GRACE Mission: Architecture of the Flight Segment

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GRACE Mission
Principles

Focus

- **"Do one thing. Do it well."**
- **"Chose an objective that is worth pursuing"**

Balance

- **"Technology without economics is not engineering"**

Risk Containment

- **"Don't stretch the limits of hardware performance"**

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Balance

- **Minimizing Total Cost**
  - Total Cost = $\sum(C_1+C_2+C_3 \ldots\ldots\ldots\ldots + C_k)$
  - For a given level of performance, Total Cost is minimum if
    - $\partial\, Perf/\partial C_1=\partial$ □□ $Perf/\partial C_2=\partial\, Perf/\partial C_3 \ldots\ldots =\partial\, Perf/\partial C_k$
  - Cost functions are very non-linear and not well known
    - Pushing technology is very costly
    - Doing things for the first time is very costly
- **Line Item Cost = (Fixed Cost) + n x (Unit Cost)**
  - GRACE Satellite Subcontract
    - Fixed cost = $11 M
    - Unit cost = $12 M / satellite
    - Better thermal control = $0.06 M total
  - Build identical units.
    - Lower total Cost and fewer spares

GRACE Mission
Focus

Heritage Gravity Missions all carried a Magnetometer

- NASA's Gravity Research Mission (GRM) proposal - died 1985
- ESA's Aristoteles proposal - died 1990 when NASA pulled out
- NASA-GSFC's GAMES proposal died 1994
- GFZ-Potsdam's CHAMP launched 2000

Heritage Gravity Missions Emphasized Spatial Resolution

- GRM proposed to fly at an altitude of 156 to 170 km
- Aristoteles proposed to fly at an altitude of 200 km

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Competing Objectives

- **Orbit Design**
  - Magnetic field missions prefer an inclination of 85 degrees
  - Gravity mission prefer an inclination of:
    - First choice - near 90 degrees
    - Second choice - sun-synchronous orbit at 97 degrees
- **Structural Stability**
  - Magnetometers want to be located on a long boom
    - 1 nano-Tesla
  - A satellite for a Gravity Mission needs to be very stable
    - 1 µm @ 2x per orbit, or 5E-12 m/s2 - .0002 to .04 Hz
- **Root Cause of the Problem: Organizational**
  - Funding for gravity missions came NASA's Geo-potential Fields Program Office

GRACE Mission

The Seminal SST Gravity Mission

Milo Wolff, MIT-SAO - JGR, Vol.,74, No. 22, Oct. 1969

- **Two geometrically identical satellites**
- **Equipped to measure relative velocity**

$$\Delta U = V_{mean\ orbital} \times \Delta v_{along\ track}$$

- **200-km separation - Altitude ≥ separation**
- **USO + Transponded RF signal, or Laser doppler system**
- **Doppler (i.e. $\Delta v_{along\ track}$) sampled every 10 seconds**
- **Store and forward data to the ground**
- **Non-gravitational forces controlled by careful design and accounted for by modeling**

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GRACE - How it Works

Microwave Link
- Tracking Phase - Range change
- 24 & 32-GHz - Ionosphere
- Dual One-way - Clocks

GPS
- Relative Clocks
- Location

Star Cameras measure attitude

Mission Ops predicts the orbits for each GRACE

Accelerometers -
- Non-Gravitational Forces

Each GRACE points at the predicted location of the other GRACE

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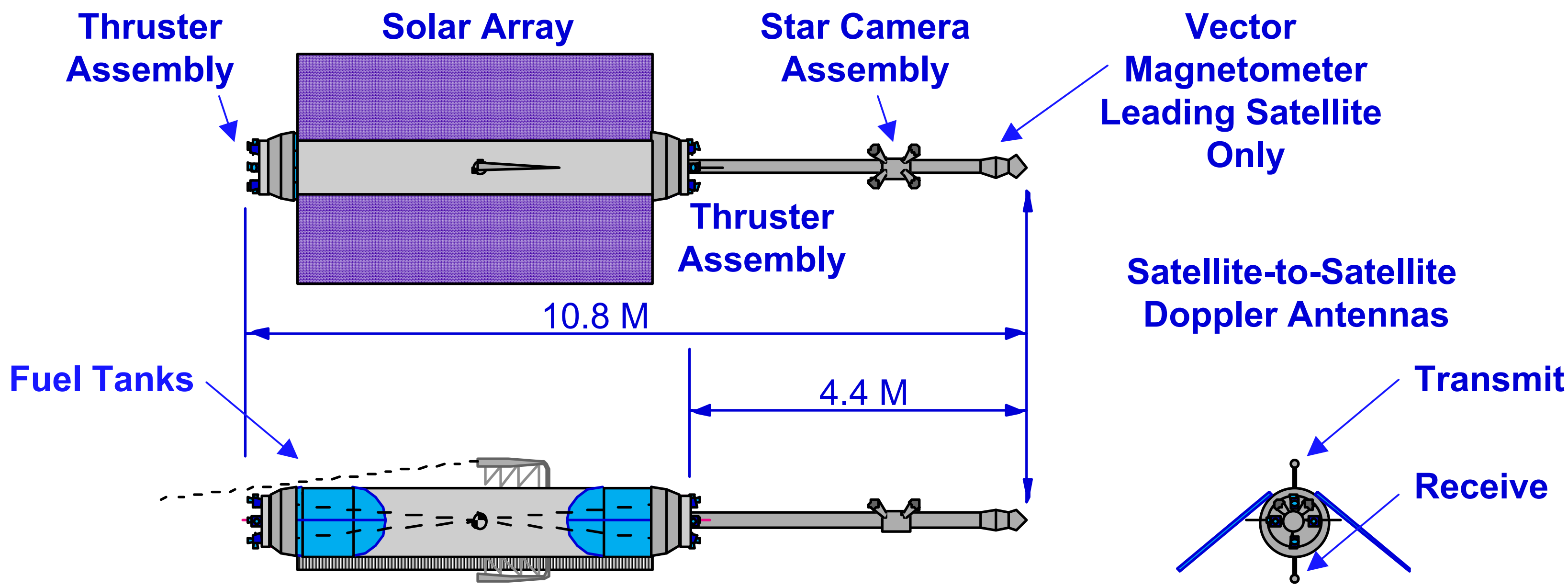
Gravity Research Mission -1985



Unfriendly Features

- 1200 kg of Hydrazine Fuel
- Flexible Boom & Solar Arrays
- Multipath on the SST RF link

Challenges

- No feasible operational safe mode
- Continuous Drag Compensation
- Time synchronization

