EXTREMELY LARGE SWARM ARRAY OF PICOSATS FOR MICROWAVE / RF EARTH SENSING, RADIOMETRY, AND MAPPING

Progress report

March 16, 2005

Research Sub Award # 07605-003-029

Ivan Bekey
Bekey Designs, Inc.
Ibekey@cox.net
(703) 978-1125
UTILITY AND APPLICATIONS

Principal aim: support NASA’s Earth Science activities
“….improve the measurement and prediction of water-related phenomena”

Sense and measure:

• Soil moisture content
• Freeze-thaw cycles
• Snow accumulation levels
• Flooding extent and precise geographical location
• Emergency management after hurricanes and floods
• Water content and temperature profile in atmosphere
• Ocean salinity
• Coastal salinity and river effluents
• Other water-related Earth Science applications

Principal requirement:
• Observe in the low microwave frequencies because they interact best with water
OBJECTIVES
SOIL MOISTURE / OCEAN SALINITY REMOTE SENSING

• High resolution on the ground
• High sensitivity
• Rapid / frequent revisit
• Flexible scan area and pattern, or continuous dwell
• Coverage of nearly a hemisphere from one space system
• Affordable

These objectives cannot be met by any current, programmed, or even planned systems
### CAPABILITIES AND DESIREMENTS-HYDROLOGY

<table>
<thead>
<tr>
<th></th>
<th>Soil moisture</th>
<th>Ocean salinity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Earth science</td>
<td>Trafficability</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>SMOS</td>
<td>Desired</td>
</tr>
<tr>
<td></td>
<td>0.8-2.2°C</td>
<td>&lt;1°C</td>
</tr>
<tr>
<td>Resolution/spot</td>
<td>35 km</td>
<td>100-300 m</td>
</tr>
<tr>
<td>Revisit time</td>
<td>3 days</td>
<td>2-5 days</td>
</tr>
<tr>
<td>Frequency</td>
<td>1.4 GHz</td>
<td>1.4 GHz</td>
</tr>
</tbody>
</table>

- SMOS = Soil Moisture and Ocean Salinity mission. ESA. 2007. LEO
- Aquarius = Sea Surface Salinity mission. NASA. 2008. LEO
THE RADIOMETRY PROBLEM

• Earth remote sensing at low microwave frequencies is best for water detection (1.4 GHz)

• Current systems have spot sizes of 30-100 kilometers and revisit times of 2-5 days

• It is desirable to be able to resolve features 100-300 m size, and revisit them in hours

• This is not possible with current, programmed, or even planned space systems

• It requires a system in GEO, driven by the coverage and revisit needs

• But from GEO a 100 m spot size requires an antenna size of \( \approx 100 \) kilometers at 1.4 GHz

• Even with inflatable antenna technologies this would weigh \( \approx 10^{10} \) kilograms

• A new approach is clearly needed, which is the subject of this Phase I study
ACHIEVING 300 m GROUND RESOLUTION AT 1 GHz FROM GEO

Conventional rib-mesh antenna

Inflatable membrane antenna

10% sparse inflatable membrane antenna

30 kg/sq.m

3 kg/sq.m

0.3 kg/sq.m

Comparative total weight of a hypothetical 80 km diameter antenna

100,000,000,000 kg

10,000,000,000 kg

1,000,000,000 kg
THE APPROACH

• Use highly sparse space-fed array
• Eliminate all structure and trusses
• Free-flying picosat repeaters

Receiver

No truss

No Structure

Very sparse free-flying array of very many picosat transponders.

To Earth
INITIAL CONCEPT: LARGE PICOSAT SWARM ARRAY
MICROWAVE PASSIVE RADIOMETER

Receivers and/or transmitters, central computer, DGPS reference

- 10,000 - 300,000 picosats
- Weight 20 grams each
- Total weight = 200 kg - 6,000 kg in GEO

