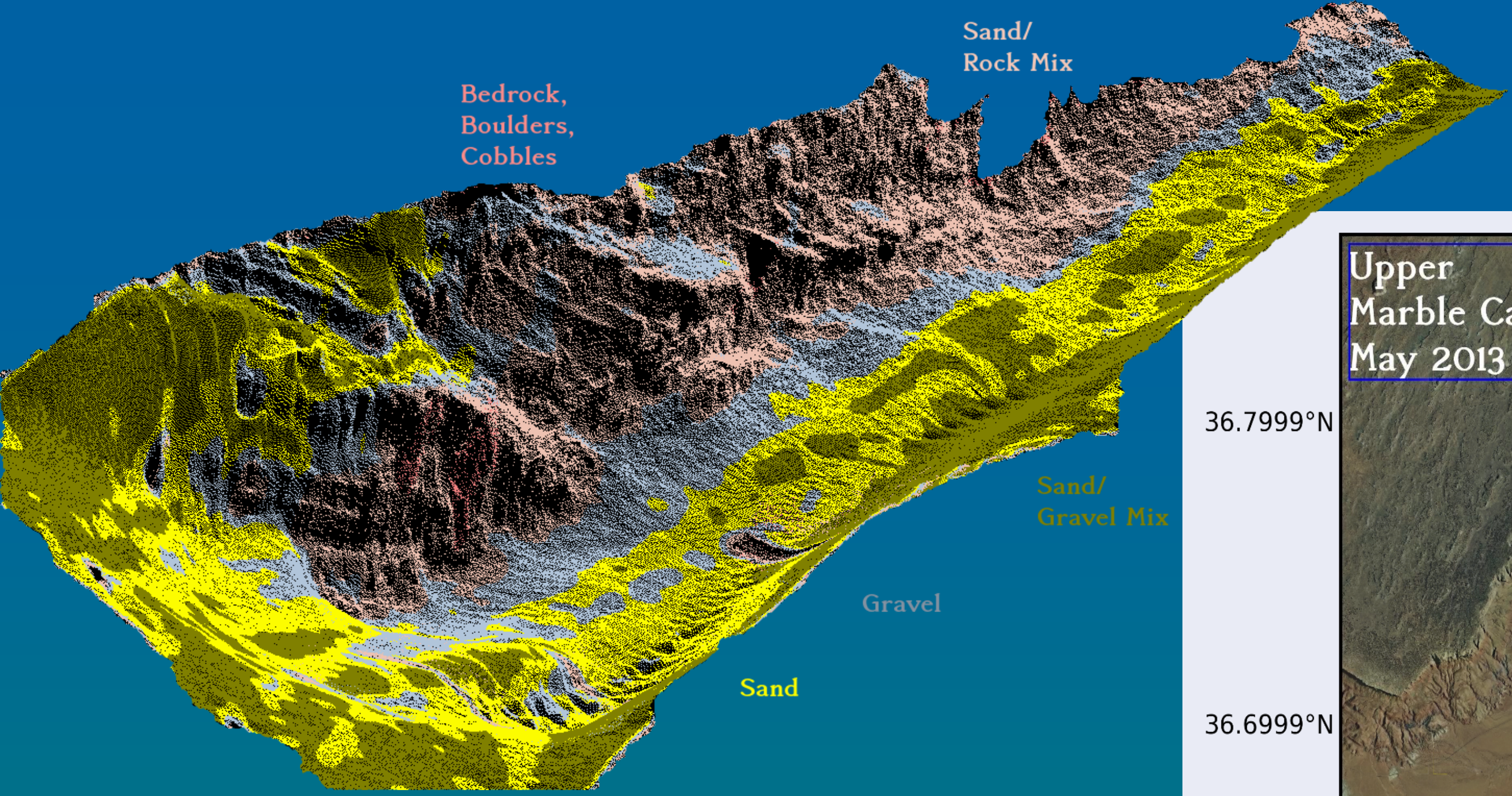


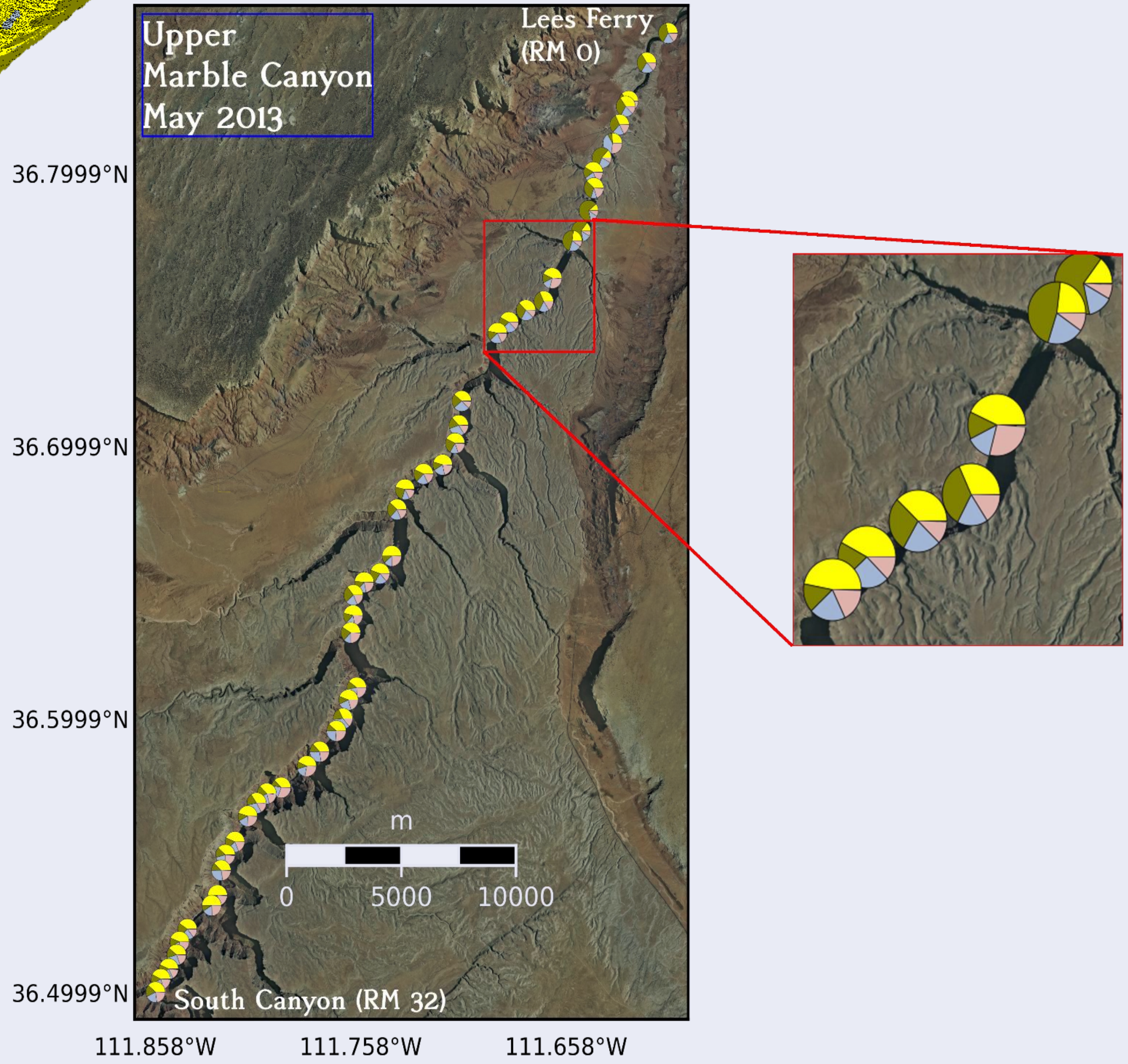
# Multibeam and filtered backscatter products






Using this technique we've mapped sediment type over 200 miles of riverbed at 25-cm resolution.

Sediment plume can be tracked!