<u>Dual One-Way Ranging Concept Developed at APL!</u>

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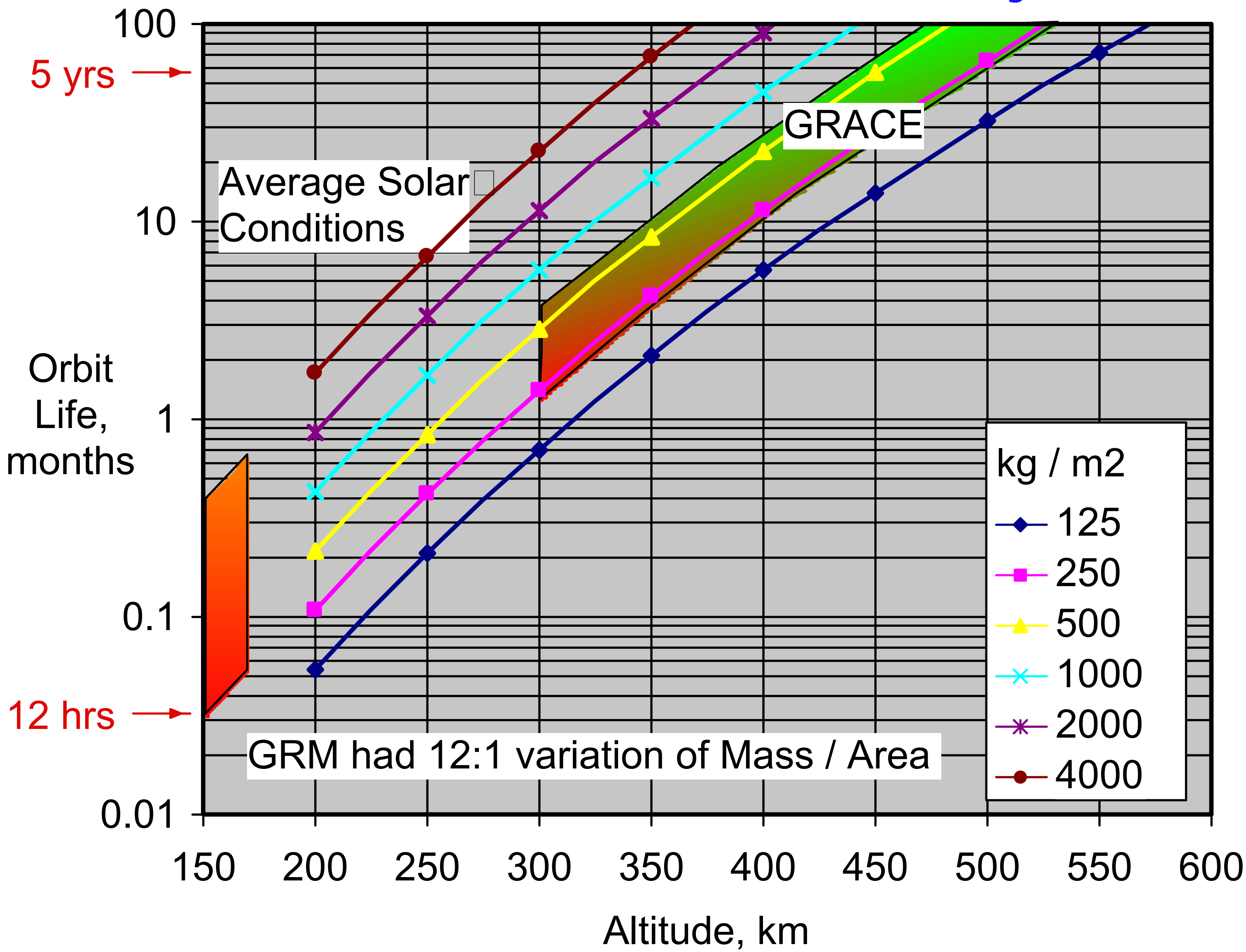
Orbit Life & Mission Safety



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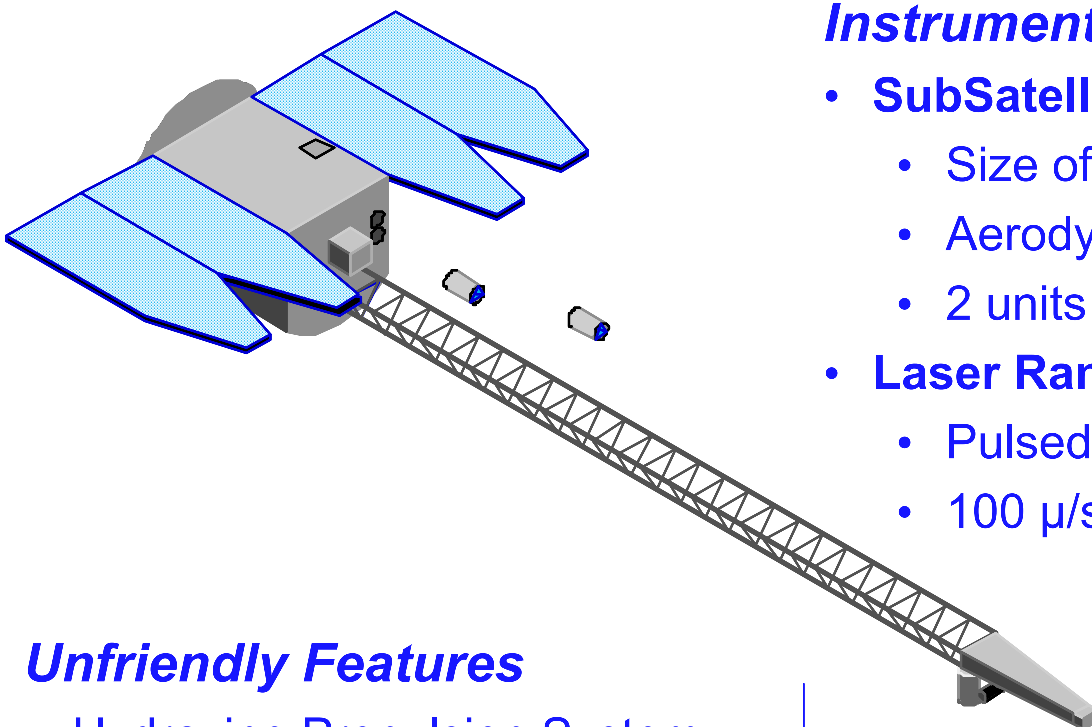
GA□MES - 1992



