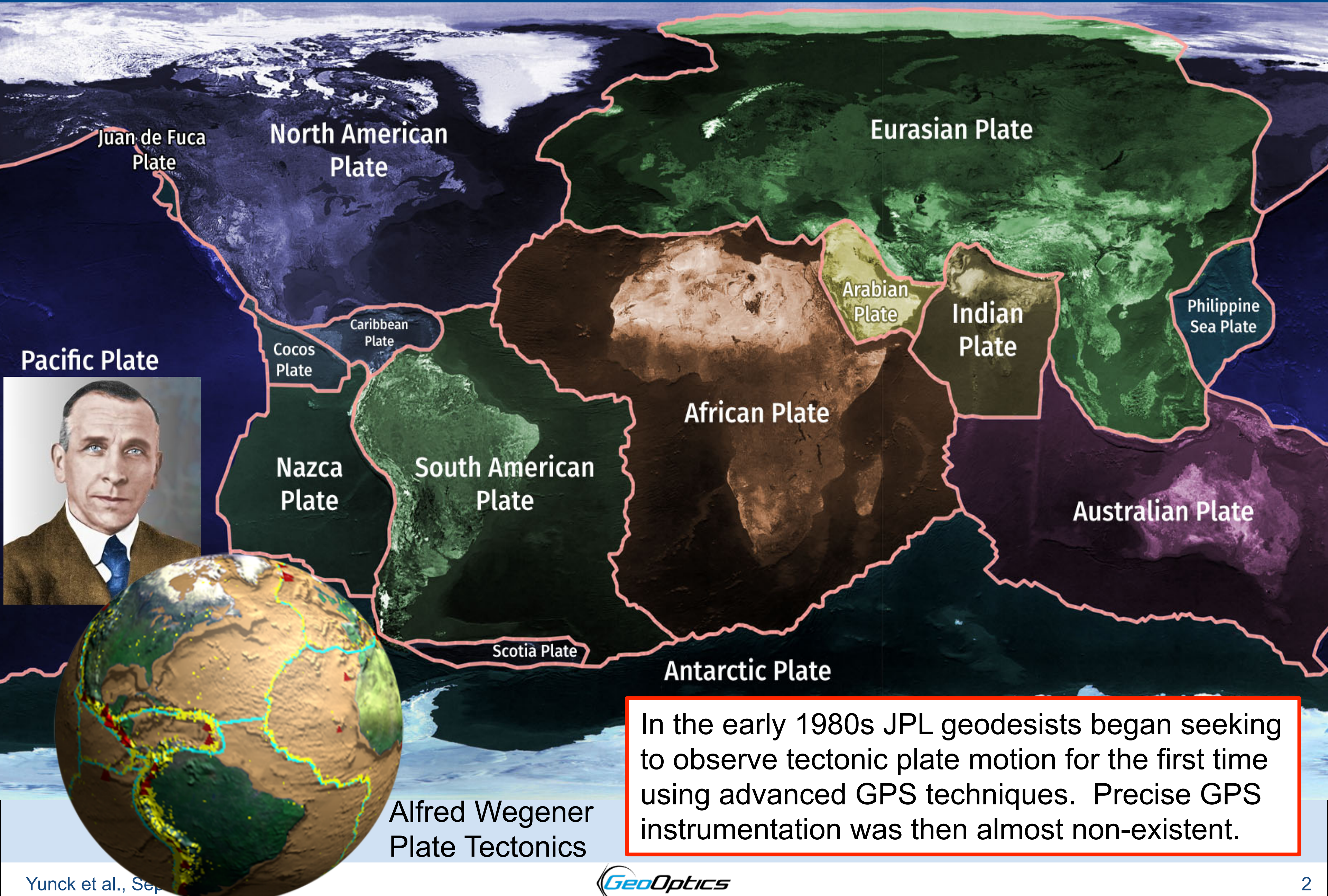
To Everything A Season

RO Coming Of Age

Tom Yunck, Conrad Lautenbacher, Alex Saltman

September 20, 2019

Origins: GPS Geodesy, Early 1980s

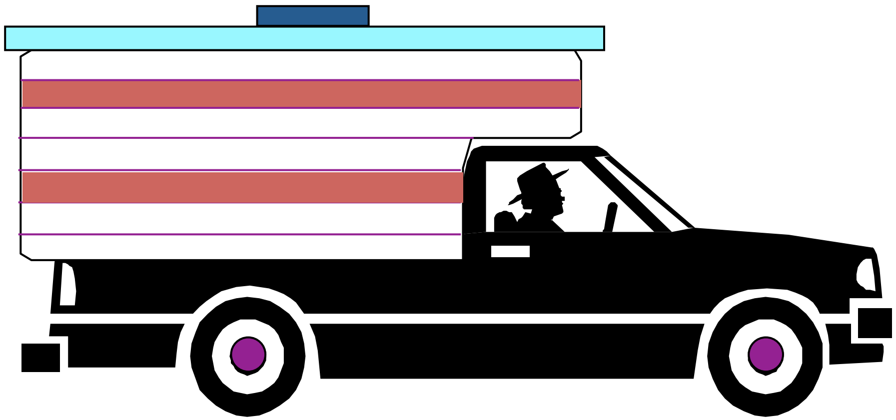


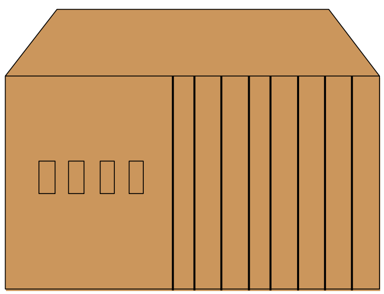
Alfred Wegener
Plate Tectonics

In the early 1980s JPL geodesists began seeking to observe tectonic plate motion for the first time using advanced GPS techniques. Precise GPS instrumentation was then almost non-existent.

1987-89

Early Mobile GPS Instrument



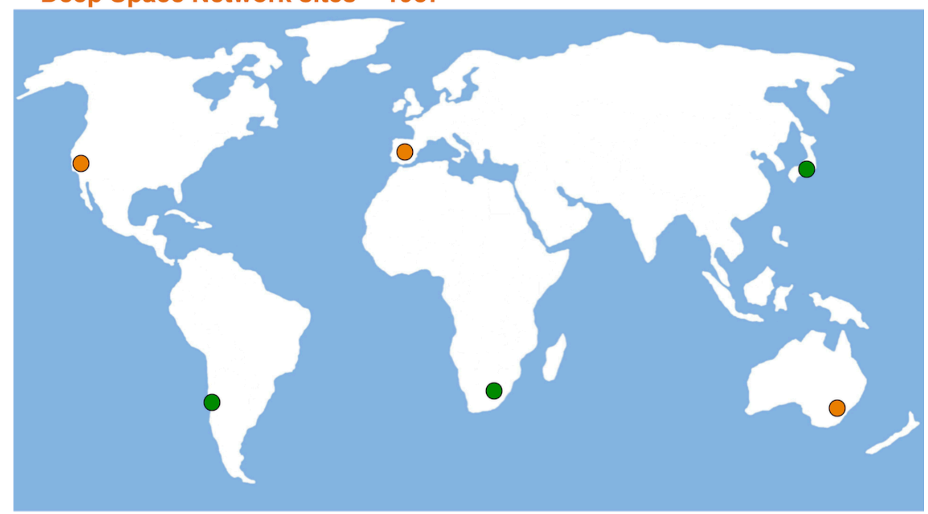


JPL's Rogue
GPS Receiver

In **1987** JPL scientists were driving the big "Rogue" GPS receiver to various points in southern California to make geodetic measurements.

Global Reference Network

Deep Space Network sites – 1987



3 Complementary sites – 1989

By **1989** NASA had installed 6 permanent Rogue (or smaller mini-Rogue) receivers around the globe to serve as reference sites for precise GPS geodesy.

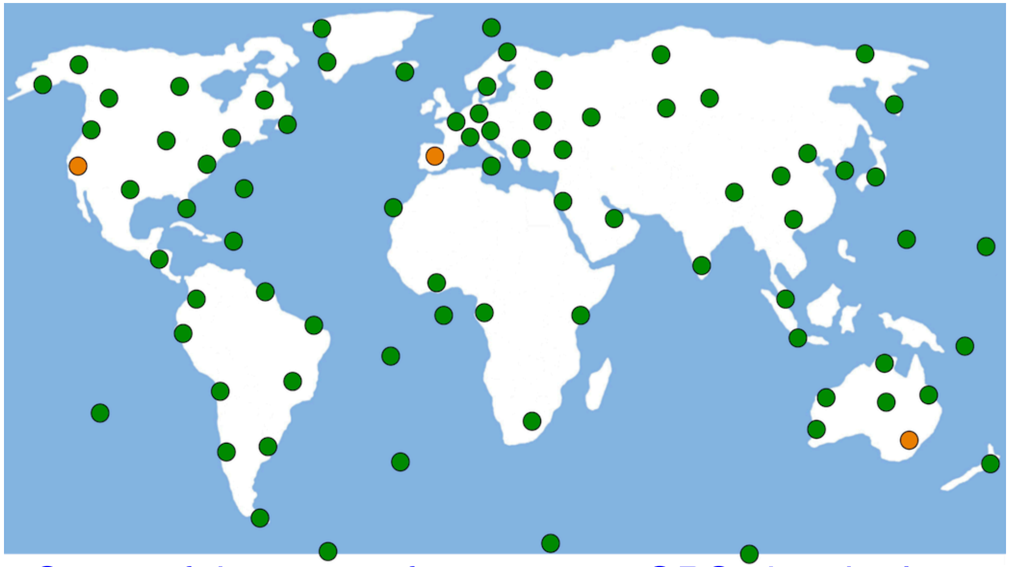
1992-93

Portable GPS Instrument

JPL's TurboRogue GPS Receiver

In **1992** JPL introduced the TurboRogue GPS geodetic receiver, which spawned imitators...and a revolution in global GPS geodesy.