# The uncertainties of uncertainty…

**“When the volumes were compared, the flux-based and morphological estimates of net erosion differed by about 150,000 m^3 (equivalent to about 0.03 m (3cm) of sand distributed evenly throughout the 50km study area)”**

Journal of Geophysical Research Earth Surface Vol118 1-21 doi:10.1002/jgrf.20050,2013

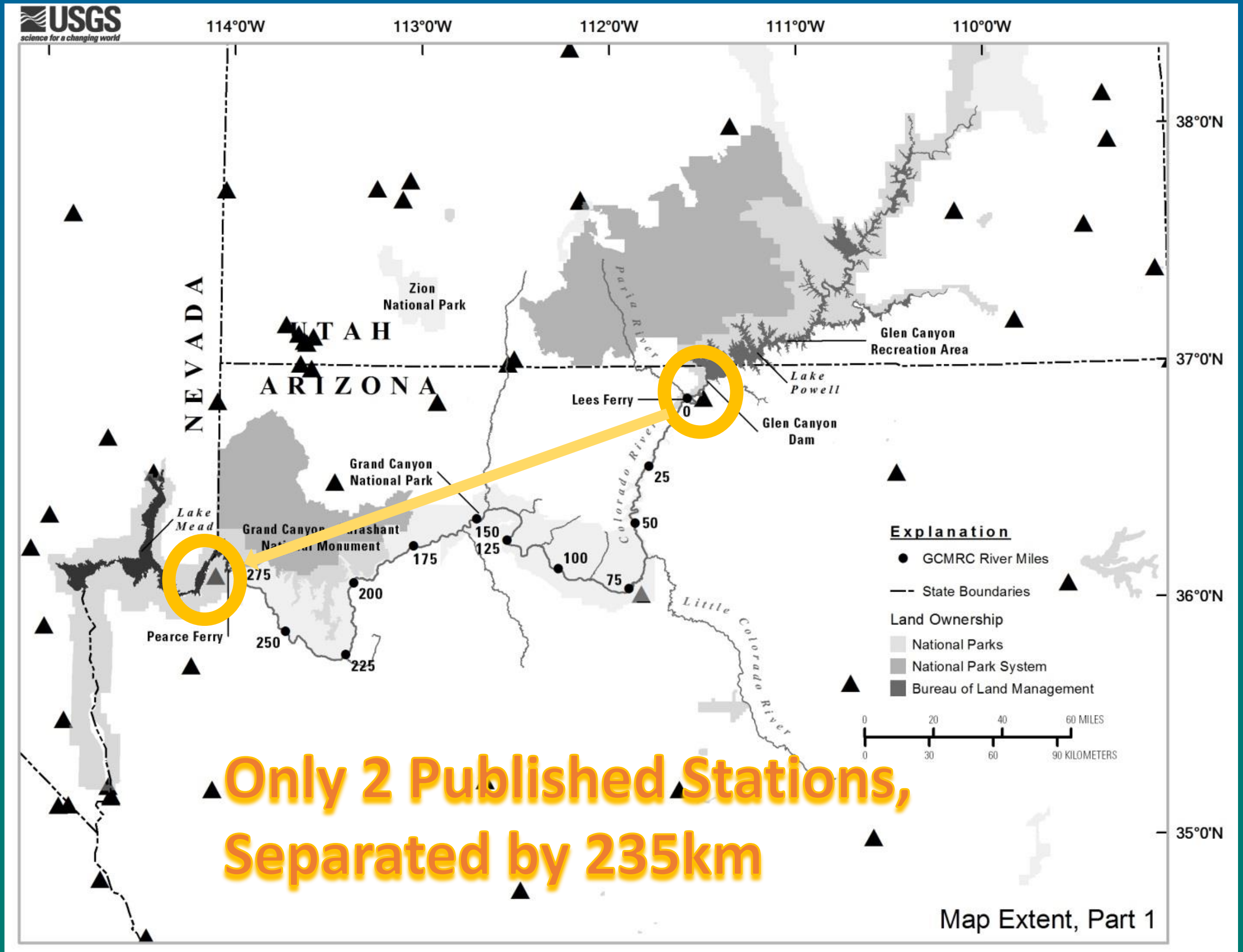
**Linking morphodynamic response with sediment mass balance on the Colorado River in Marble Canyon: Issues of scale, geomorphic setting, and sampling design**

Paul E. Grams,[1] David J. Topping,[1] John C. Schmidt,[1] Joseph E. Hazel Jr.,[2] and Matt Kaplinski[2]

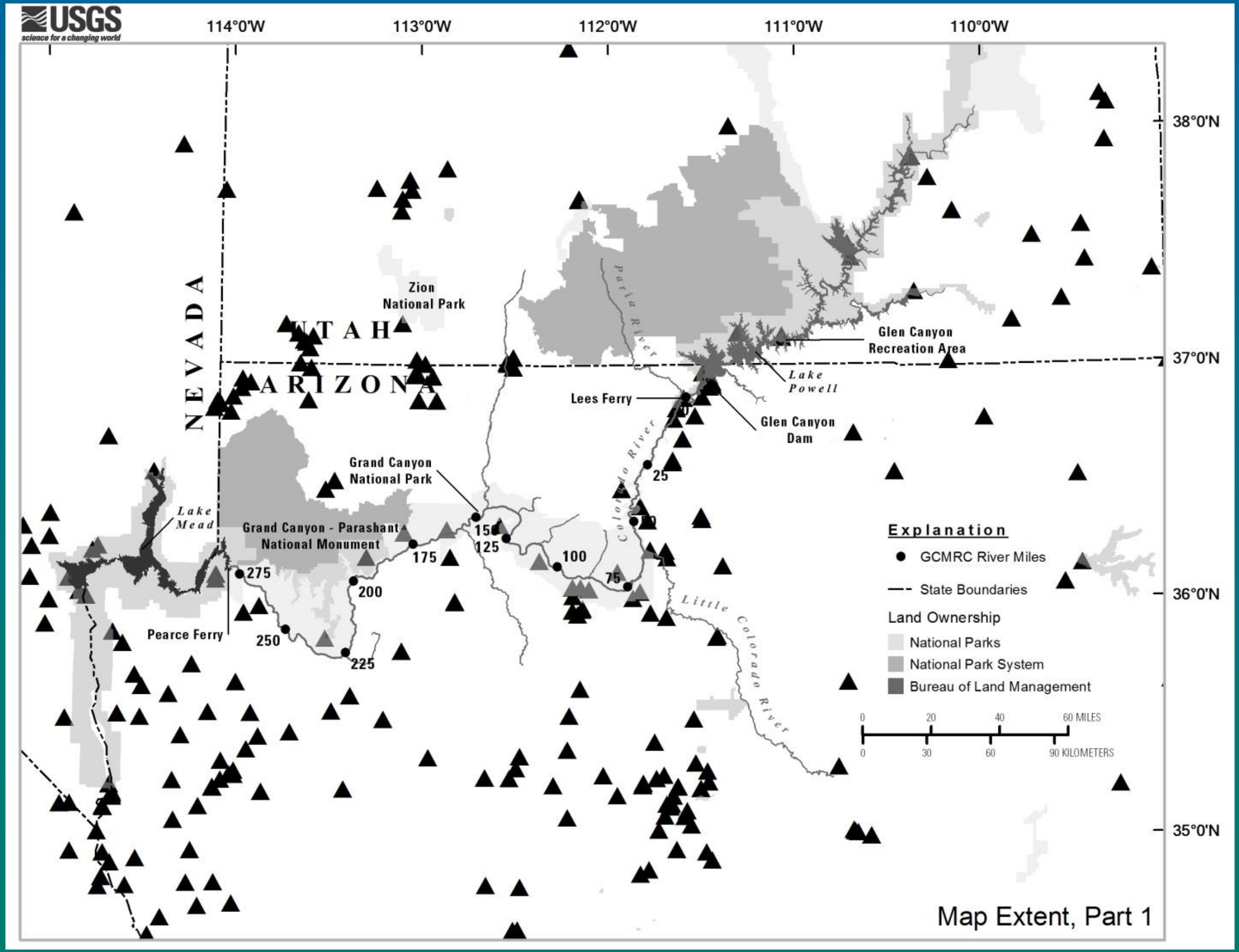
**Therefore, we require positional (and height!) accuracies commensurate with the scope and scale of the monitoring program (That is: relative accuracies at the 3cm level)**