Instrumentation Concept

- **SubSatellite Retro Reflectors**
  - Size of a Soda Can
  - Aerodynamically stabilized
  - 2 units released sequentially
- **Laser Ranging System**
  - Pulsed at 2-GHz rate
  - 100 μ/s range rate

Unfriendly Features

- Hydrazine Propulsion System
- Flexible 6-M boom
- Flexible Solar Arrays
- Uncontrolled Non-gravitational forces - aerodynamic

Challenges

- Acquisition & tracking by the laser ranging telescope
- Sub-satellite aerodynamic stability

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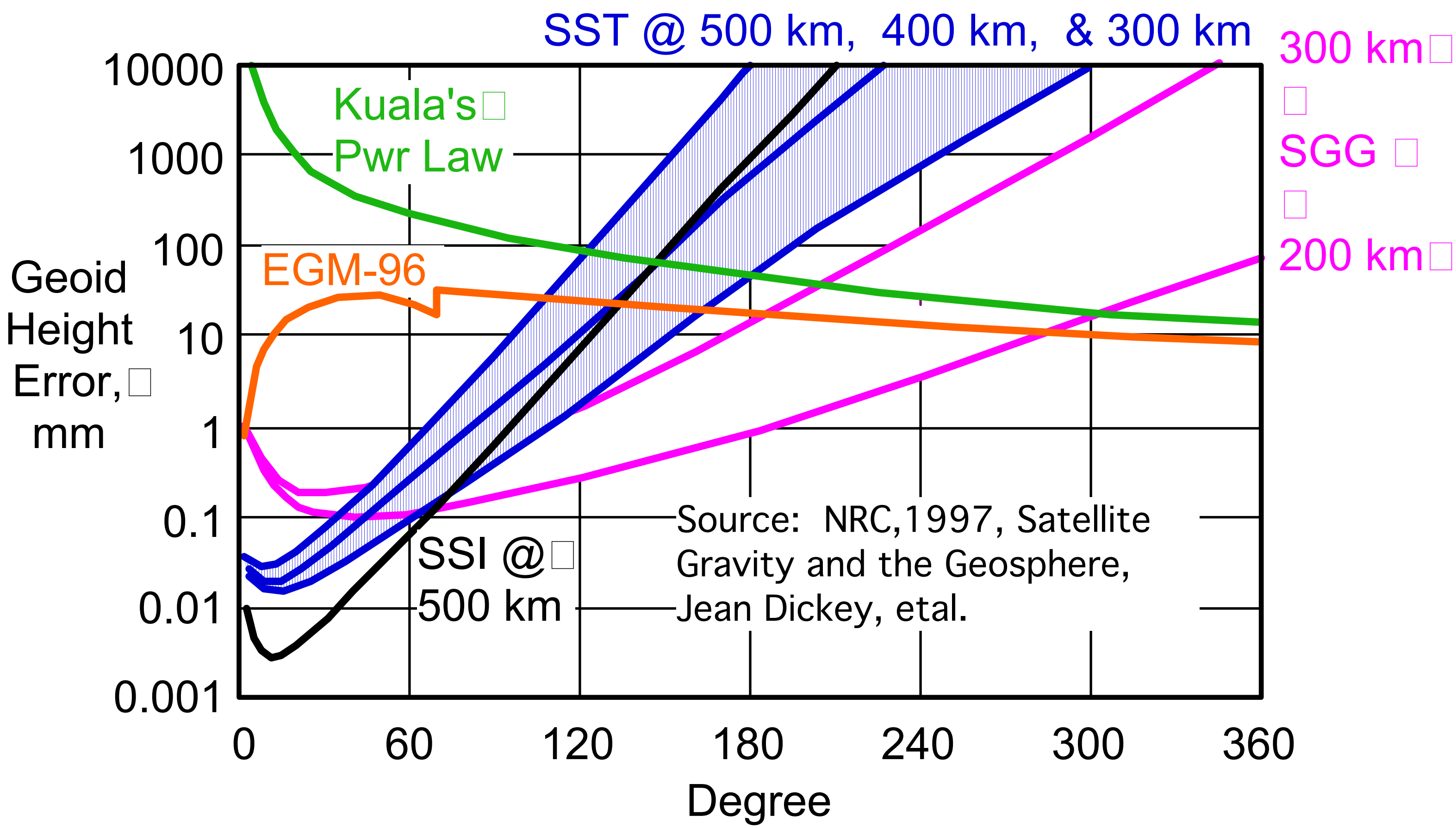
Competition vs. SST (Before GRACE)



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Listen for Simple Truths

- **Minimum Science Mission Objective - A moving target**
  - Oceanography base
    - 1994 Geoid with 5-cm accuracy cummulative to degree 50
    - 1996 Geoid with 0.5-cm accuracy to degree 50
- **Victor Zlotnicki casually commented "I wouldn't compromise the accuracy of a single low-degree term in order to improve the accuracy of the high-degree terms."**
  - Our response was to develop performance specifications for J2 - usually ignored by predecessors
- **Labrecque pushed the idea of using gravity to measure time-varying geophysical parameters - Richard Gross, B. Chao etal., - "low-degree and order terms were significant"**
- **Brooks Thomas applied signal filter theory to the problem and showed how to improve SST performance @ all scales**