Global Reference Network

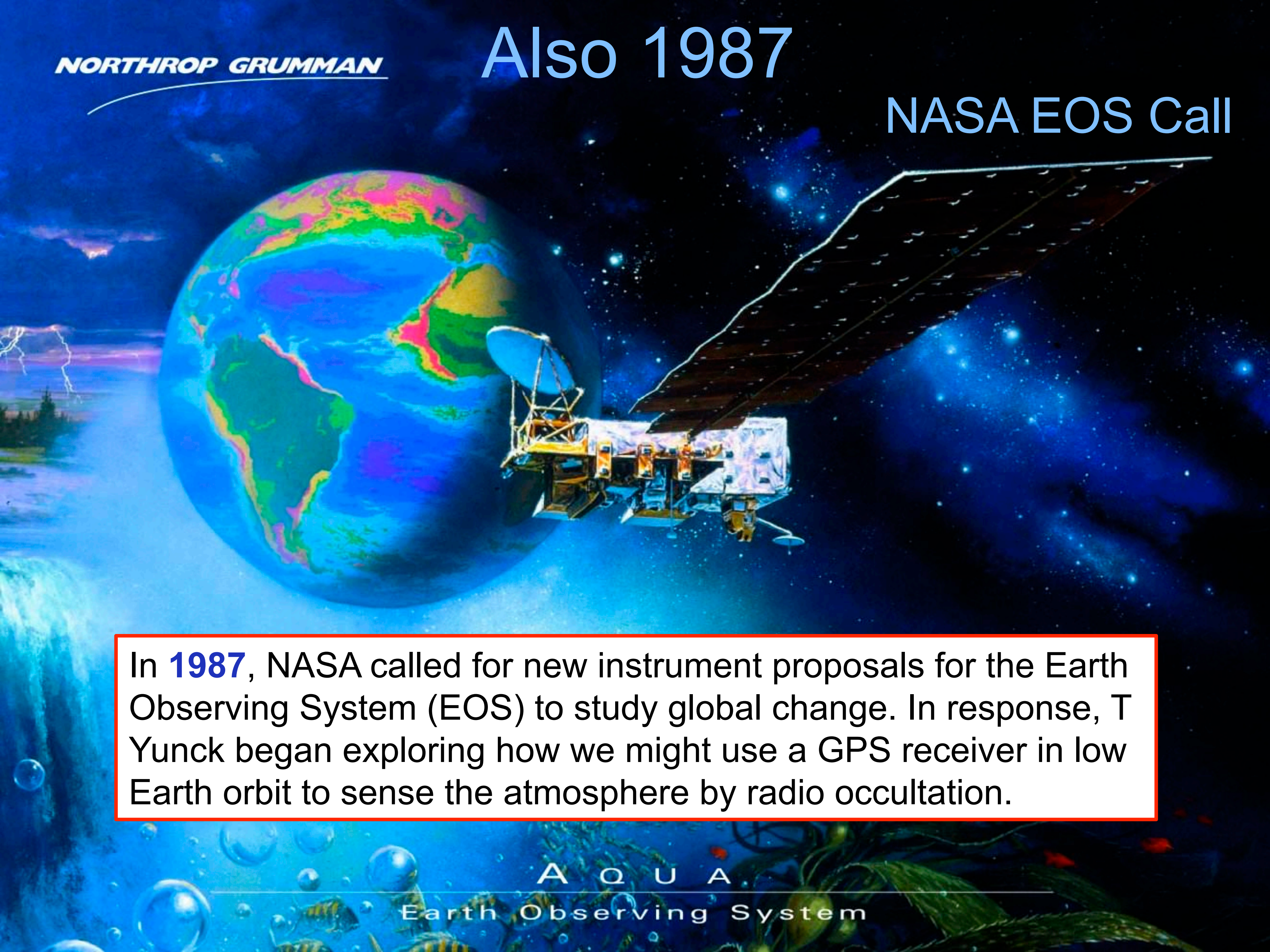


Some of the 100s of permanent GPS sites by late 1993; within a few years there were thousands.

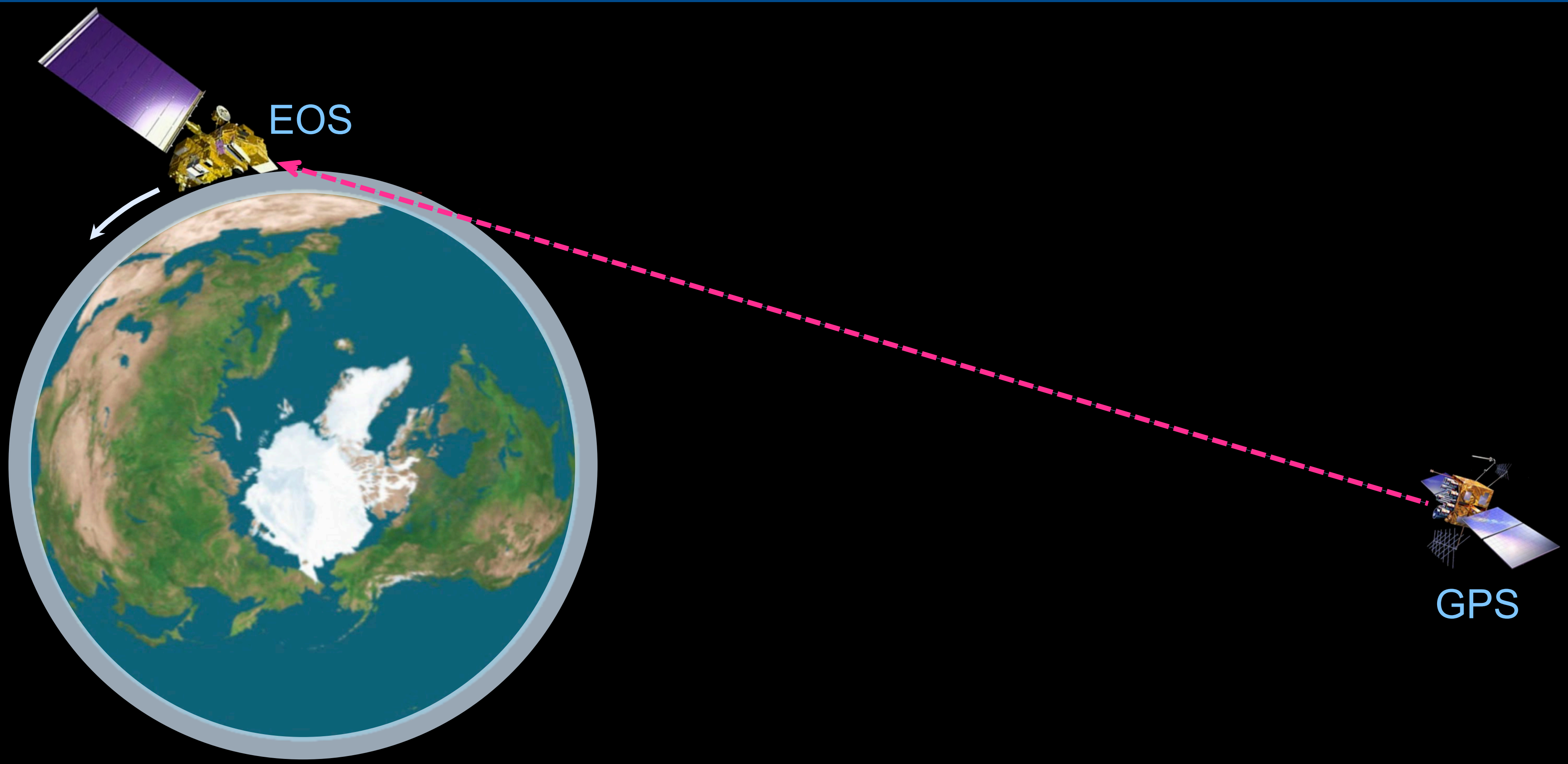
By **1993**, through strong leadership and community commitment, hundreds of permanent GPS geodetic sites were in place around the world. Just six years had gone by since the big Rogue was being trucked from point to point.