# Step 1: Improve and densify the National Spatial Reference System

## HARN (1992)




## NAD83(2011)



# NGS Bluebooked GNSS campaigns

| Year | Project ID | Project name | GCMRC control stations occupied in project |
|---|---|---|---|
| **1992** | GPS376 | Arizona 1992 HARN survey | L 404, NAVAJO POINT |
| **1994** | GPS404 | Nevada 1994 FBN/CBN and FAA airports | AIRPORT |
| **1994** | GPS633 | Utah 1994 FBN/CBN | AIRPORT |
| **1996** | GPS1154 | 1996 Arizona ANA GPS Survey | L 404, NAVAJO POINT |
| **1999** | GPS1347 | 1999 Arizona FBN Survey | L 404, NAVAJO POINT, SIGNAL HILL, T 96 |
| **1999** | GPS1356 | Nevada 1999 FBN | AIRPORT, DAVIAN, L 404, NAVAJO POINT |
| **1999** | GPS1370 | Utah 1999 FBN | DAVIAN, L 404 |
| **2001** | GPS1544 | AZ FBN Replacement Survey | DAVIAN, DESERT VIEW, EMIN, L 404 |
| **2003** | GPS1871 | Grand Canyon Rim | ABYSS, AIRPORT, CAPE, DAVIAN, DESERT VIEW, ECHO, EMIN, FRAZ, GCNRA, JACK, L 404, LFRG, MUSIC MOUNTAIN MINE, SIGNAL HILL, SOUTH CANYON TRAILHEAD, T 96 |
| **2004** | GPS2062 | Glen Canyon Rec Area, Lake Powell | L 404, LFRG, MARBLE CANYON, BEEHIVE NORTH, BF1, BF2, FH6, R151, DR1, DR2, U148, HC1, HC2, HITE1, HITE2, HITE3, Z114, P115, N141, N373 on the San Juan |
| **2005** | GPS2159 | Grand Canyon Rim – Vertical | ABYSS, AIRPORT, DAVIAN, DESERT VIEW, ECHO, EMIN, FRAZ, L 404, LFRG, MUSIC MOUNTAIN MINE, SOUTH CANYON TRAILHEAD, T 96, A511,D7,E78,E487,150DOR,2879,A116, B508,C54,M62,P499,Q61,S285,T61,T403, Z53 |
| **2008** | GPS2510 | Mohave County – Kingman | MUSIC MOUNTAIN MINE |
| **2011** | GPS2831 | 2009 Grand Canyon aerial mapping and 2010 Coconino County Height Modernization surveys | ABYSS, AIRPORT, AIRPORT RM 1, AIRPORT RM 2, ALT, APIN, BADGER, BIG, CAPE, CAVE, DAVIAN, DESERT VIEW, DWARF, ECHO, EMIN, EMIN REF 1, FRAZ, GCNRA, JACK, L 404, LFRG, MUSIC MTN MINE, MUSIC MTN REF1, MUSIC MTN REF2, Q 389, R 389, SALT, SALT CANYON, SB POINT, SHIVWITS, SIGNAL HILL, SOUTH CANYON TH, T 96, TENDERFOOT, WHITMORE, CARDENAS, 6866 |

# Step 2: Develop a GNSS-based control network within Grand Canyon

## However, poor GNSS solutions are inherent in deep canyon environments!!

East/West orientations with high-angle (>45°) horizon obstructions

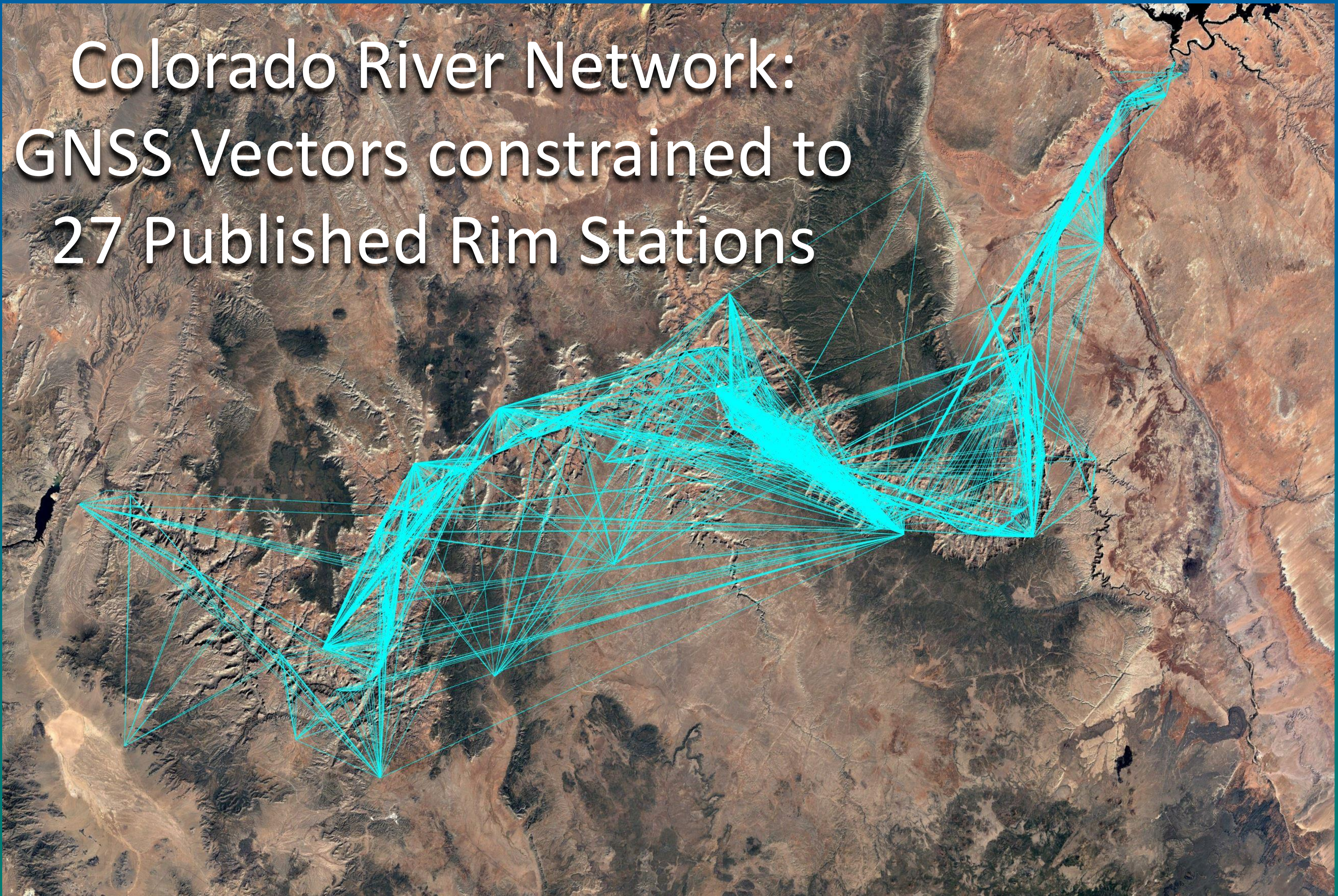
South side of river has particularly poor satellite visibility

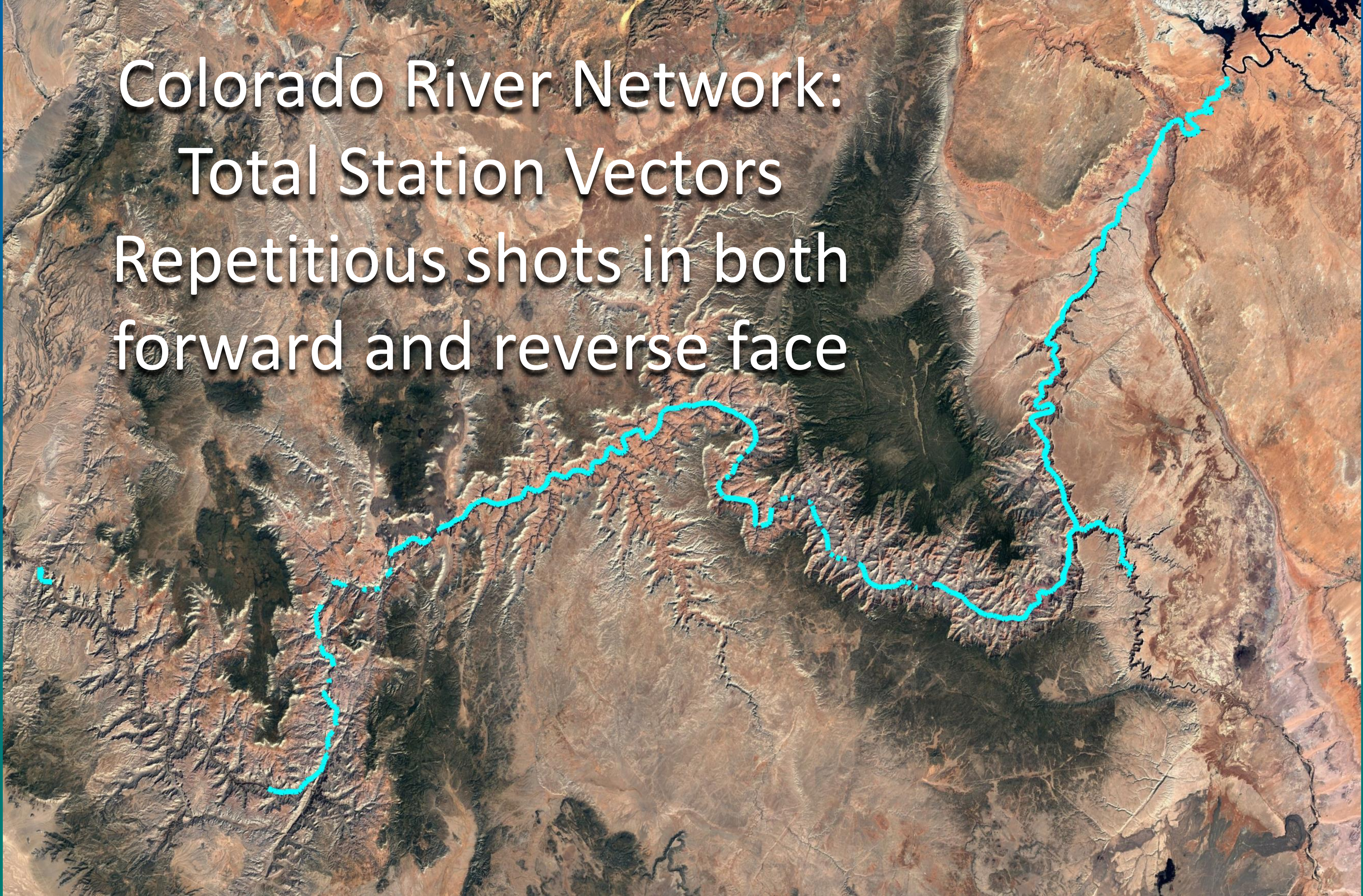
Demands shorter baselines, longer occupations