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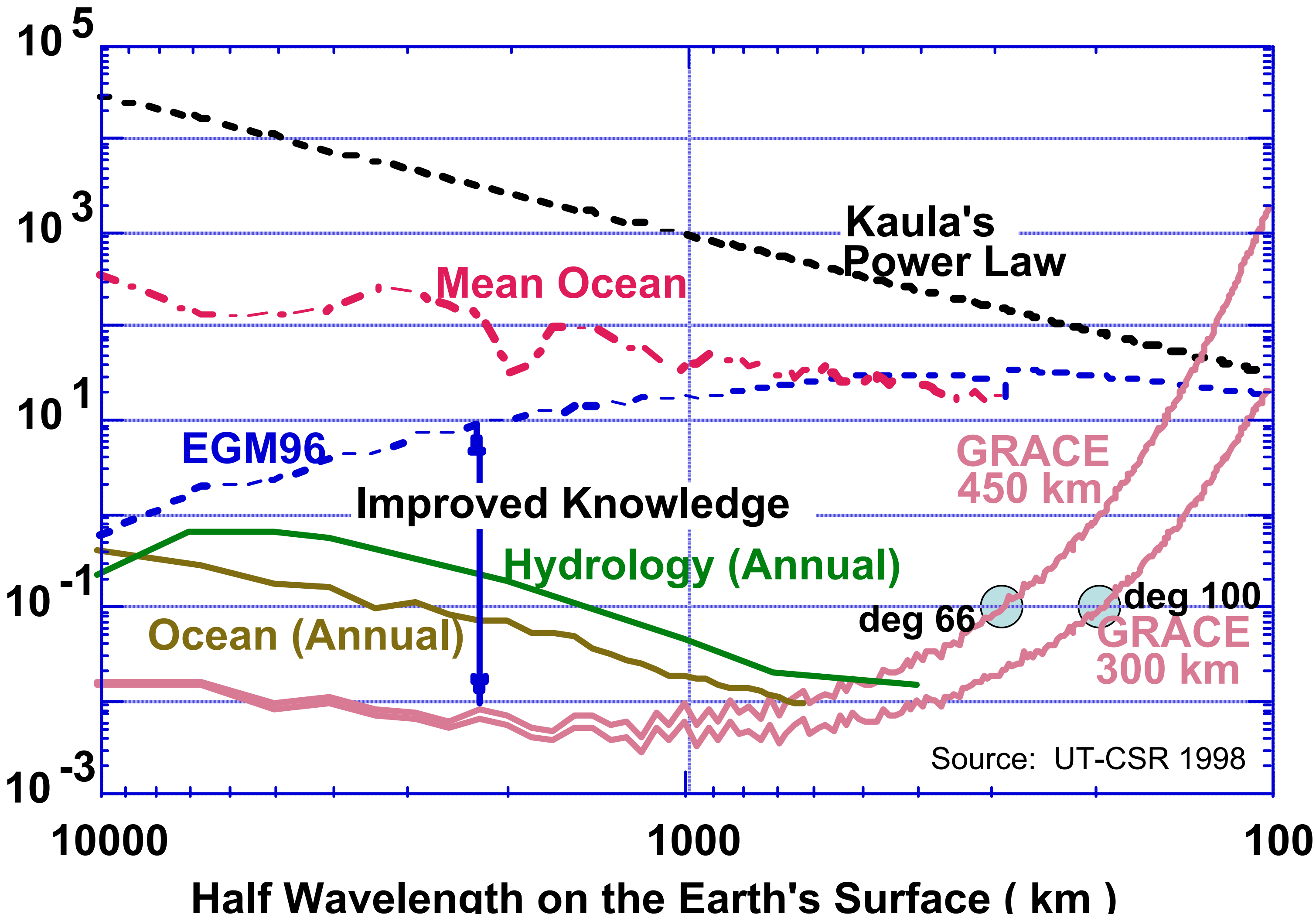
Focus on the Long Wavelength



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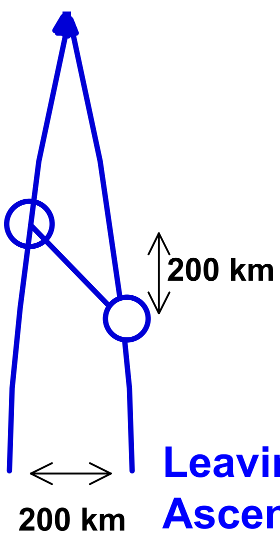
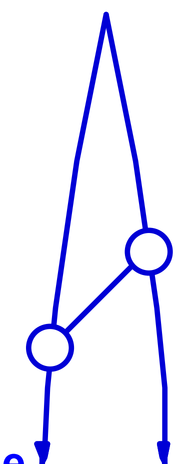
Abandoned Orbit Design

- **Baseline Co-planar Orbit has one drawback**
  - The partial derivative of the m=n terms of the spherical harmonics are ~zero for the baseline co-planar, polar, orbit
    - **Option for improvement**
      - Offset the LAN's of the twin satellites
      - 40-km offset: Marginal improvement
        - Drag & control penalty similar to the baseline
      - 200-km offset: Significant improvement
        - Drag penalty is high
        - Exceeded out-of plane ACC performance
        - The plane change would be costly



Leaving the Ascending Node



Approaching the Descending Node

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Impact of the Advanced Digital Filtering

Higher Data Rate for ACC & K-Band data

- Brooks wanted 50 Hz
- Compromised at 10 Hz
- Cost: $0.0

Attitude Control Pointing

- ≤ 1 mr not good enough
- ≤ 0.5 mr needed
- Cost uncertain

Control on the PSD of the noise from attitude control

- 20-mN thrusters too strong
- 10-mN thrusters needed
- Cost: $ 0.0 (available)

Center of Mass Control

- ≤500 microns not good enough
- ≤100 microns needed
- Cost: $2,000,000 for on-orbit adjustment
- Cost $50,000 for tank valving

Accelerometer Performance

- 10E-9 $ms^{-2}Hz^{-1/2}$ no longer good enough
- 10E-10 needed
- Cost: $ 0.0 (available)

Digital Filtering the data by 335

- Incremental Cost: Worth it!