Also 1987

NASA EOS Call



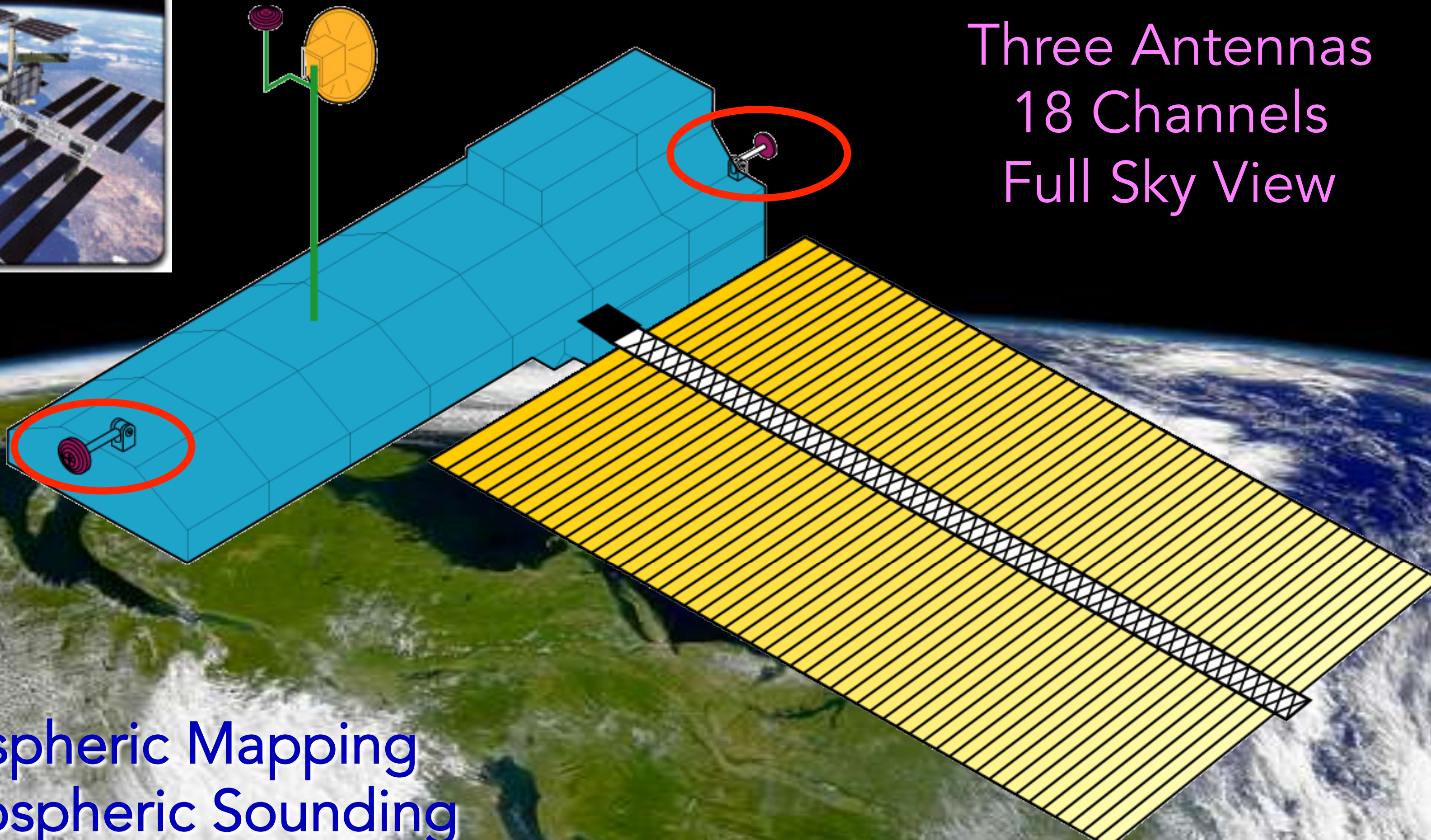
In **1987**, NASA called for new instrument proposals for the Earth Observing System (EOS) to study global change. In response, T Yunck began exploring how we might use a GPS receiver in low Earth orbit to sense the atmosphere by radio occultation.



Tom connected with Gunnar Lindal, a planetary RO pioneer, and explained how geodetic techniques could defeat GPS obstacles at the time (selective availability, anti-spoofing, one-way transmission, suppressed carrier). This led to the **1988** GPS Geoscience Instrument (GGI) proposal for GNSS RO.

GPS Geoscience Instrument

Figures from the 1988 GGI proposal



Three Antennas
18 Channels
Full Sky View

Ionospheric Mapping
Atmospheric Sounding

GPS/MET on NASA's MicroLab

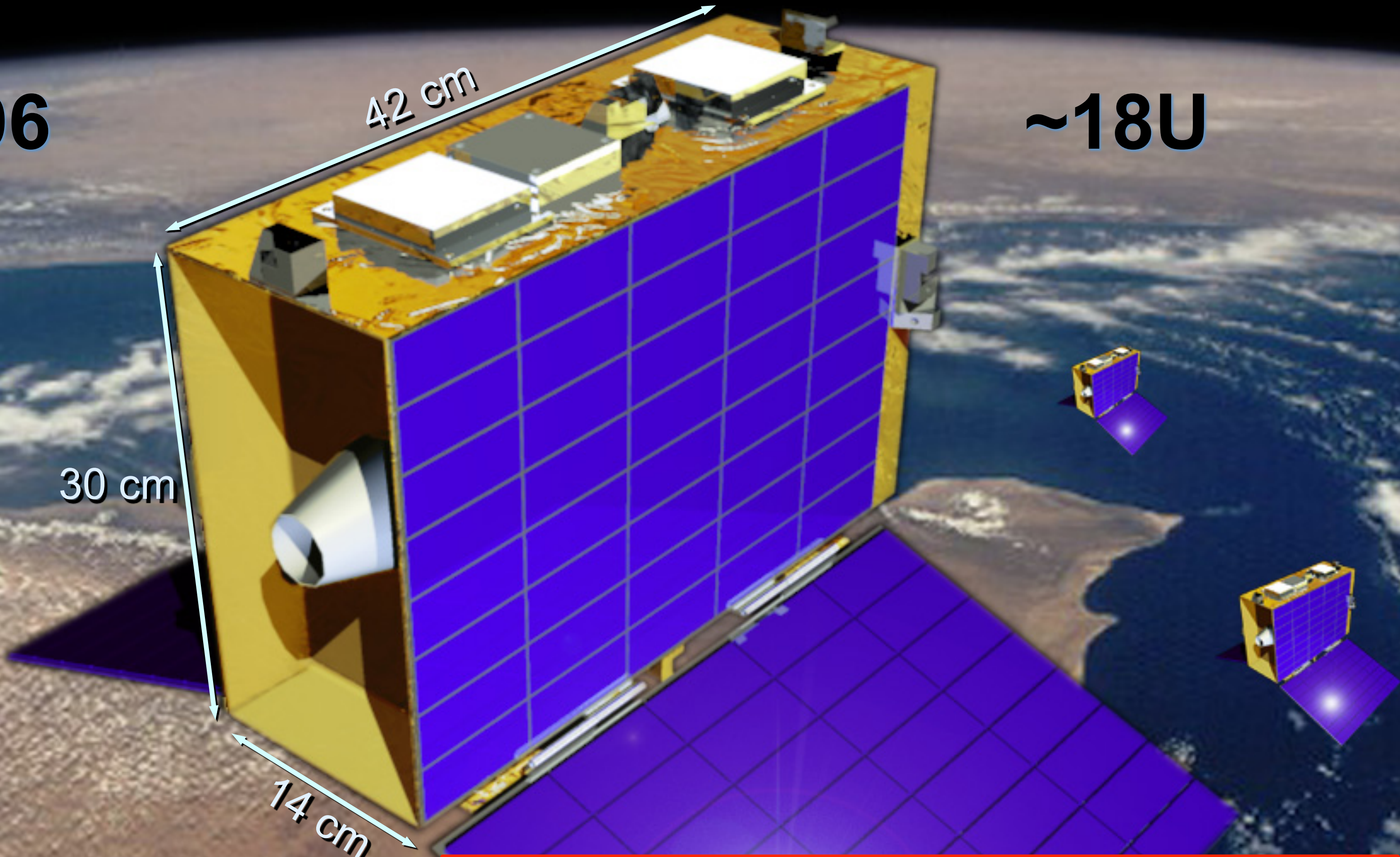
Micro Lab

1995

In 1992-93, UCAR landed the GPS-MET project, funded by the NSF and other US agencies, to demonstrate GPS-RO for the first time. UCAR partnered with JPL to convert the newly introduced TurboRogue into a space receiver – the TRSR. The breakthrough GPS-MET mission flew successfully from 1995-97.