20 g Picosat

Ground resolution
- 3 km at 100 MHz
- 300 m at 1 GHz
- 30 m at 10 GHz

Sampling scanning

Pushbroom scanning
REQUIRED CONSTELLATION DIAMETER IN GEO

Ground resolution spot size, meters

Frequency = 1.4 GHz
DETERMINING REQUIRED NUMBER OF PICOSATS

Parameters of interest
- Planck’s constant $h = 6.6 \times 10^{-34}$ Js
- Boltzman’s constant $k = 1.38 \times 10^{-23}$ J/ºK
- Speed of light $= 3 \times 10^8$ m/s
- Temperature $T = 300$ ºK
- Frequency $F = 1.4 \times 10^9$ Hz
- Bandwidth $B = 1 \times 10^7$ Hz
- Integration time $= 1$ s
- Radiating area $= 300^2 \pi /4$
- Capture area $= d^2 \pi /4$
- Distance $R = 3.6 \times 10^7$ m
- Steradians subtended $sr = d^2 / R^2$

Planck’s law for thermal flux
$$F = \frac{2hf^3}{c^2} \left[ \frac{1}{e^{hf / kT} - 1} \right] = 1.8 \times 10^{-19} \frac{J}{m^2 \times sr \times Hz}$$

Distance $= R$

Constellation diameter

Equivalent total capture area of all picosats $= a$

Subtended solid angle $= sr$

- Receiver noise $P_n = kTB$
  - $kTB = 6.55 \times 10^{-14}$ Watts
- Received signal $P_r \geq 2P_n$
  - $P_r \geq 9.82 \times 10^{-23} d^2$ Watts
- $d^2 = 8.42 \times 10^8$
- $a = 6.6 \times 10^8$ m$^2$
- Individual picosat capture area $= a$
  - $a = \frac{R^2}{4\pi} = 0.0035$ m$^2$

BLACK BODY RADIATION FROM THE EARTH

Sweet spot for water measurements
ACTIVE ILLUMINATOR SYSTEM
PICOSAT SWARM ARRAY MICROWAVE EARTHSENSING

Central receiver, feed, metrology center, navigation reference, processor/computer, command center, command/control, communications with ground

• 1,000 - 100,000 picosats
• Constellation size = 100 km diameter

100 km tether

Counterweight and navigation reference

• Ground resolution spot = 100 meters
• Flexible scan/dwell pattern

1,000 - 100,000 picosats

100 km

100 km

GEO

Illuminator: 1.4 GHz CW, large antenna

Picosats

Earth
NUMBER OF PICOSATS REQUIRED-ACTIVE SYSTEM

Picosats have omnidirectional antennas

- Ground resolution spot size, meters
- Illuminator power = 100 W
- Illuminator power = 1 kW
- Illuminator power = 10 kW

Illuminator has 20 m antenna
NUMBER OF PICOSATS REQUIRED-ACTIVE SYSTEM

Picosats have 50 cm long Yagi antennas

Illuminator power = 100 W
Illuminator power = 1 kW
Illuminator power = 10 kW

Ground resolution spot size, meters

Illuminator has 20 m antenna
• Halo orbits obeying Hill’s equations are set up for picosats
• Picosats deployed into an apparent plane in relative coordinates.
• Picosats rotate around a central point in GEO
• Plane is inclined 30 degrees to local horizontal
• The motions of the picosats are circular around the central point at the 30 degree plane inclination
• The constellation is 100 km in diameter
• Its projection on the ground is an ellipse
• There are 1,000 to 100,000 picosats in the constellation
• Their location in the constellation is made quasi-random during deployment
• The average separation between picosats is 1 km in a 10,000 picosat constellation
• The $\Delta V$ required for stationkeeping is an order of magnitude less than if in non-Keplerian orbit
FUNCTIONING OF SPACE-FED PHASED ARRAY

Incoming signals are in phase to $\lambda/20$ and add coherently. Final signal is sum of individual picosat signals.

Phase delays introduced by picosats are calculated based on precision position metrology relative to the central receiver. The actual picosat positions are not critical.

Added phase delays, modulo $2\pi$ ($\phi_4 > \phi_5 \geq \phi_6$)

A global phase shift pattern is superimposed on the individual picosat shifts across the array to focus and steer the beam.

Reference plane

Incoming plane wavefronts

Spherical wavefronts

Picosats
PATTERN OF SPARSE MICROWAVE ANTENNA

Width of main lobe = $1.22 \lambda / \text{constellation diameter}$

Amplitude of near sidelobes reduced by tapering the aperture illumination

Grating lobes are suppressed by randomizing the position of the picosat positions

Amplitude of far sidelobes = $1/\text{number of picosats}$

- Angle off boresight +
FOCUSING THE ANTENNA BEAM SPOT

Focusing (and scanning) is accomplished by superimposing a phase pattern across the entire antenna array.