Requires creative outlier detection of poor-fitting solutions

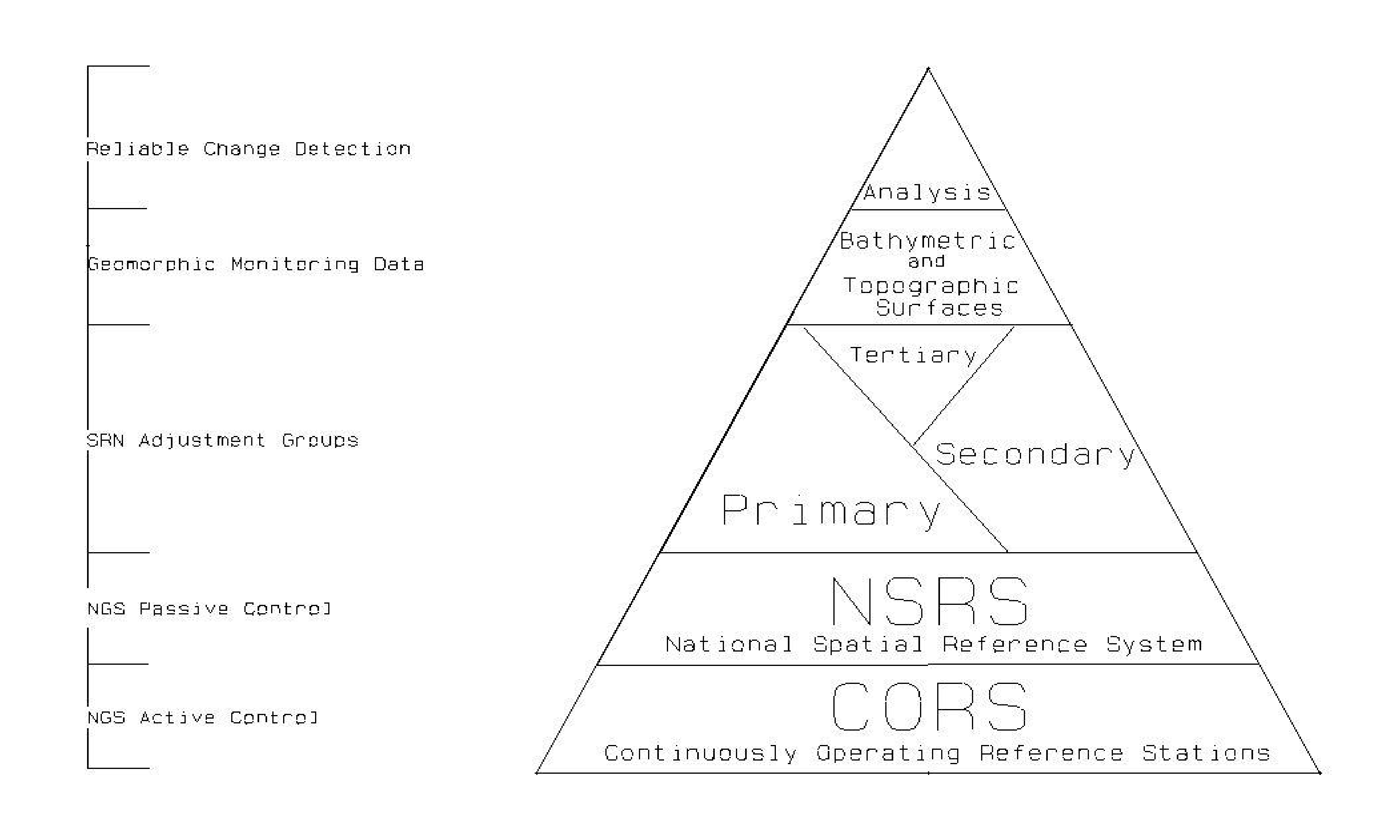
More reliance on optical (Total Station) survey methods and less on RTK

# Colorado River Network: GNSS Vectors constrained to 27 Published Rim Stations




Colorado River Network:
Total Station Vectors
Repetitious shots in both
forward and reverse face

# Network Design

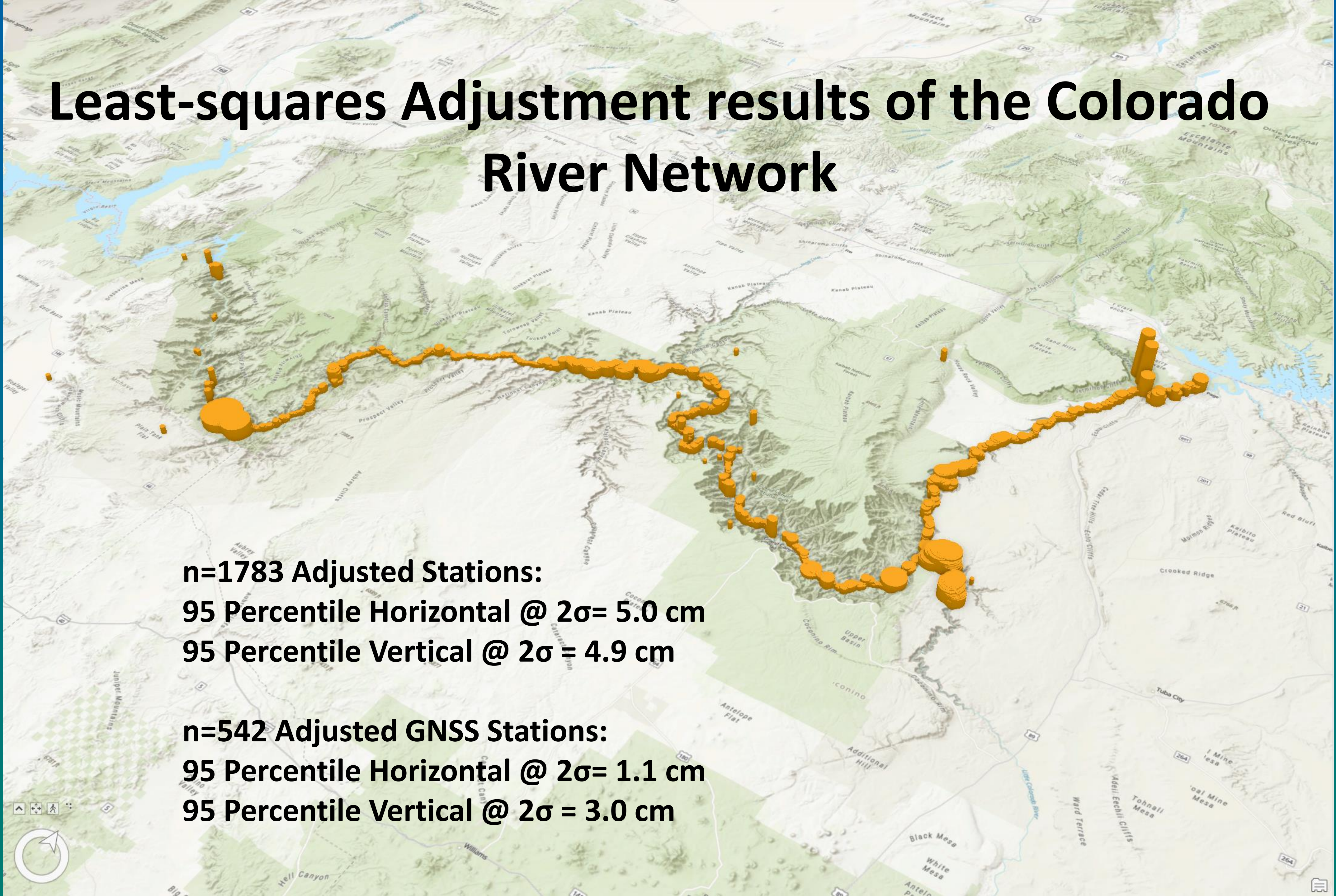


## Network Statistics:

38736 Degrees of Freedom
9324 GNSS vectors
8895 Optical Total Station vectors (Repetitious)
1787 Adjusted Stations with redundancy
650 stations with GNSS observations