1996

~18U



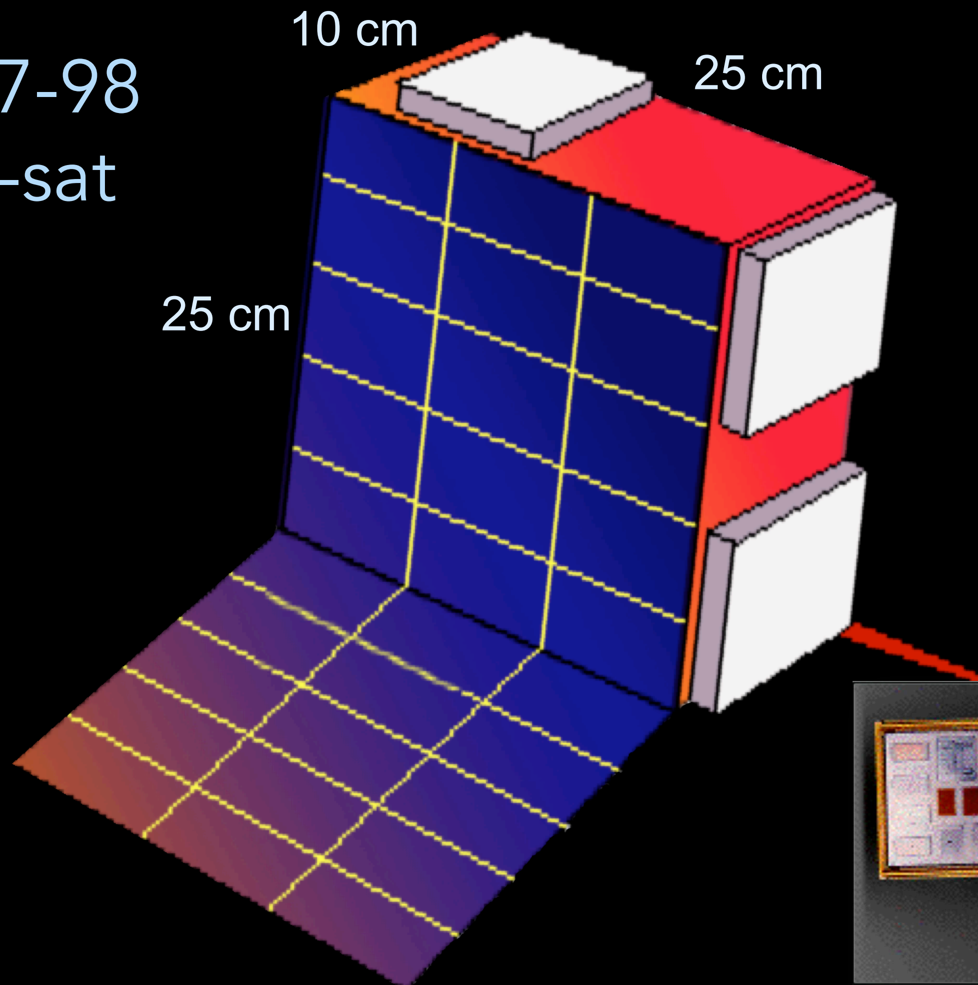
GPS-CLIM

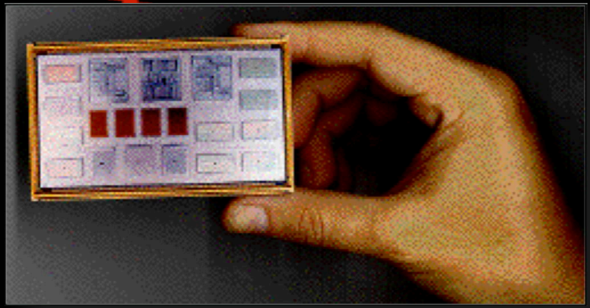
NASA ESSP Proposal

In 1996 JPL wrote a proposal for a constellation of six small (18U) RO spacecraft in response to NASA's initial Earth System Science Pathfinder solicitation. The "GPS-CLIM" proposal received the highest science score of the 44 submissions but was passed over for a lidar mission that was later cancelled when it far exceeded its budget.

1997-98
RO-sat

~6U

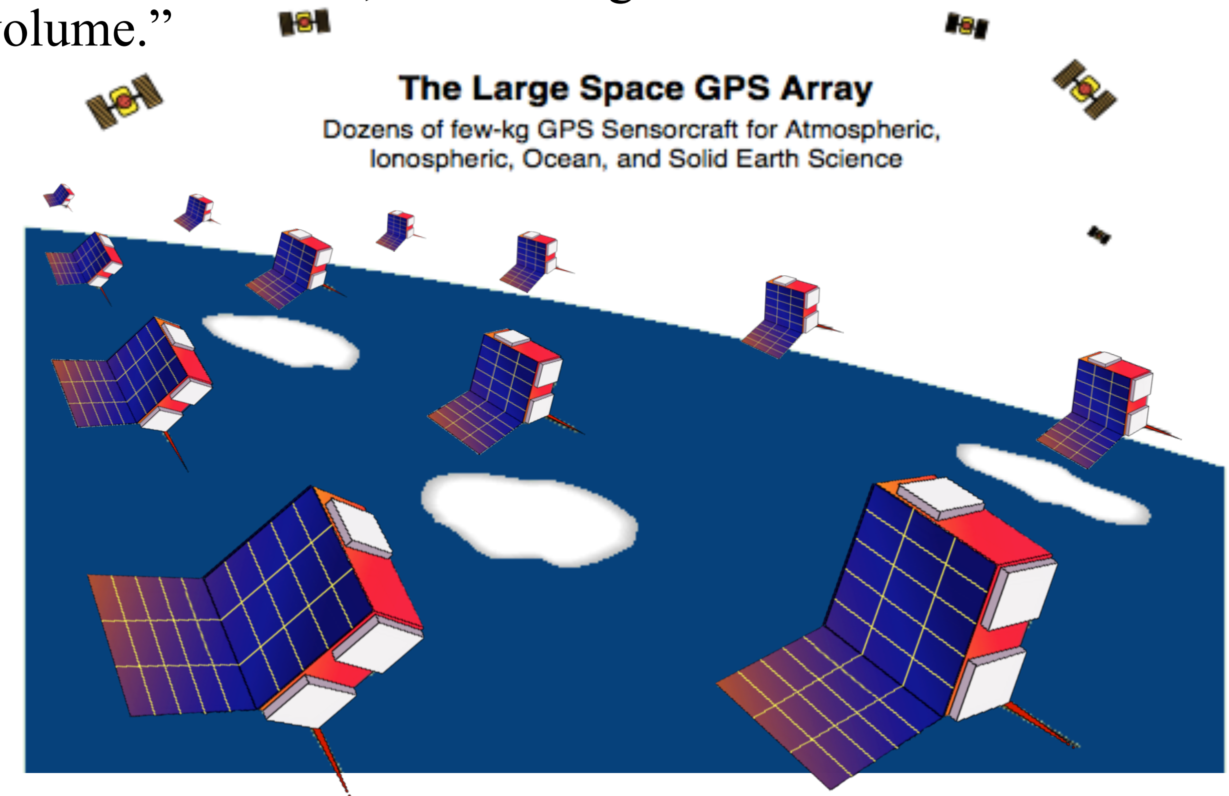




The JPL team then devised concepts for a compact RO receiver mated with a micro-spacecraft. The new RO smallsat concept topped out at around 6U.

A History of GPS Sounding (Yunck, Liu, Ware; *TAO*)

"[In the future] the COSMIC model will be taken to its logical extreme: flight systems will be further miniaturized and we will see dedicated constellations of dozens or even hundreds of tiny free-flyers, each with a mass of a few kilograms, consuming less than 10 watts, and costing a few hundred thousand dollars each to produce in volume."



This concept was touted in, among other places, a special issue of *TAO* on COSMIC, quoted above. Written in 1998, it appeared in print in 2000.

NASA's Easton Workshop

GPS-RO Requirements

Notional Mission	Science Needs	Measurement Requirements
OP-3: GPS-RO Constellation	Atmospheric Temperature & Humidity	Global measurement: - horizontal res. 50 km, - vertical res. 1 km - temp accuracy 1K - moisture precision 10-20% - revisit time 2x per day

50 km daily resolution => ~200,000 daily profiles
50 km twice-daily res. => ~400,000 daily profiles

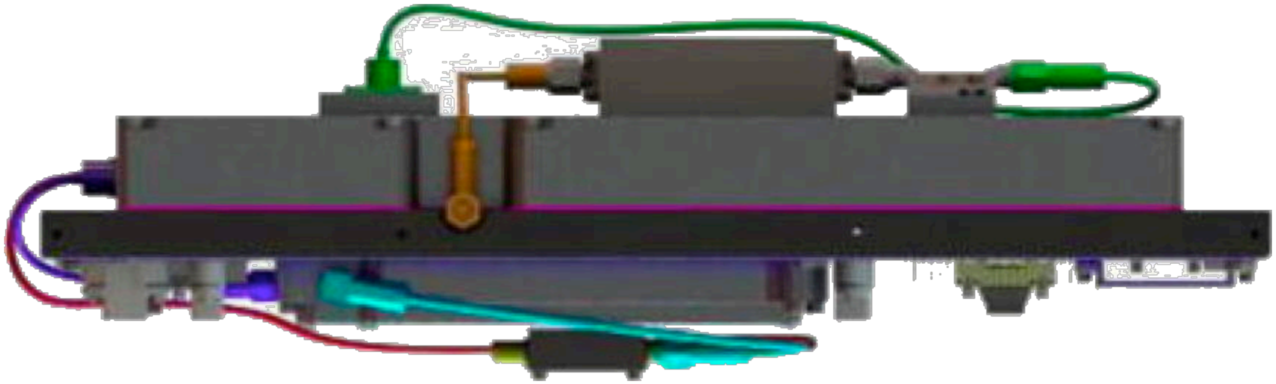
Again in 1998, a NASA workshop on future Earth observation needs held in Easton, Pennsylvania, recommended a GPS-RO constellation realizing an average horizontal resolution of 50 km, twice daily. That would require as many as 400,000 daily occultation soundings.

The CICERO Constellation

In 2017 GeoOptics launched the first of their 6U CICERO (Community Initiative for Continuous Earth Remote Observation) RO nanosatellites.