Distance to spot is $3.6 \times 10^7$ m.

Diffraction limited near-field spot focused to 100-300 m.

Far field minimum spot size = 100 km.

Focusing the beam is possible in the near field of the antenna, within a distance of $2D^2/\lambda = 1 \times 10^{11}$ m.
Set up a GPS-like local navigation environment: a CMS (Constellation Metrology System)

- 5 reference units have stable oscillators and low power (short range) transmitters
- Each picosat determines its own position, and then computes its required phase delay
- Accuracy will be high: no ionosphere, atmosphere, or high relative velocities (highest is 4 m/s)
- Navigation chips for picosats will be cheap. (Cell phone-mandated GPS chips will cost $10-30 by end of 05)
- Could use GPS cell phone chips as-is, just add shielding. Total cost will be higher
- Or make new CMS chips. Will be simpler: no security coding, anti-jam, or spread spectrum needed
- These new chips might cost $1,000 in lots of 10,000-100,000. But this might still be too expensive

Alternative # 1
- Each picosat has a beacon. Navigation units triangulate picosat positions and send to master

Alternative # 2
- Master units transmits ranging tones which are retransmitted by picosats. Master computes range and range rate to each picosat. Three masters compute picosat positions

Alternative # 3
- Same as above except that masters send ranging pulses rather than tones
## PICOSAT POSITION KNOWLEDGE REQUIREMENTS IN A SPACE-FED ARRAY

<table>
<thead>
<tr>
<th></th>
<th>Center picosats</th>
<th>Edge picosats</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sensitivity, m/Δ</td>
<td>Δ for 1 cm path delay</td>
</tr>
<tr>
<td>Normal to plane</td>
<td>0 kilometers</td>
<td>0.3</td>
</tr>
<tr>
<td>In-plane</td>
<td>0.00005 Δ²</td>
<td>22.4 m</td>
</tr>
</tbody>
</table>

![Diagram showing distances and positions of picosats in a space-fed array]
• Need to control phase to about $\frac{\lambda}{20}$
• Worst case: this is equivalent to about 1 cm at 1.4 GHz
• But space-fed array increases the worst case to 3.3 cm, or $\frac{\lambda}{6}$
• Since can go modulo 2 pi, need only control phase to 6 increments
• This implies a 3 bit phase shifter. These are easy
• Need to determine and set phase frequently due to 3.3 cm tolerance:
  • Velocity around constellation outermost diameter is 3.6 m/s relative to center
  • Thus phase must be adjusted every 10 ms
  • Command to set phase @3 bits 100 times/sec requires 3,300 bps in one channel
  • Set up 100 channels with 100 picosats each and command requires 3.3 kbps per channel

• However the tolerances are much looser than 3.3 cm in most directions of drift
  • So that on average this command link will not be stressed

• Furthermore, if picosats compute their own phase then command is only required to set global phase for beam steering and focusing
  • This requires even lower bit rate because changes are expected very slowly
• Picosats will deploy themselves from central unit.
• Each picosat requires 8 micrograms of propellants (100 g picosat) at 3000 Isp for deployment
• Picosats will return to central storage depot when nearing EOL.
• Central depot holds all 10,000 picosats (1,000 kg).
• Depot has doors and sensors, and internal baffles/nets
• Picosats are commanded from master to deploy; and then to return to depot for storage
• If a picosat dies prematurely a scavenger unit is sent to retrieve it and swallow it
• The scavenger stays at the last dead picosat location until it has to go swallow another one
• Returning to central location until needed again would require more propellants
• This requires less propellant than to dispose of dead picosats into above-GEO disposal orbits
• Scavenger can hold 1000 dead picosats (10% picosat failure rate).
• Scavenger needs only about 9 kg of propellants total. Its gross weight is 300 kg
FIRST COVERAGE CALCULATIONS
AREA COVERED AS A FUNCTION OF REVISIT TIME:
10 BEAM RECEIVER

Trafficability
Soil moisture/Water salinity

1,000 m spot
316 m spot
100 m spot

United States
California
Chesapeake Bay
San Franisco Bay
Atlanta
Georgia tech

1 hour
1 min.
1 day
ACTIVE ILLUMINATOR SYSTEM
PICOSAT SWARM ARRAY MICROWAVE EARTHSENSING

Central receiver, feed, metrology center, navigation reference, processor/computer, command center, command/control, communications with ground