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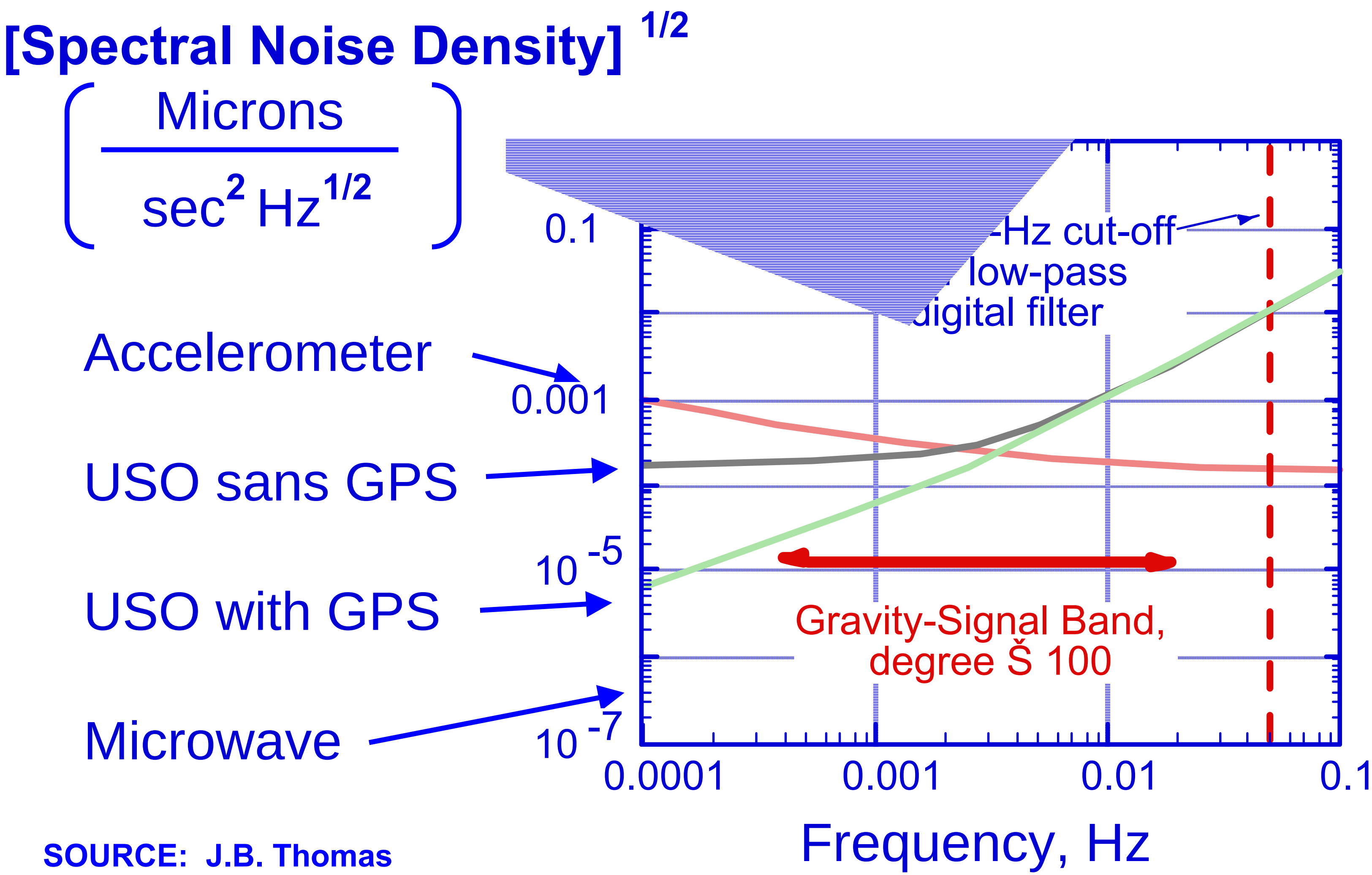
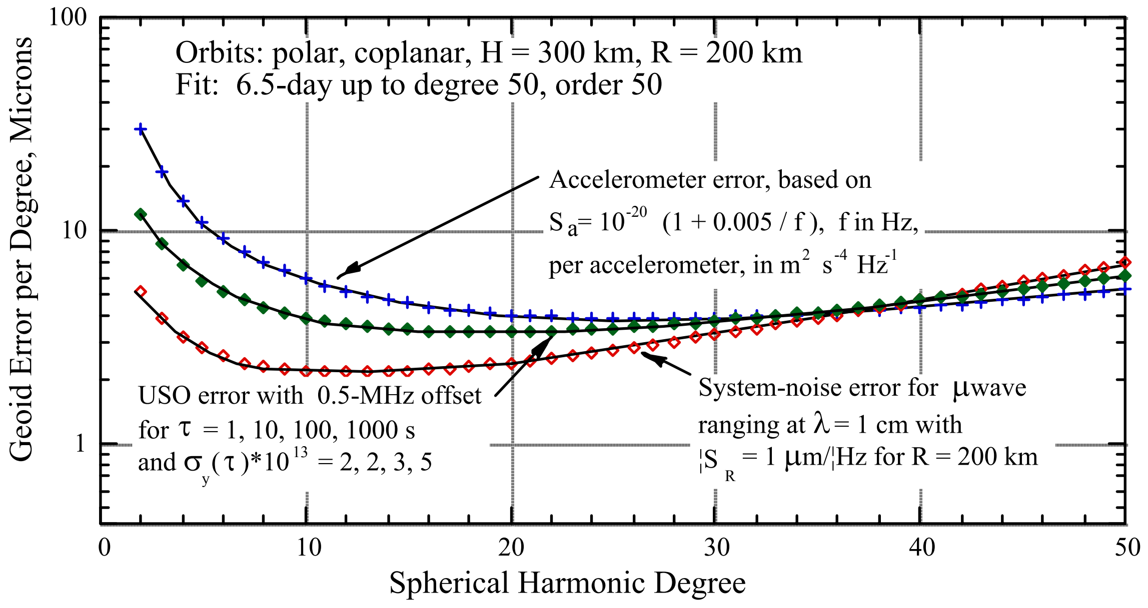
Limiting Error Sources



SOURCE: J.B. Thomas

Limiting Errors Mapped to Geoid

The key to the long wavelength terms is the Accelerometer



The satellites must be mechanically quiet

- **Avoid Parasitic Harmonic Oscillators**
- **No rotating machinery**
- **Limit Thrusting**
- **Heaters mounted on Low conductivity material - limit Lenz-Law effects**
- **Well staked cables**