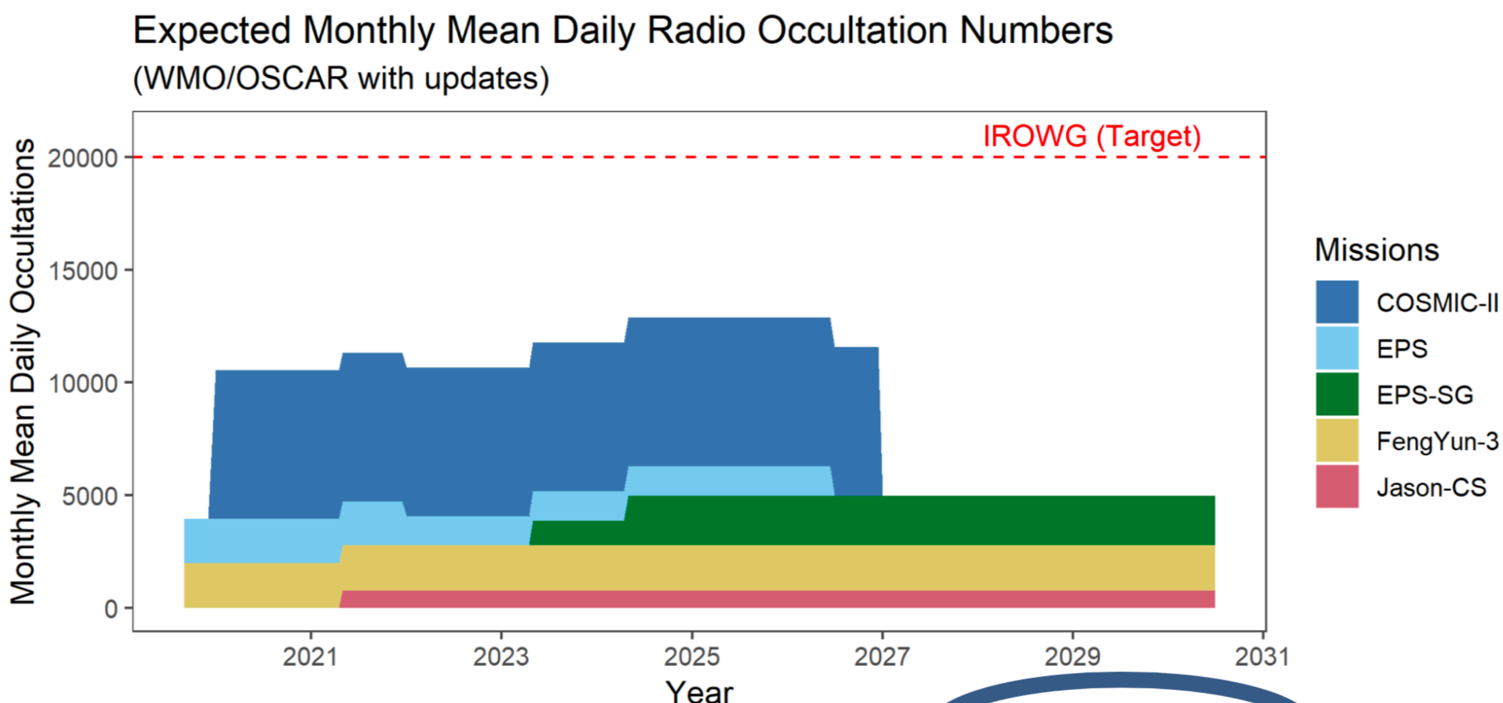
The Compact Cion GNSS-RO Instrument

Miniaturized TriG: GPS, Glonass, Galileo RO



CICERO flies the first-generation Cion GNSS-RO receiver, developed jointly by JPL, Tyvak Nanosatellite Systems, and GeoOptics. The Cion is a miniaturized version of the TriG instrument flying on COSMIC-2. It occupies about 1U of volume and consumes about 6.7 watts of power.

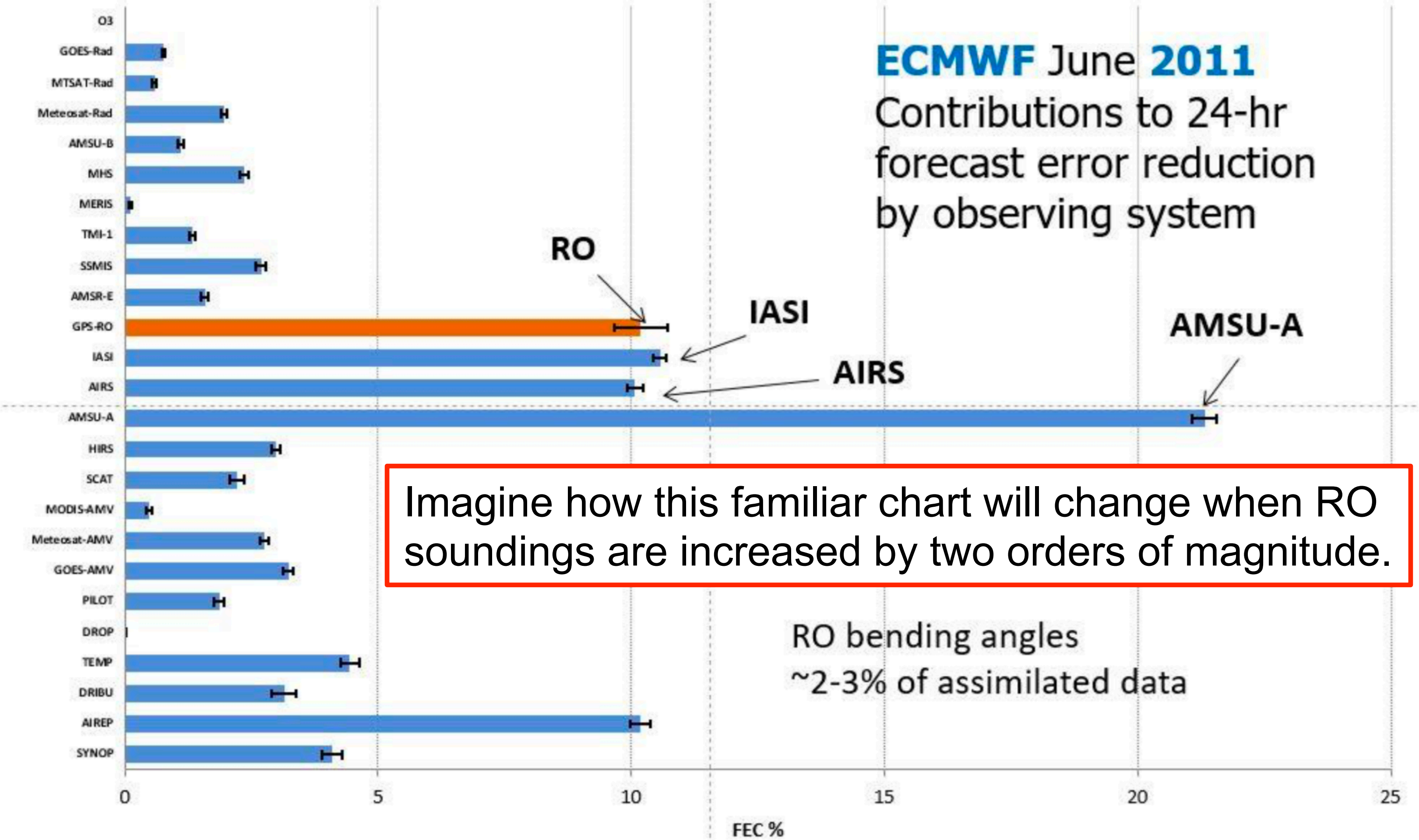
Future Status of RO



EUMETSAT (May 2019)

This chart shows an IROWG target of 20,000 RO profiles/ day indefinitely, though OSSEs show the value of (and the Easton workshop recommended) much higher numbers.

RO Impact on NWP

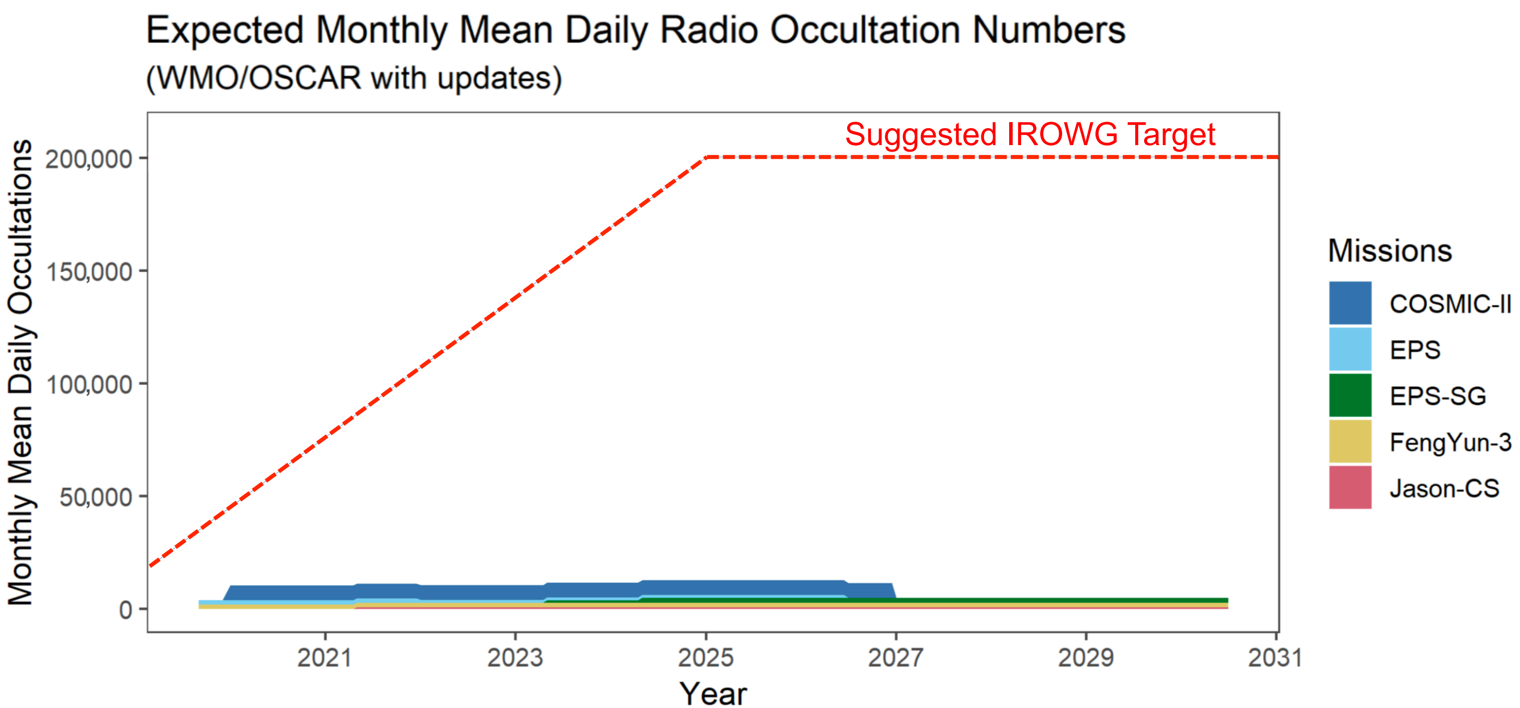


Imagine how this familiar chart will change when RO soundings are increased by two orders of magnitude.