- 1,000 - 100,000 picosats
- Weight 20-200 grams each
- Constellation plane tilted 30 deg to local horizontal
- Constellation size = 100 km circle
- Picosat locations randomized in constellation

Navigation reference units

100 km tether

2-250 cm

20-200 g satellite

Picosat antennas could be omnidirectional stubs or 6-16 element Yagi arrays (shown)

100 km

Deployer/retriever stationed at center

Counterweight and navigation reference

Illuminator: 1 kW CW, 20 m antenna

• Ground resolution spot = 100 meters
• Flexible scan/dwell pattern

GEO

Earth
STATUS/SUMMARY

• Initial concentration is on Earth Science hydrology missions

• System sizing is nearly complete

• An active illuminator system has been chosen

• The resolution and coverage far exceed anything by SSIS, SMOS, Aquarius, Hydros

• The choice of GEO altitude results in very flexible scanning and coverage

• The concept configuration and its elements still appear viable

• No showstoppers have been found to date

• Its utility will be unprecedented, and likely to be welcomed by the science community

• Phase I will be completed on schedule
MISSION/SCIENCE CONTACTS MADE TO DATE

NASA HQ

• Granville Paules
• John LaBreque
• Craig Dobson
• Eric Lindstrom
• Jarred Entin

• NASA GSFC

• Waleed Abdalati
• Edward Kim

• JPL

• George Hajj
• Cinza Ruffada
• James Zumberge

• Other

• Phil Schwartz--Aerospace Corporation
• Numerous web sites for systems: SMOS, Aquarius, Hydros, SSIS, others
AREA COVERED AS A FUNCTION OF REVISIT TIME
1 BEAM RECEIVER

1 min. 1 hour 1 day

1,000 m spot
316 m spot
100 m spot

United States
California
Chesapeake Bay
San Francisco Bay
Atlanta
Georgia Tech

Trafficability
Soil moisture/Water salinity

Revisit time, Days


0.001 0.010 0.100 1.000 10.000

Soil moisture/Water salinity
Trafficability

1.E+04 1.E+03 1.E+02 1.E+01

1,000 m spot
316 m spot
100 m spot
SPARSENESS OF SWARME D APERTUI

Picosats in space-fed array
- Operate as repeaters
- Frequency = 1 GHz
- Each has 10 dB antenna

Aperture diameter, meters

% filled with 1000 picosats
% filled with 10,000 picosats
% filled with 100,000 picosats

100 1,000 10,000 100,000
# Choice of Constellation Altitude

<table>
<thead>
<tr>
<th></th>
<th>PRO</th>
<th>CON</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LEO</strong></td>
<td>• Revisit time OK</td>
<td>• Large $\Delta V$ in picosats for stationkeeping</td>
</tr>
<tr>
<td></td>
<td>• Constellation size small--1 km</td>
<td>• High orbital debris creation problem</td>
</tr>
<tr>
<td></td>
<td>• One constellation suffices--global coverage</td>
<td>• High impact probable with other satellites</td>
</tr>
<tr>
<td></td>
<td>• Few picosats required in constellation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Passive system OK</td>
<td></td>
</tr>
<tr>
<td><strong>MEO</strong></td>
<td>• Orbital debris not a problem</td>
<td>• Very long revisit time</td>
</tr>
<tr>
<td></td>
<td>• Medium size constellation</td>
<td>• Medium size constellation</td>
</tr>
<tr>
<td></td>
<td>• Medium number of picosats needed</td>
<td>• Need many constellations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Must use active system</td>
</tr>
<tr>
<td><strong>GEO</strong></td>
<td>• Short and flexible revisit time</td>
<td>• Large constellation size</td>
</tr>
<tr>
<td></td>
<td>• Flexible scan/dwell patterns/options</td>
<td>• Active system required</td>
</tr>
<tr>
<td></td>
<td>• Picosats can use omni small antennas</td>
<td>• Many picosats required</td>
</tr>
<tr>
<td></td>
<td>• One constellation covers $\approx$ a hemisphere</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Orbital debris problem moderate</td>
<td></td>
</tr>
</tbody>
</table>