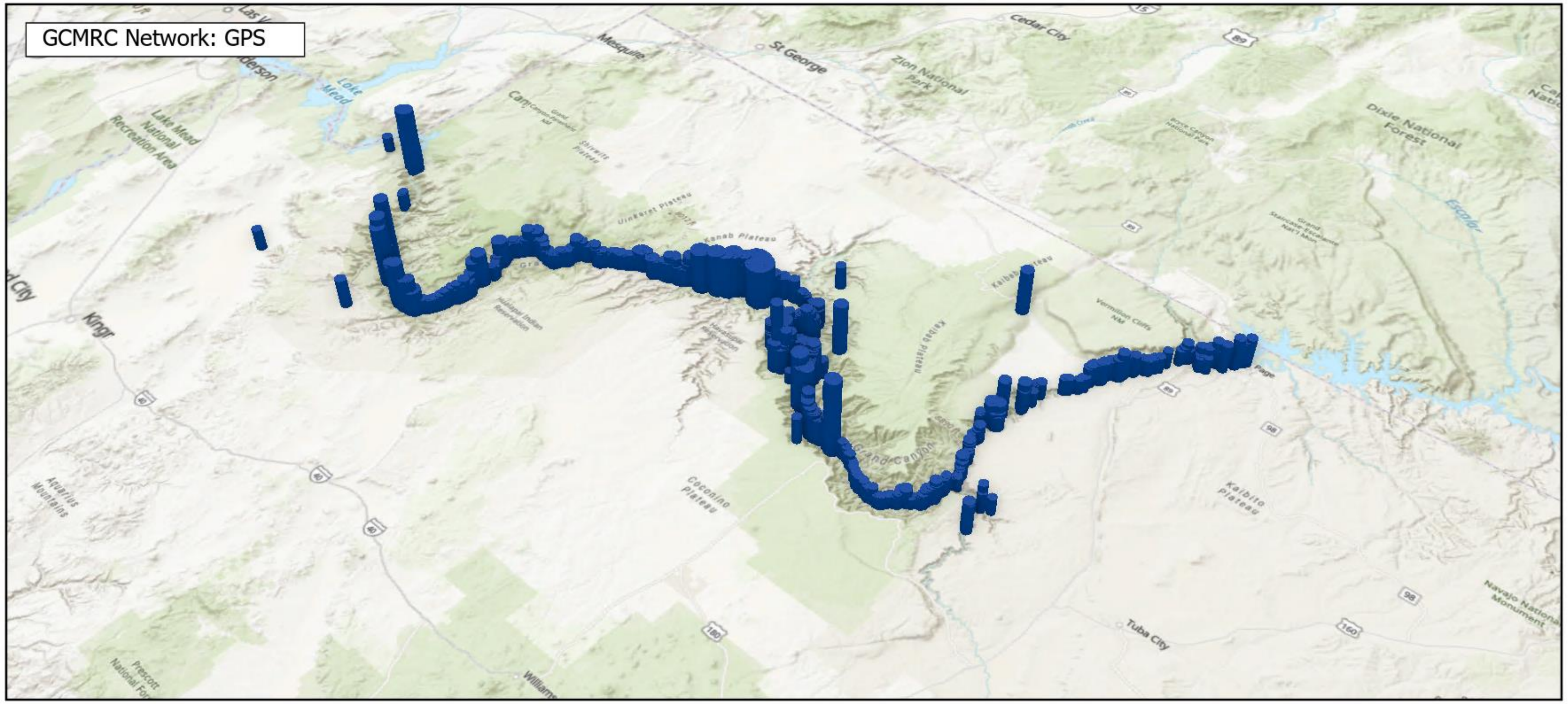
| Assessment | count | vertical uncertainty 95% | horizontal uncertainty 95% |
|---|---|---|---|
| Least-Squares results Constrained to Passive control | n=1787 | 5.0cm | 4.9cm |
| Least Squares results Vs OPUS projects Primary River Network | n=22 | 4.6cm | 1.7cm |
| Least-Squares comparisons (Published Control Constrained Vs. Free results ) | n=27 | 3.7cm | 1.8cm |
| Least-Squares comparisons (CRE Stations Constrained Vs. Free results) | n=1713 | 1.3cm | 1.0cm |
| Least-Squares comparisons (Unpublished Rim Stations Passive Vs. Active results) | n=4 | 2.0cm | 0.9cm |
| May 2021 Overflight (Passive Constrained, Active Free) | n=9 | 4.3cm | 2.7cm |
| May 2021 Overflight (Passive Free, Active Constrained) | n=12 | 3.4cm | 3.0cm |
| May 2021 Overflight (Passive Free, Active Constrained) excluding 3 airport control stations | n=9 | 3.3cm | 2.1cm |

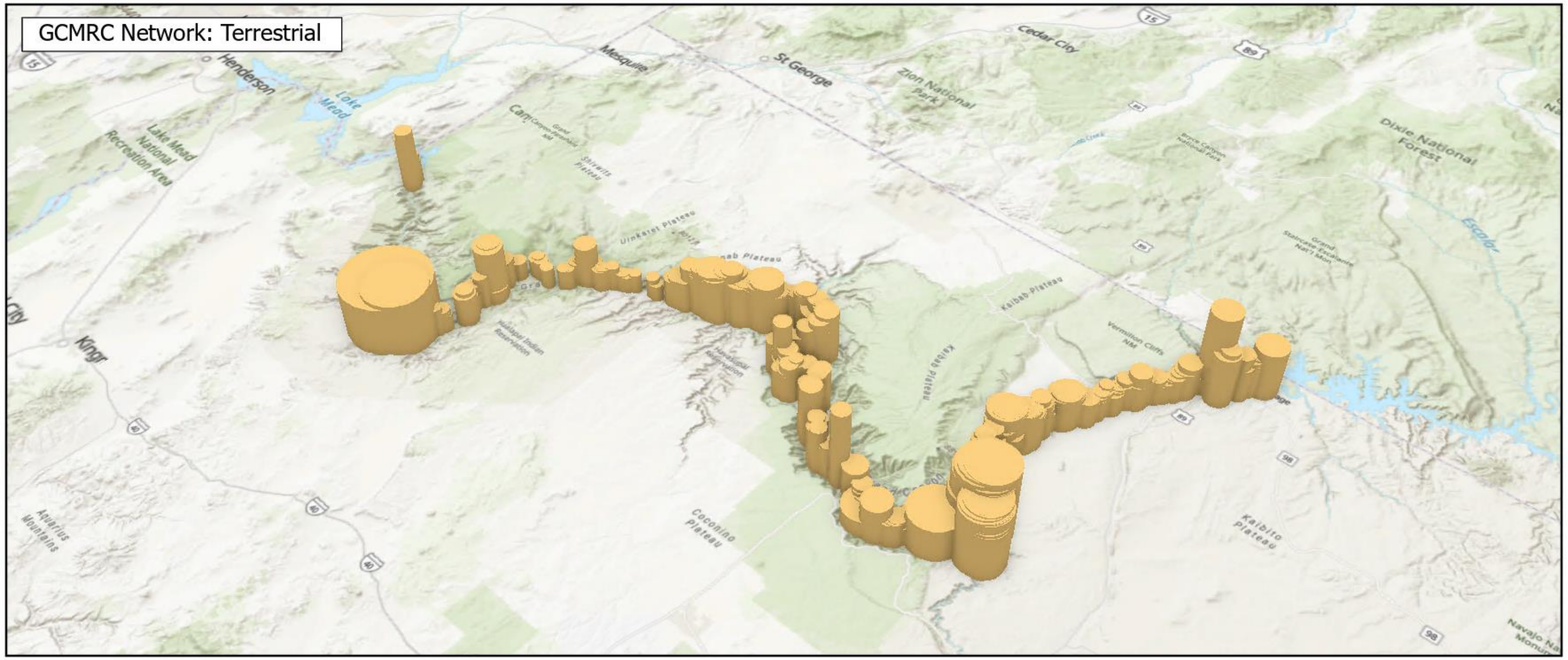
# Least-squares Adjustment results of the Colorado River Network