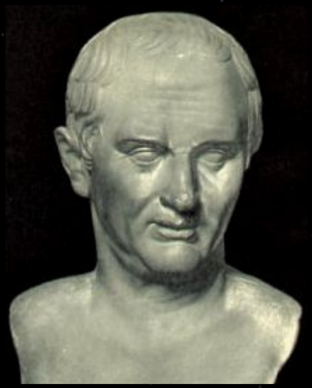
Past high NWP impact cannot be sustained

Coordination Group for Meteorological Satellites

Future Status of RO



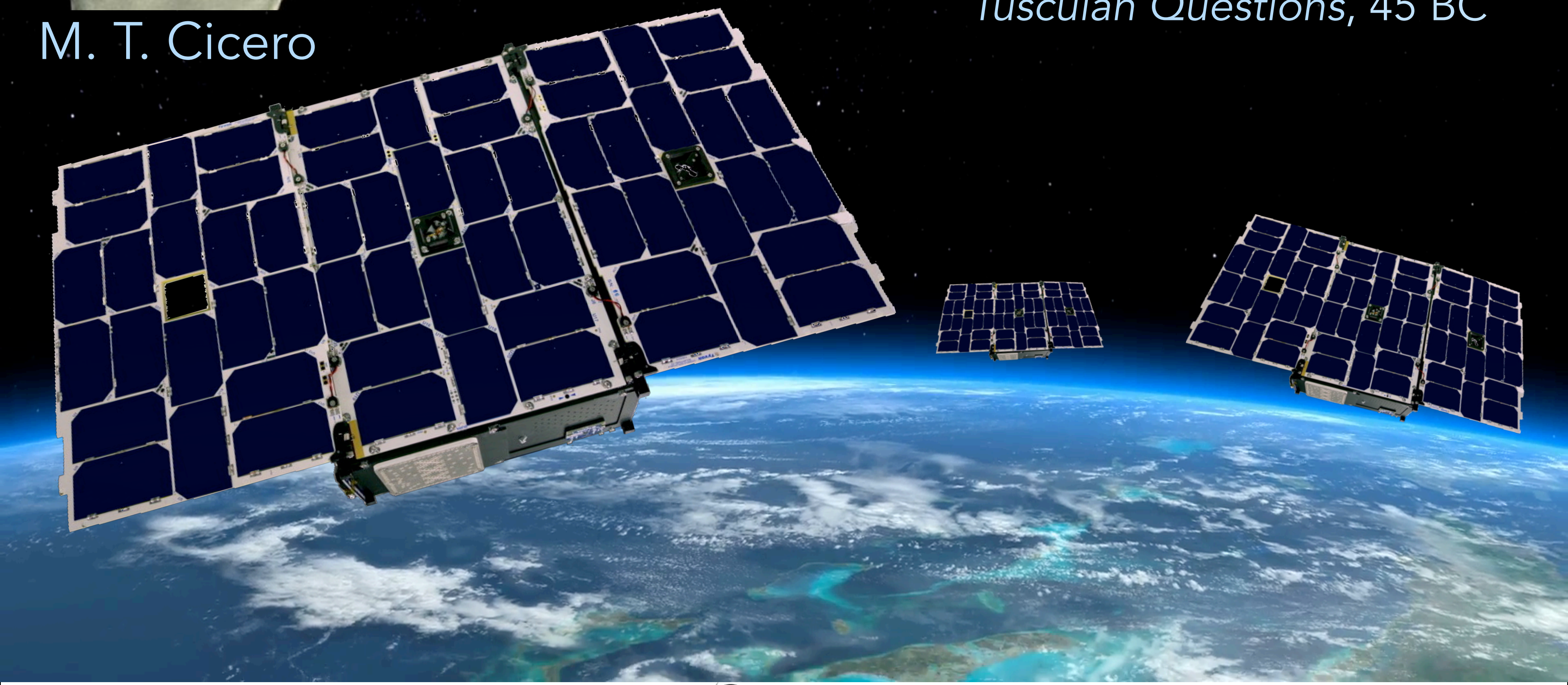
Next-generation RO micro-spacecraft will soon be able to deliver 200,000 top-quality RO profiles daily at a cost to orbit of under $100 million. In that light, we propose that the IROWG should reevaluate the near-term target, recalling the dedicated commitment of GPS geodesists in the late 1980s.



M. T. Cicero

"What kind of sight do you imagine that will be when the whole earth is laid open to our view?"

Tusculan Questions, 45 BC



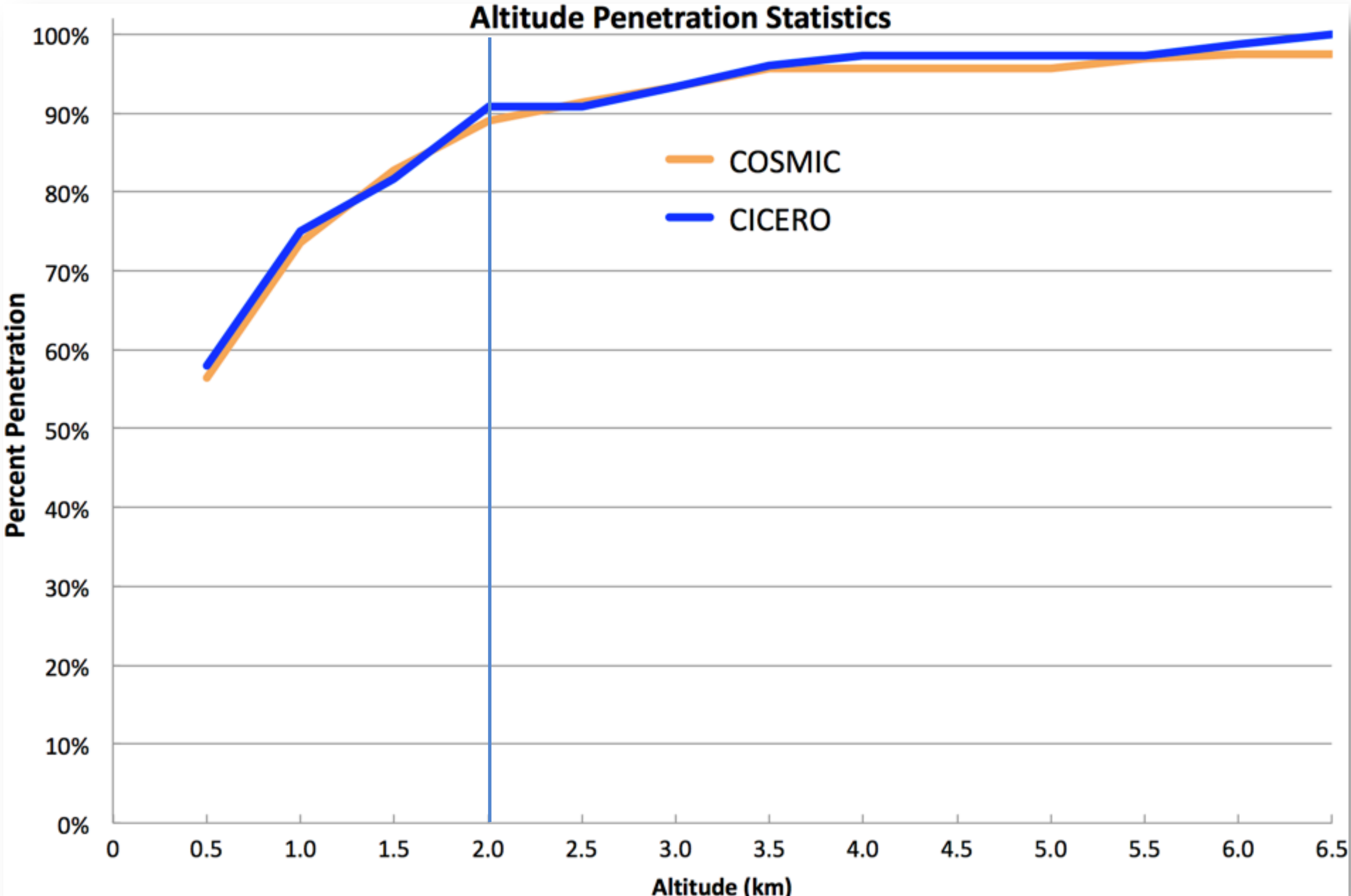
Acknowledgments

We thank the many JPL scientists and engineers who pioneered early GPS geodetic technology, including: Jack Fanselow, Pete MacDoran, Tom Meehan, Bill Melbourne, Don Spitzmesser, Jeff Srinivasan, Brooks Thomas and Larry Young.