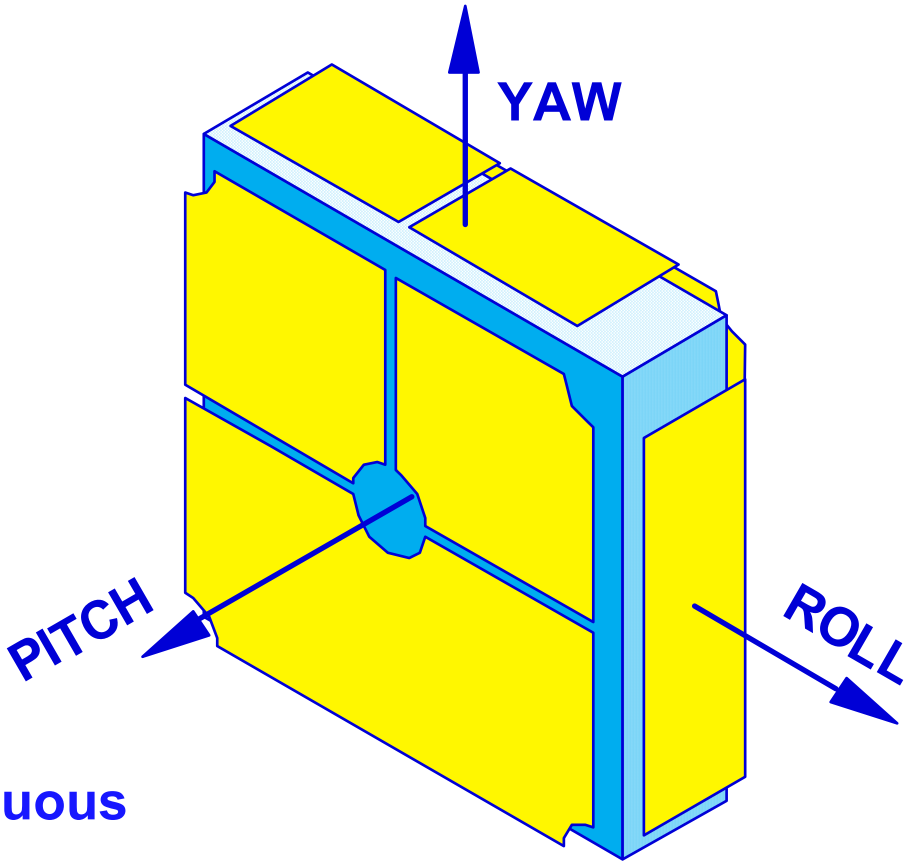
French Electrostatic Accelerometer

70-gram Proof Mass
- 1x 4x 4-cm Titanium block
- Not caged

Electrostatic Suspension
- 10-volt bias
- 150-micron gap
- 12-micron free motion

Performance
- Noise 10^{-10} m/s^2 Hz$^{-1/2}$
- Full Scale 5×10^{-5} m/s^2

Architectural Implication
- **No requirement for continuous drag compensation!**



Source: ONERA

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Non-Gravitational Effects

Non-Gravitational Forces

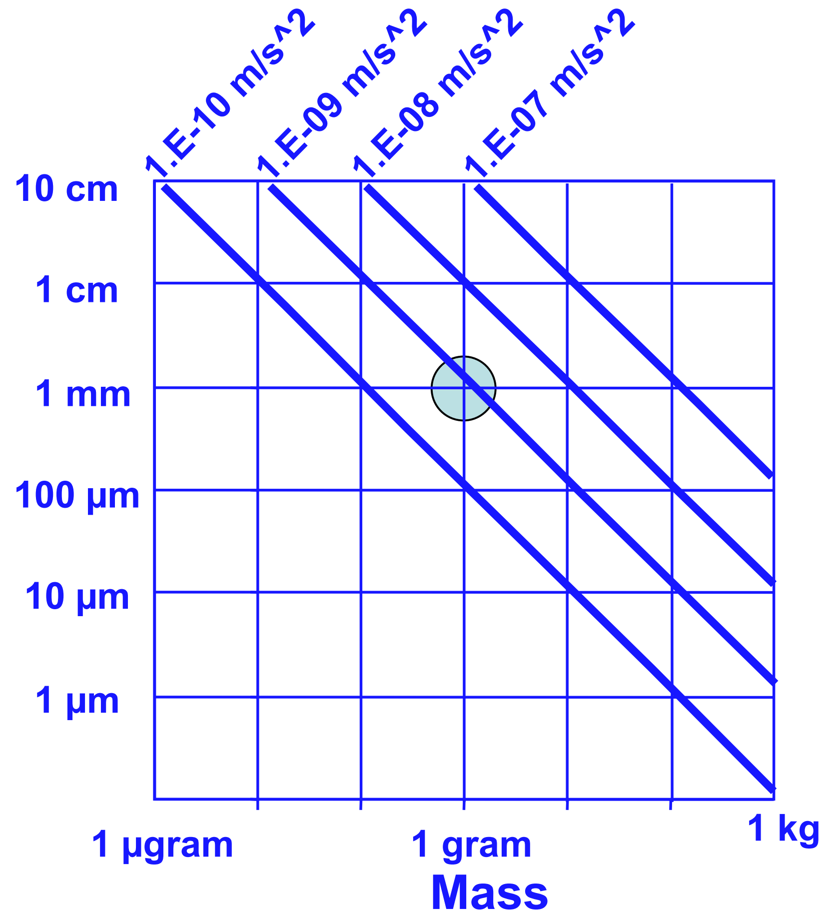
- Solar pressure = 50E-09 m/s2
- Drag @ 500 km = 1E-07 m/s2
- Drag @ 300 km = 5E-06 m/s2

Parasitic Harmonic Oscillators

- @ frequency 0.1 Hz, 1-gram parasitic oscillator with amplitude of 1mm results in a satellite acceleration of 1E-09 m/s2

Rotating Machines

- Reaction wheel run at 600 to 3000 rpm
- This is 10 to 50 Hz
- Interferes with ACC control loops they have a resonance at ~30 Hz



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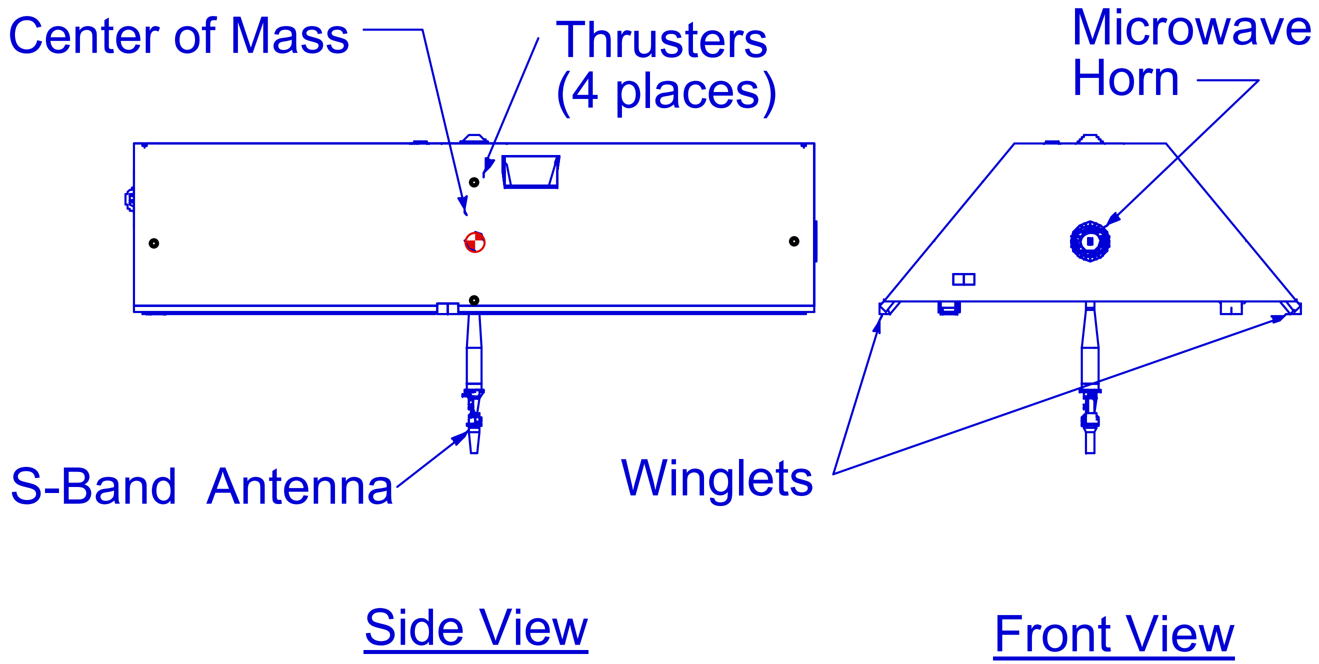
Controlling Torques