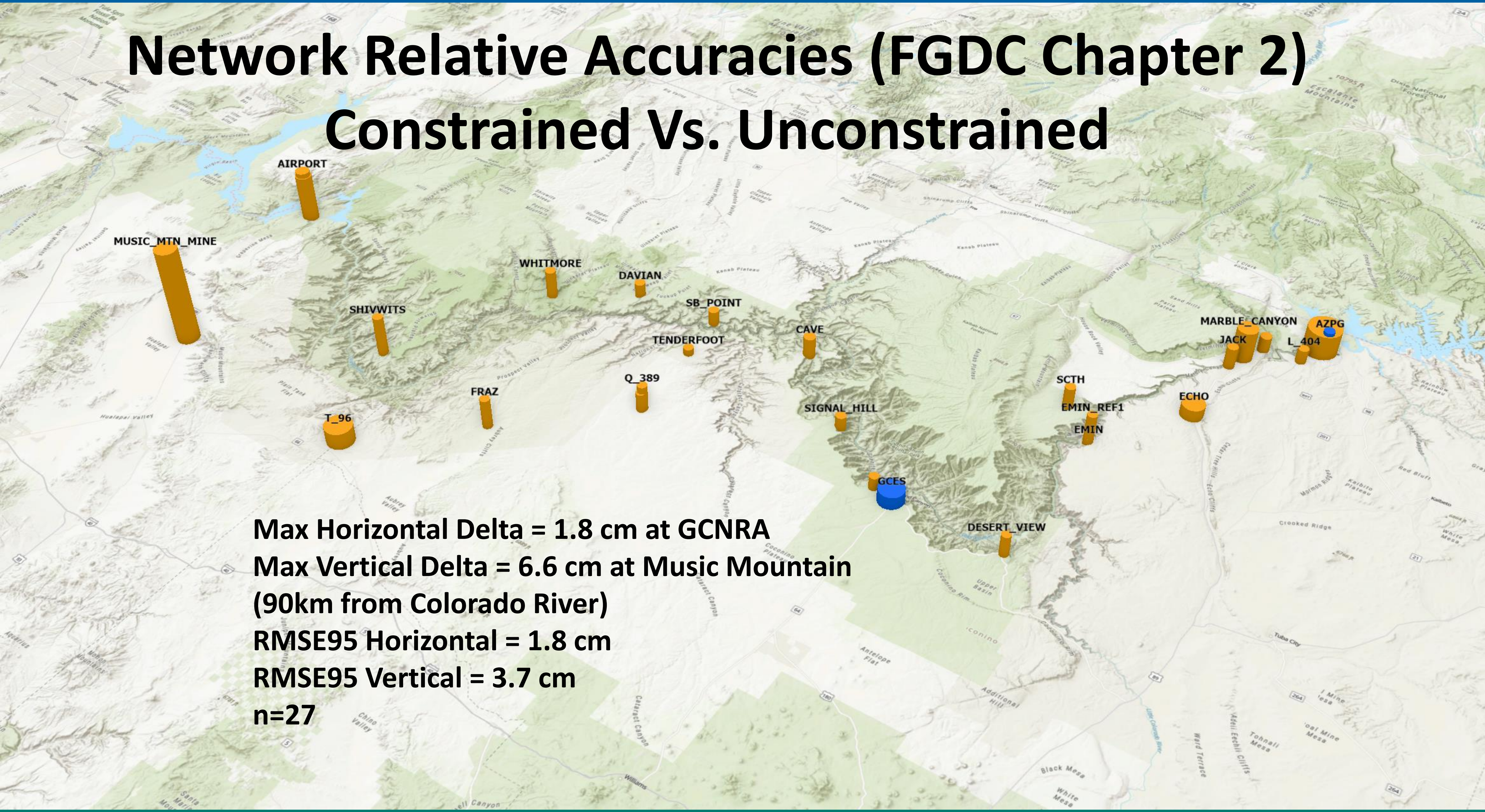
**n=1783 Adjusted Stations:**
**95 Percentile Horizontal @ 2σ= 5.0 cm**
**95 Percentile Vertical @ 2σ = 4.9 cm**

**n=542 Adjusted GNSS Stations:**
**95 Percentile Horizontal @ 2σ= 1.1 cm**
**95 Percentile Vertical @ 2σ = 3.0 cm**


GCMRC Network: GPS
Mesquite
St George
Cedar City
Zion National Park
Lake Mead National Recreation Area
Dixie National Forest
Uinkaret Plateau
Kanab Plateau
Kaibab Plateau
Vermilion Cliffs NM
Grand Canyon
Coconino Plateau
Kaibito Plateau
Tuba City
Aquarius Mountains
Page
Kingman

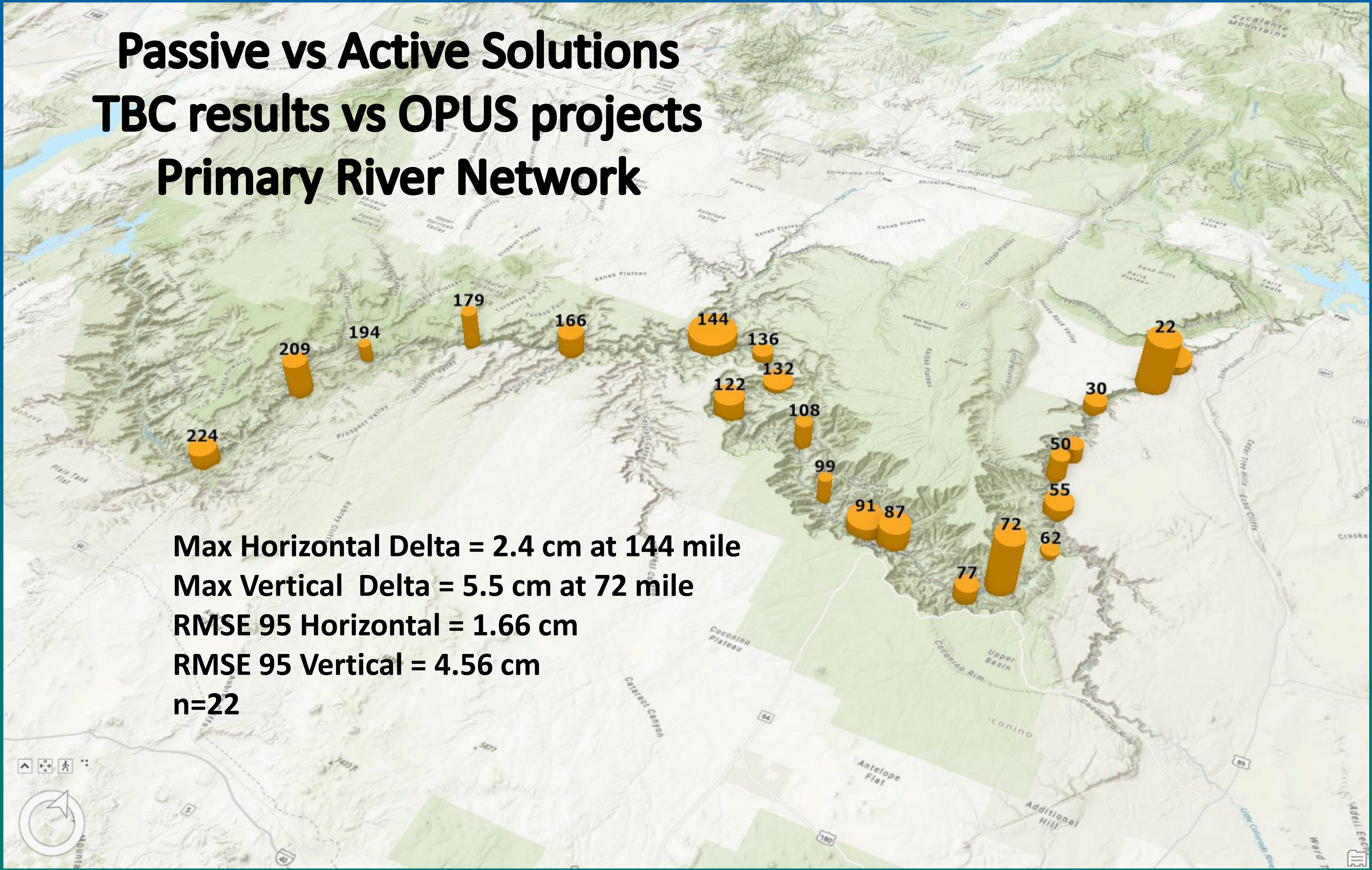

GCMRC Network: Terrestrial
Henderson
Mesquite
St George
Cedar City
Zion National Park
Lake Mead National Recreation Area
Dixie National Forest
Uinkaret Plateau
Kaibab Plateau
Vermilion Cliffs NM
Coconino Plateau
Kaibito Plateau
Aquarius Mountains
Kingman