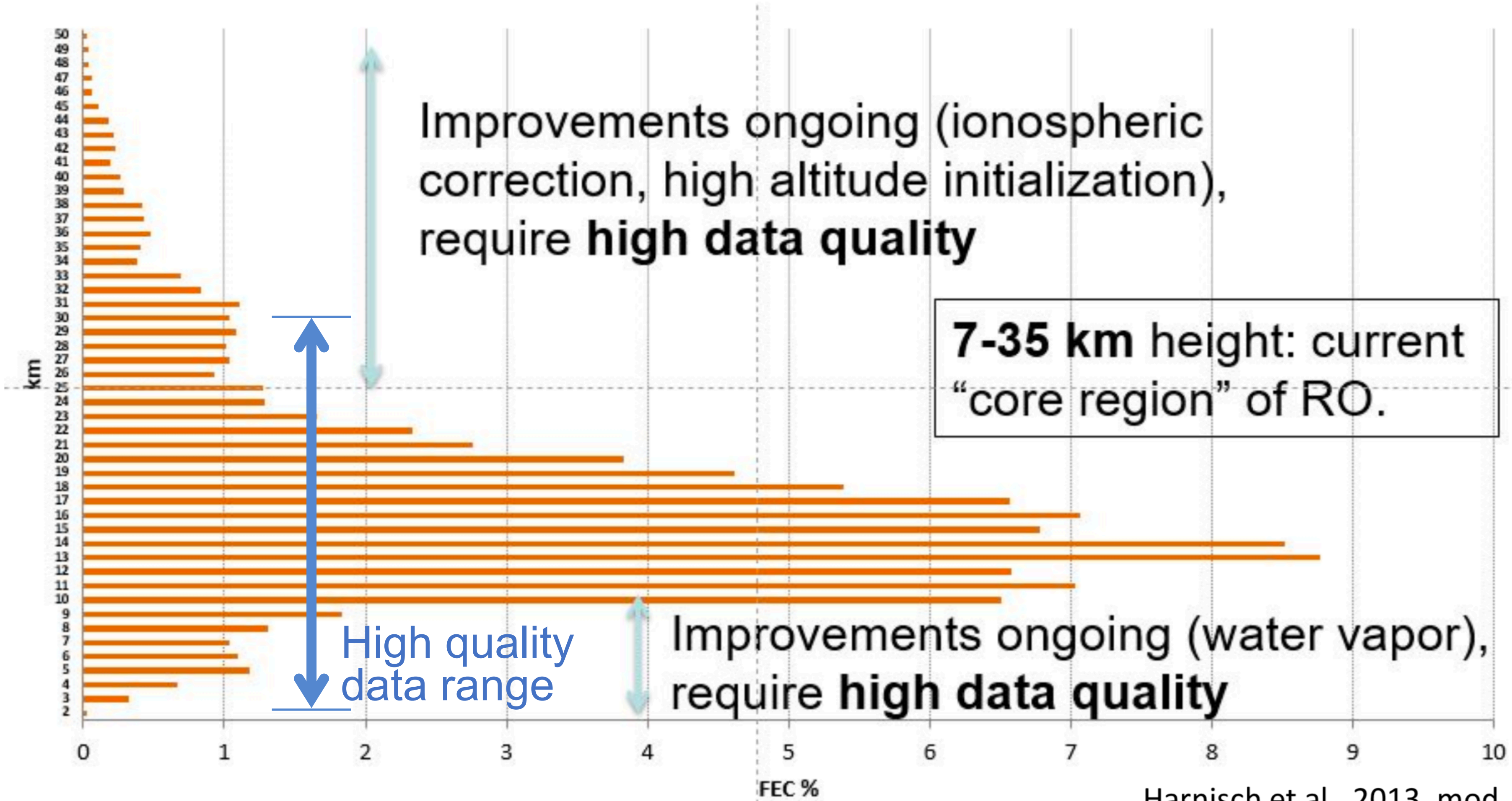
We also thank our current partners at JPL & Tyvak who co-developed the still rapidly evolving Cion RO instrument and multi-function CICERO spacecraft, persons too numerous to mention by name.

Backups

Depth of Penetration: CICERO v COSMIC



RO Impact on NWP

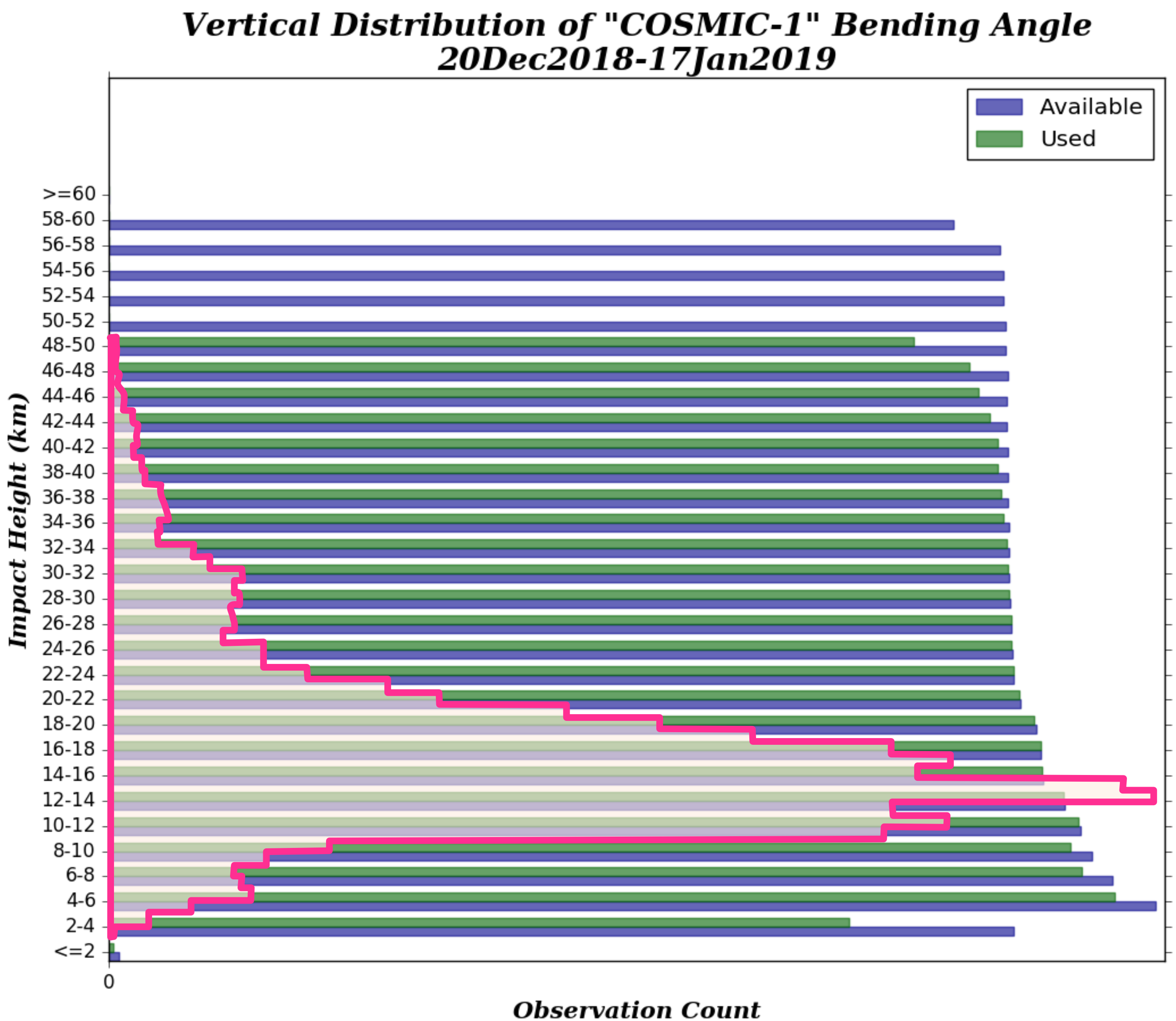


Harnisch et al., 2013, mod.

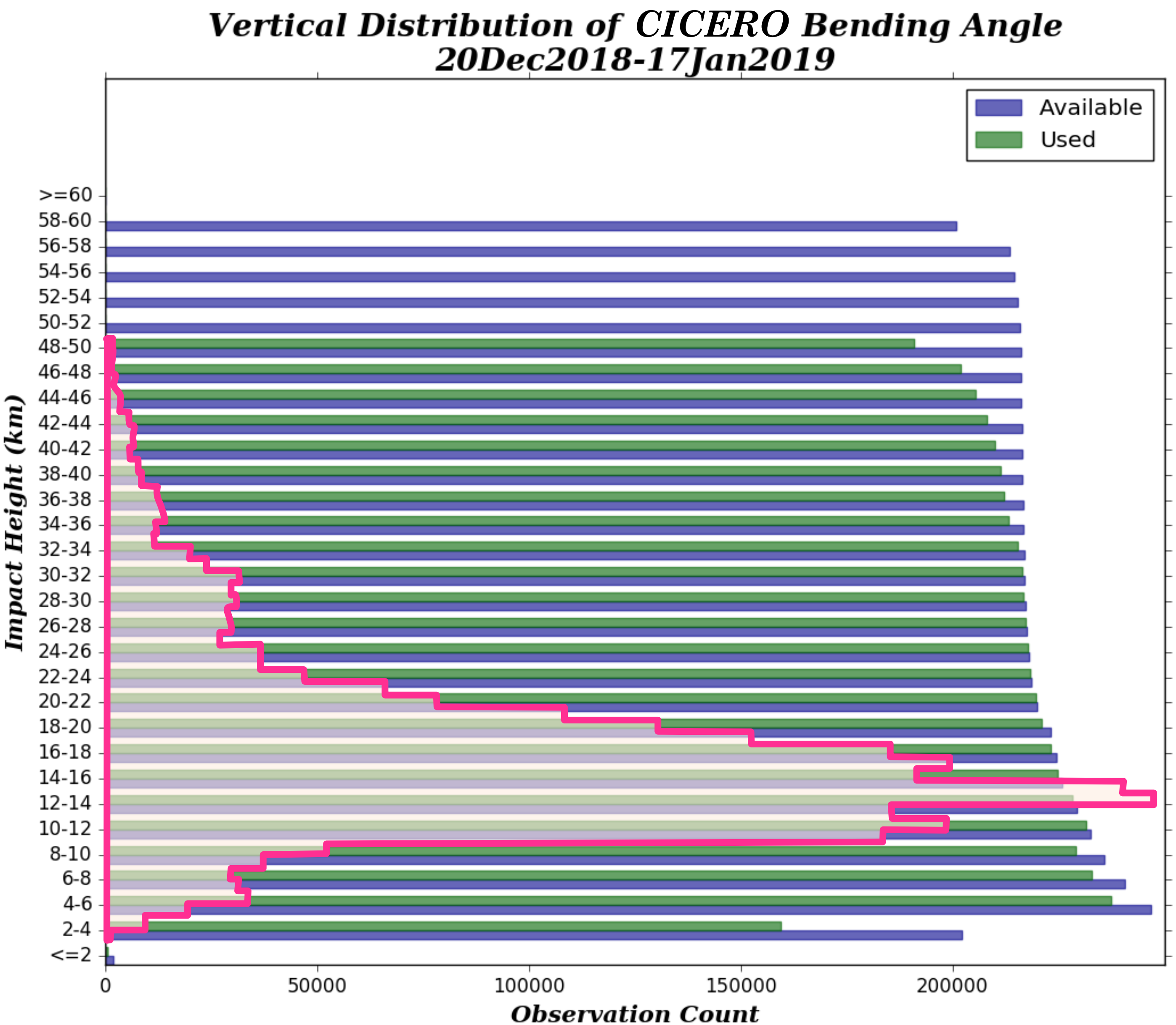
Ongoing work: expand the RO “core region”