Astrium, GmbH

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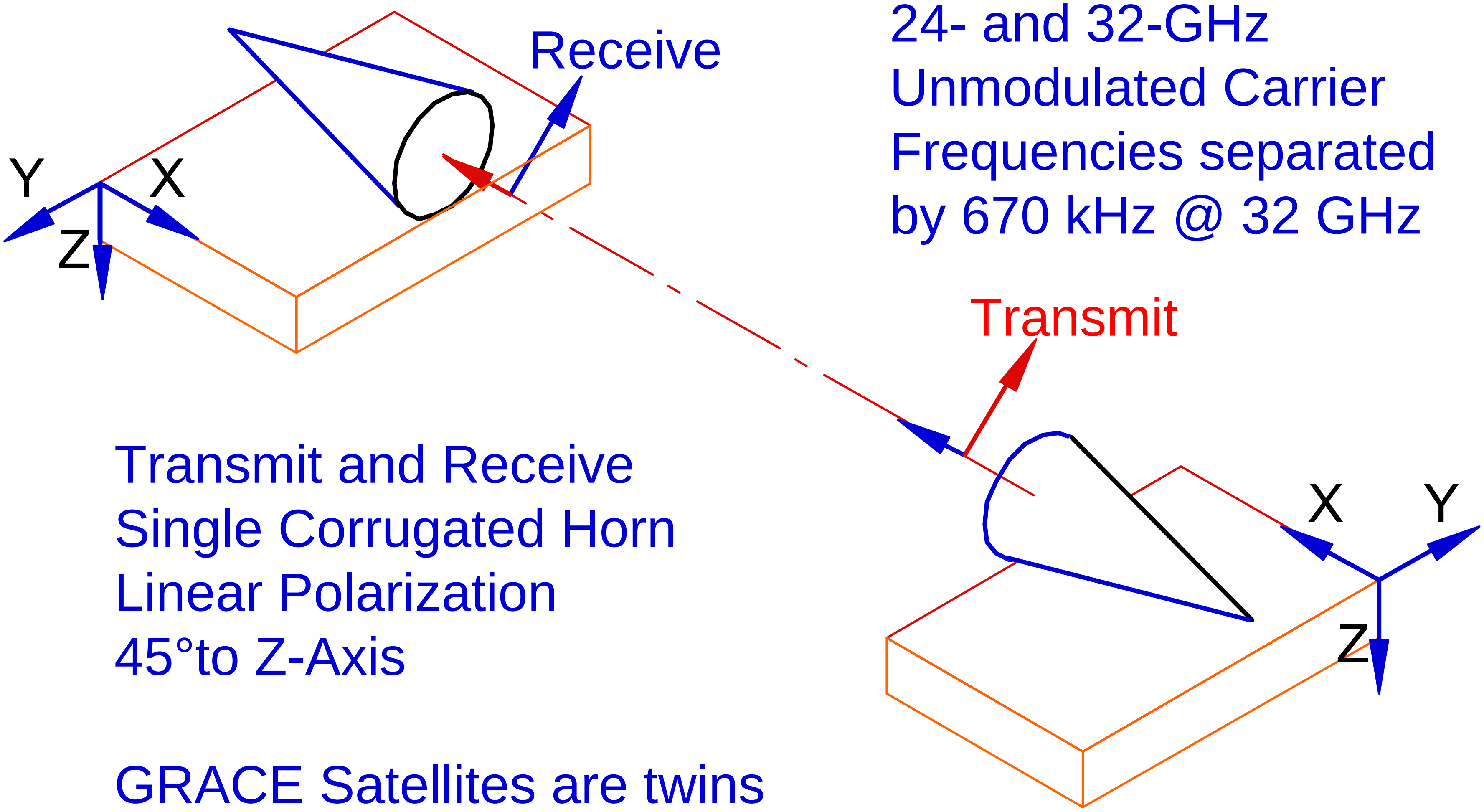
K-Band Ranging