# Network Relative Accuracies (FGDC Chapter 2)
# Constrained Vs. Unconstrained




**Max Horizontal Delta = 1.8 cm at GCNRA**
**Max Vertical Delta = 6.6 cm at Music Mountain**
**(90km from Colorado River)**
**RMSE95 Horizontal = 1.8 cm**
**RMSE95 Vertical = 3.7 cm**
**n=27**

# Passive vs Active Solutions
# TBC results vs OPUS projects
# Primary River Network

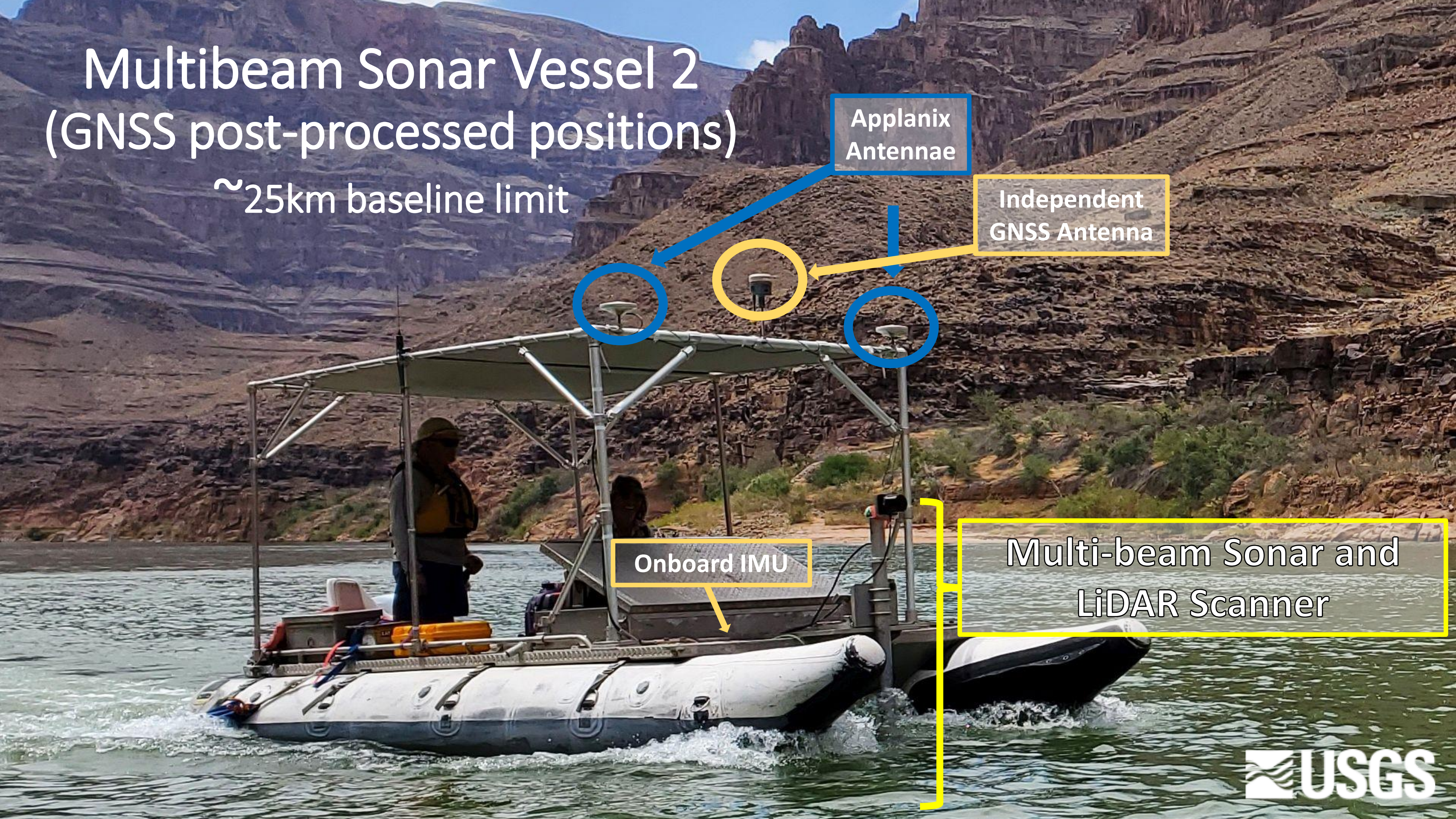



**Max Horizontal Delta = 2.4 cm at 144 mile**
**Max Vertical  Delta = 5.5 cm at 72 mile**
**RMSE 95 Horizontal = 1.66 cm**
**RMSE 95 Vertical = 4.56 cm**
**n=22**

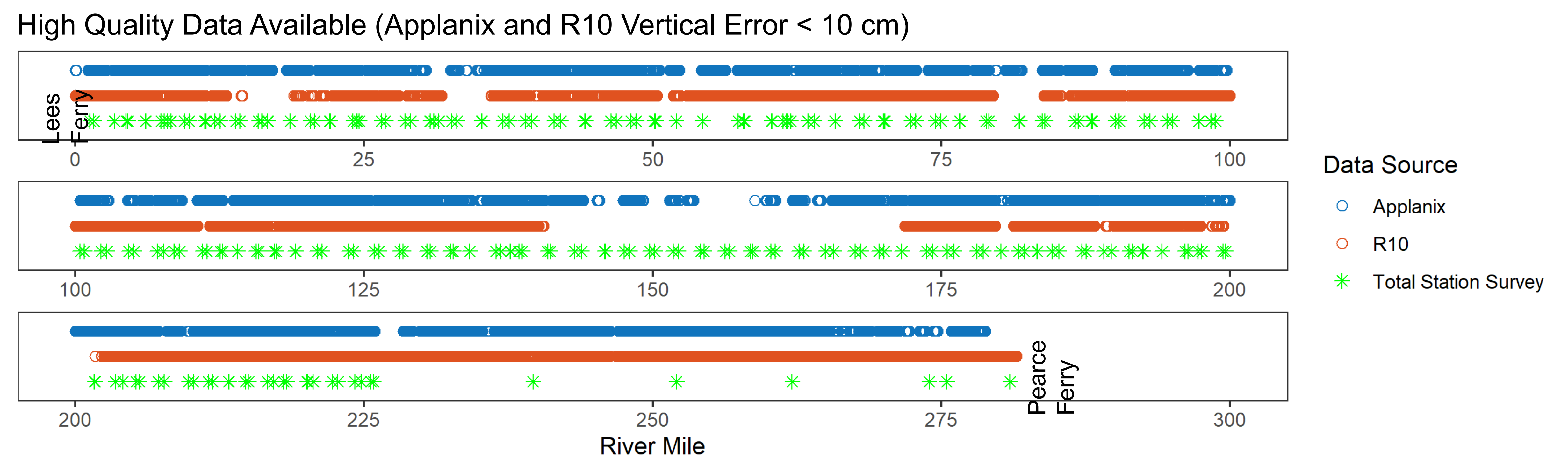
# May 2021 Overflight included a Longitudinal Profile with water surface and thalweg for 440km of the Colorado River

8 days of data collection under 8000 cfs steady flow conditions utilizes:

- NSRS Control (GNSS constraints for aerial and boat platforms)
- River Control Network  (Total Station surveys for ground truthing and 160 photo panels set prior to mission)
- Kinematic GNSS (Multibeam swath orientation and water surface referenced to rim control)
- Airborne Imagery collection from 2 planes. 2 Base stations within 50km of CRE are observed (20cm resolution imagery and orthorectified DTM)
- Multibeam Sonar (Depths and water surface elevations for ~440 km)
- Boat mounted LiDAR system (Identifies cut banks and water’s edge location)


Multibeam Sonar Vessel 2
(GNSS post-processed positions)
~25km baseline limit
Applanix Antennae
Independent GNSS Antenna
Onboard IMU
Multi-beam Sonar and LiDAR Scanner
USGS