Coordination Group for Meteorological Satellites

JCSDA Analysis: COSMIC 1



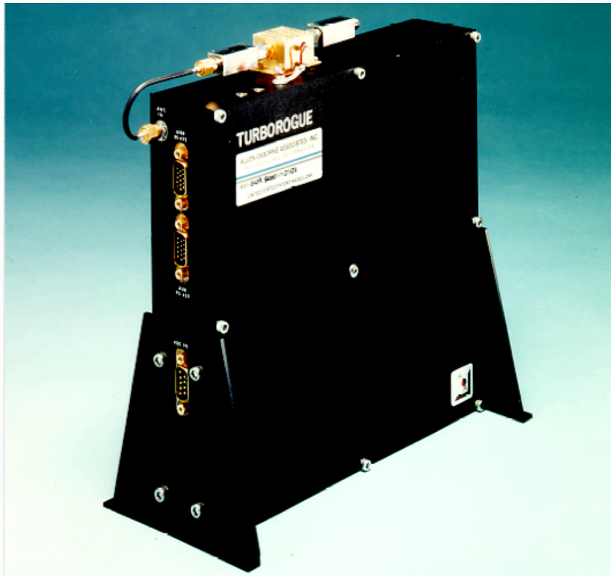
JCSDA Analysis: CICERO



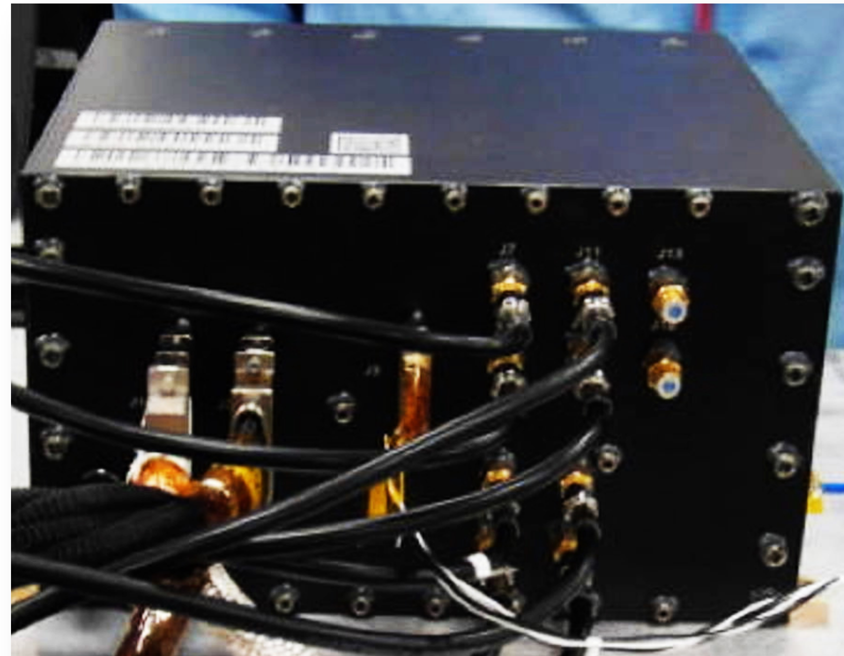
GeoOptics

GNSS-RO Instruments

TRSR, c. 1995

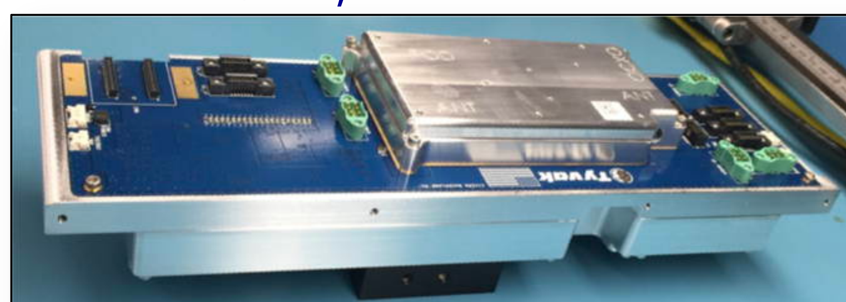


TriG, c. 2012: ~60W



BlackJack, c. 2000

Cion, 2016: 6.5W



Early Mobile GPS Technology

JPL's SERIES Codeless Receiver c. 1981

(Satellite Emission Radio Interferometric Earth Surveying)

Global GPS Sites

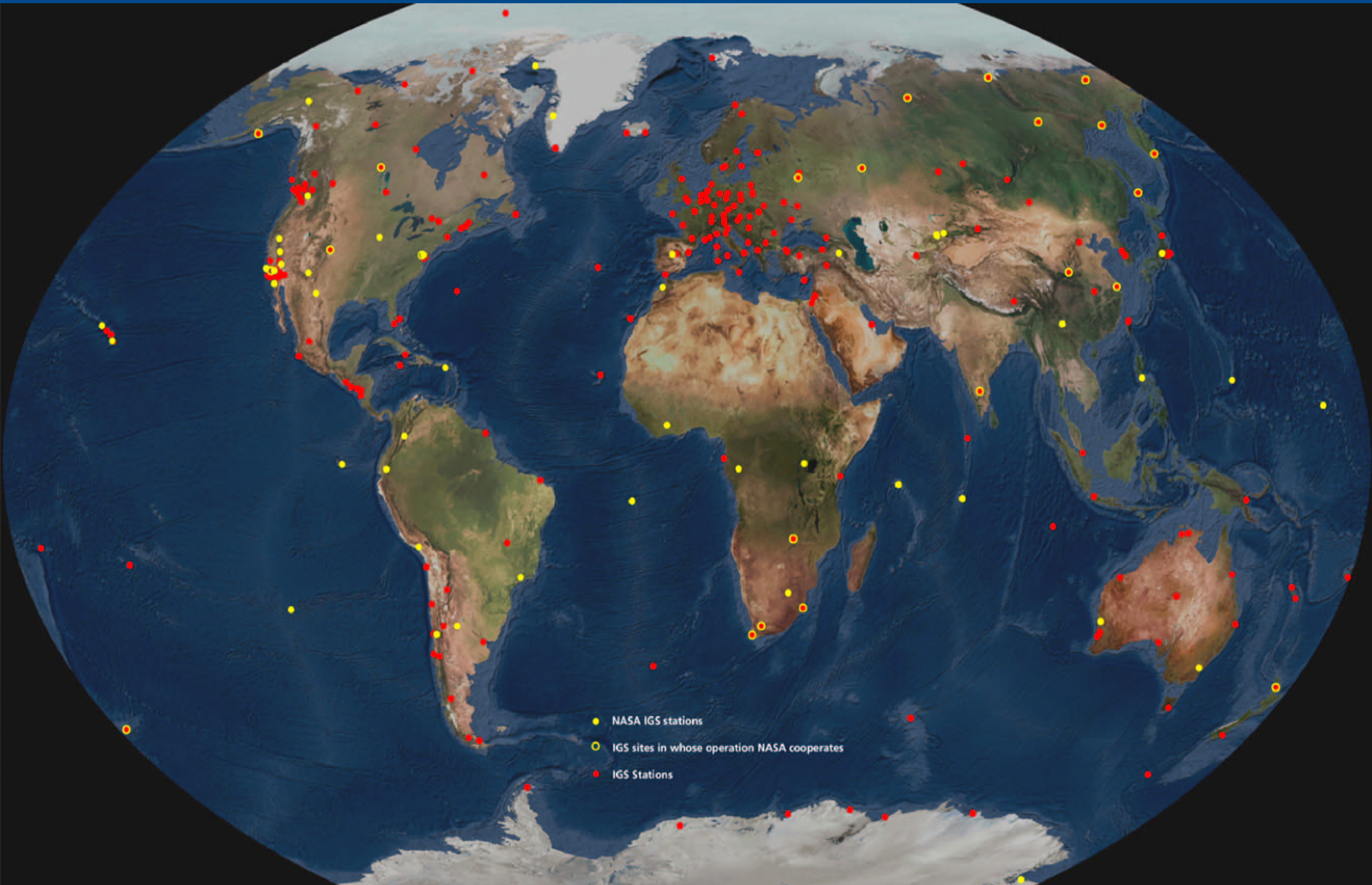


Plate Velocity Map