24- and 32-GHz
Unmodulated Carrier
Frequencies separated
by 670 kHz @ 32 GHz



Transmit and Receive
Single Corrugated Horn
Linear Polarization
45°to Z-Axis

GRACE Satellites are twins

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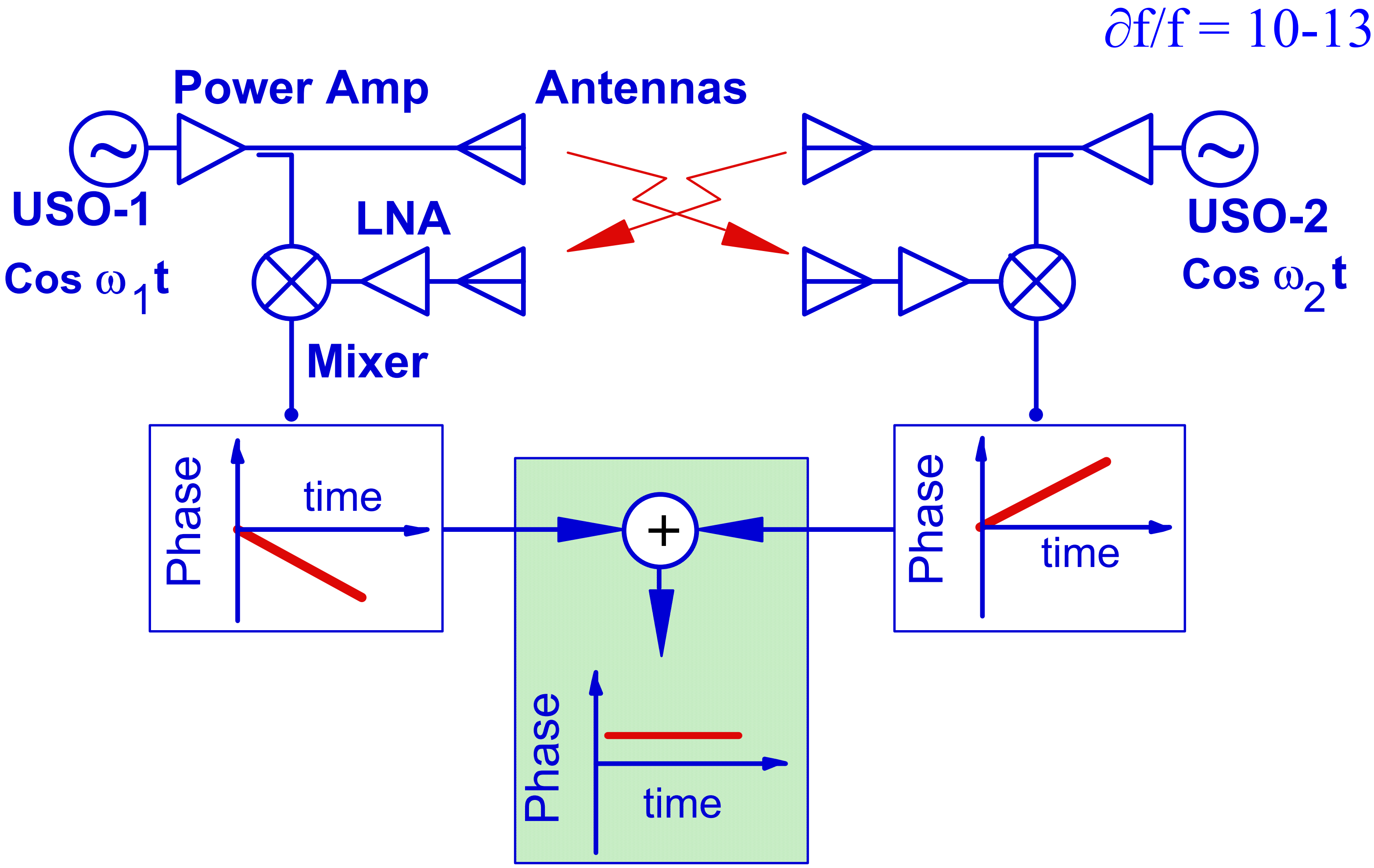
Dual One-Way Ranging



SOURCE: C.E. Dunn

The Laser Interferometer Option

Advantages

- The Transmit and Receive frequency are the same
  - Potential to Improve Ranging performance for the longest wave length terms

Microwave Offsets

- Lowered the offset between K-Band frequencies to under 1 MHz
  - Spitzmesser showed it could be done

Challenges in 1996

- Frequency stability 1E-12 was not demonstrated
  - SIM was working on a cavity stabilization approach objective 1E-11
- Needed arc-second level pointing to make fringes
  - An optical concept with less stringent pointing rqt had poor SNR

Abandoned after a 6 week preliminary design effort

Risk Containment

Level of Integration into the I□PU

- GPS
- K-band Tone Tracking
- Timing Signals
- Star Camera Image Processing

Star Camera Configuration

Redundancy

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Level of IPU Integration

K-band Tone Tracking

- Essential integration to achieve 100 psec time synchronization

Timing Signals 1-Hz OBDH

- Synchronize telemetry and command with the instrumentation

Timing Signals 10-Hz ACC 1-MHz ACC

- Required to synchronize the10-Hz ACC data with the 10-Hz K-Band ranging data. Simplifies the digital filtering of the data by the Science Data System

Star Camera Image Processing

- Intel 486 micro-processor from DTU Ğexpected similar problems to the 603e used in the BlackJack
- Utility of K-band data depends on star camera data
- Unit cost of Processors > $250,000 (needed at least 4)

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Star Camera Configuration

- **Two Star Cameras 45 degrees to Zenith - Camera pointed away form the Sun is "Prime" and used by AOCS.**
  - Simultaneous Sun and Moon blinding in both occurs monthly
  - Simply letting the satellite float with control actuators OFF works for 5- to 8-minute moon intrusions in the "prime camera"
  - Every 160 days, the sun shifts from one side of the satellite to the other. Prime camera must be switched at this point.
  - If one camera fails, the IMU provides an inertial reference during those periods when the Sun interferes with the only camera.
  - If the both the IMU and a camera fail on one Satellite, then leading satellite must switch places with the trailer
- **Three- & Four-camera options abandoned -**
  - Packaging close to the ACC was too difficult

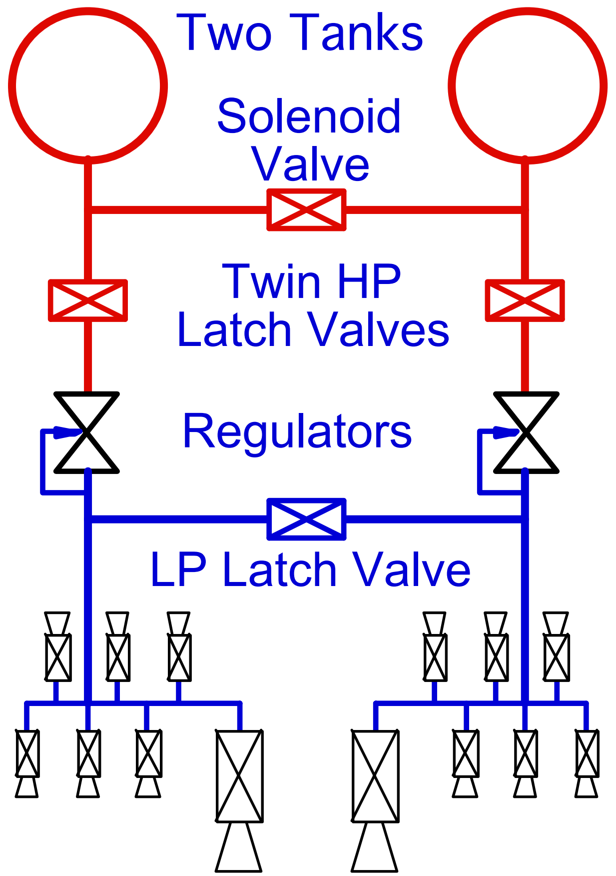
Cold Gas Sub-System

Center of Mass Stability

- CHAMP manifolds the two tanks together and has one high pressure regulator & 2 low pressure latch valves
- **1°K ΔT between Tanks moves the CoM 80 μm**

GRACE Dual-String Architecture

- No mass exchange between tanks from ΔT
- Redundant regulators
- Compensates for tuck-open thruster
- X-axis CoM is controlled by single string operation of orbit control maneuvers



Twelve 10-mN Thrusters □
Two 40-mN Thrusters