# Water Surface Profile – 3 Sources

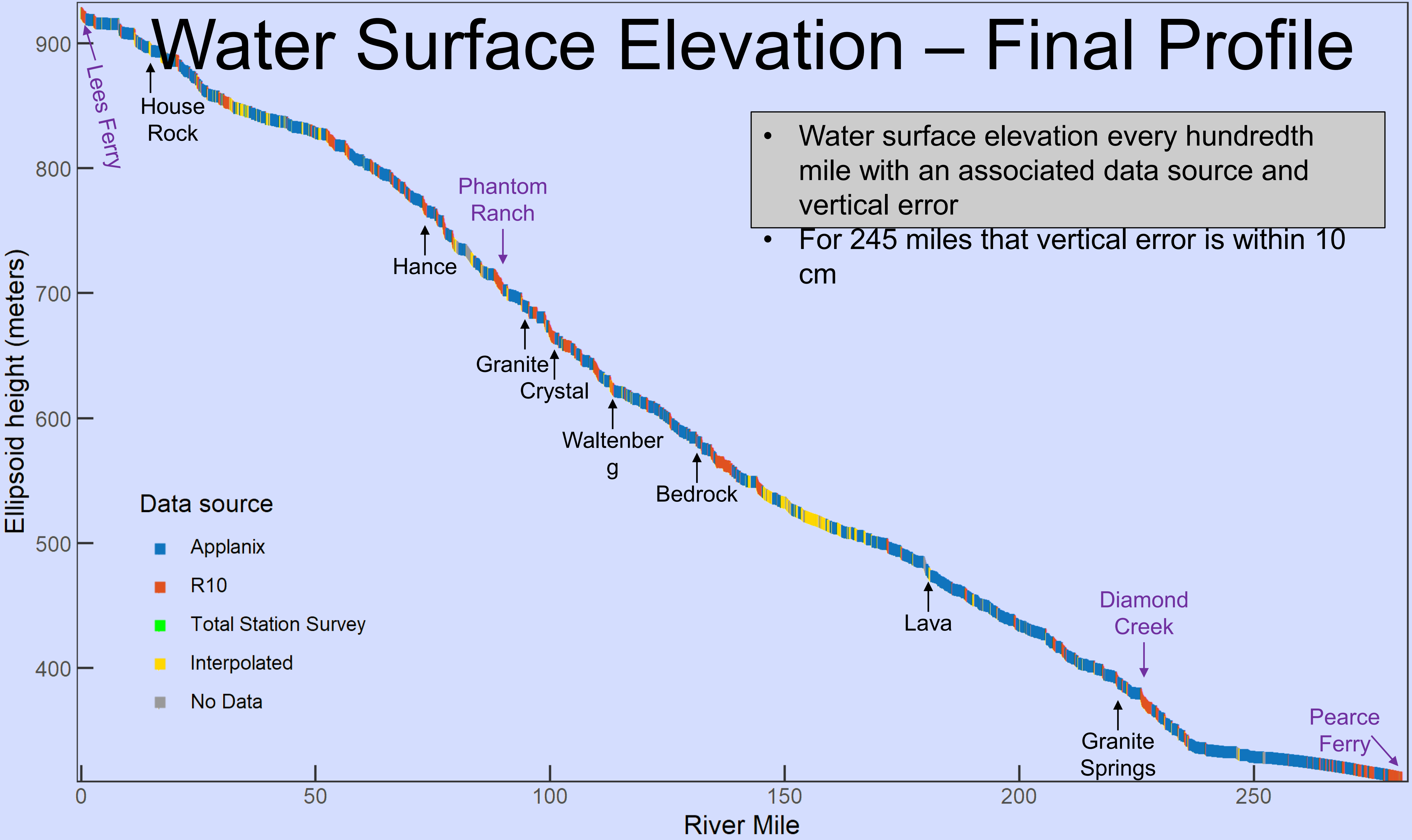



Total station surveys referencing the river network **validate** the NSRS referenced Applanix and R10 solutions by **comparing stages** at the same river mile

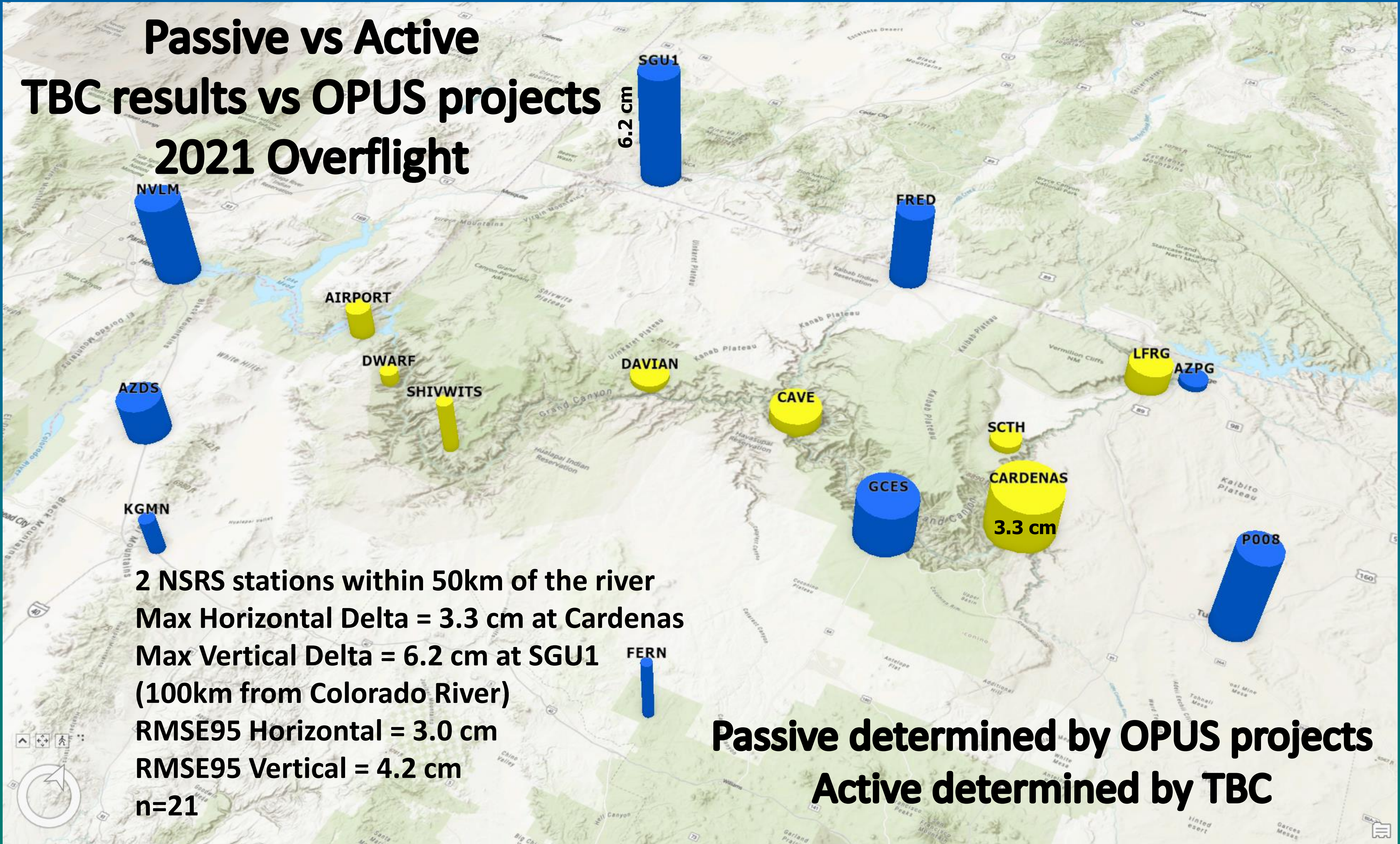
- **201.5 miles of high quality Applanix Data (VE < 1**
- **211.3 miles of high quality R10 data (VE < 10cm)**
- **578 total station survey points at 316 unique river hundredth-miles**

# Water Surface Elevation – Final Profile

- Water surface elevation every hundredth mile with an associated data source and vertical error
- For 245 miles that vertical error is within 10 cm



# Passive vs Active
# TBC results vs OPUS projects
# 2021 Overflight




2 NSRS stations within 50km of the river
Max Horizontal Delta = 3.3 cm at Cardenas
Max Vertical Delta = 6.2 cm at SGU1
(100km from Colorado River)
RMSE95 Horizontal = 3.0 cm
RMSE95 Vertical = 4.2 cm
n=21

**Passive determined by OPUS projects**
**Active determined by TBC**

# Geodetic summary…

# Datum Realizations:
# NAD83(HARN) to NAD83(2011)

Passive NSRS Network progression

- 1992 HARN to 1999 FBN (Via CORS96)
  - (8cm lower)
- 1999 FBN to NSRS 2007
  - (<1cm)
- NSRS2007 to NAD83(2011)
  - (3cm north, 3cm lower)

# Future Datum Realizations: NAD83(2011) to NATRF(2023)

Passive to Active (Relative to 9 distant CORS up to 100km away)

*GCES, AZPG CORS added in 2015 and after NAD83(2011) adjustment

- NAD83(2011) to NATRF(2023) (2021 overflight data)
  - RMSE 95 Vertical=4.2cm
  - RMSE 95 Horizontal = 3.0 cm
- GCES CORS Station Fixed, 28 free
  - Changes to Passive control (95%): 2.3cm Horizontal, 2.5cm Vertical
- GCES CORS Station Unconstrained, 29 Constrained
  - 1.8cm North, 0.3cm West, 1.0cm up

# Thank you !

Check out our Glen Canyon Map!:

ArcGIS Enterprise - Colorado River Glen Canyon Channel Map (usgs.gov)