DISTRIBUTED METROLOGY AND CONTROL FOR LARGE RADAR APERTURES

Annual Report

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A. OBJECTIVES

In this effort, a systems architecture was developed, along with supporting analysis and modeling tools, for a novel design concept which will allow development of lightweight, inexpensive space-borne antennas with apertures of hundreds of square meters. The concept is based upon a phased-array antenna that is able to measure its own performance and adjust the elements to compensate for deviations from the ideal.

B. STRATEGIC FOCUS AREA

Large Aperture and Wavefront Control

C. RELEVANCE TO STRATEGIC FOCUS AREA

In recent years, radar antennas with ever-larger apertures have been desired to improve the resolution and performance of radar measurements made from orbit. Traditionally this has required massive or complex mechanical structures to hold the necessary shape or position of the antenna within the required tolerances (usually stated as 1/20th of a wavelength, or similar). Complicating the problem further is that these large structures must be deployed on-orbit from a much smaller volume.

The concept architecture developed in this work (Figure 1), relieves the radar designer of being caught in the dual bind of needing a larger structure that simultaneously is more rigid and weighs less. The distributed processing provides a scalable architecture; the resources available for metrology and calibration increase as the array size increases. Wireless interconnects for control and radar-signal distribution eliminate the need for cabling among the elements, which is particularly troublesome in deployable structures.

D. APPROACH AND RESULTS

The development of a conceptual architecture and high-level requirements was done in several steps, starting with a set of generalized bounding requirements and constraints. Initial metrology and control requirements were developed in the context of the design concept, to identify required measurement precision and control-loop-update rates. Modeling codes were developed to calculate antenna patterns from simulated element locations and excitations, from which overall antenna performance can be determined.

A dataflow model was developed to document the processing required and the parameters needed in the metrology and calibration process. This dataflow model will be an important tool in establishing error and performance budgets when translating the architecture to a specific design. The dataflow model was also used to develop initial estimates of internal data-communications rates.

A metrology approach was developed, based on a combination of optical and RF measurements. The dataflow model was used to determine preliminary functional partitioning and performance requirements, including assessing the performance of existing technology. Two critical aspects of the RF metrology approach (oscillator stability, mutual element interactions) were evaluated further.

Generalized System Requirements

The initial bounding set of requirements was based on published reports, the ESTIPS (Earth Science Technology Integrated Planning System) database [1], proposed mission scenarios, and interviews with radar scientists and structures staff. There was no intent to come up with an actual mission-requirements set, but more to develop an "order of magnitude" set of requirements to bound the scope of the measurement-and-control problem. The overall requirements are summarized in Table I.

Table I - Performance Requirements:

Apertures on order of 100-400 m^2, 50m linear extent

Hardware ROM mass near 2kg/m^2

Compensate to <1/20th wavelength at L band (1.2 GHz, 23 cm) (*i.e.* 1 cm)

- Mechanical deviations on order of 1 meter at 1Hz (*i.e.* few m/s velocities)
- RF property changes due to adjacent element interaction, aging, temperature
- Control loop bandwidths on order of 100Hz

These requirements were used to estimate individual element-performance requirements, particularly with respect to the level of phase-and-amplitude control needed to produce the desired antenna-system performance based on well-known array-design principles [e.g. 2, 3, 4]. The expected mechanical and structural performance of large lightweight structures has been addressed in the literature at length [e.g. 5, 6]. A set of modeling codes was developed as a framework to evaluate performance for arbitrary element configurations and performances. This software is designed to take advantage of the highly parallel nature of the computations, so even though the computations themselves are not particularly efficient, a parallel cluster can be effectively used to generate results quickly.

Development of metrology and calibration concept

The metrology concept (Figure 2) is based on using optical image sensors at each element to detect beacons to measure the position and orientation of the elements. RF metrology is used to measure the electrical performance of the individual elements. A key aspect of the metrology concept is that it is distributed, not centralized, which lends itself to scalability and survivability.

Optical Metrology

Review of available CMOS sensor technology indicated that angular measurements could be made with off-the-shelf inexpensive components with precisions on the order of 1 part in 500, using standard techniques of finding the centroid of defocused images of the point source beacons. The relative precision of 1:500, in the context of an array with a linear extent of 10s of meters, indicates that the physical position of an element can be resolved to less than one RF wavelength. The absolute precision depends on the field of view (FOV) of the sensor, and the geometry of the elements and beacons. Future system designs will make tradeoffs between the number and configuration of beacons and the element-sensor FOV. The impact of initial optical-sensor calibration and aging remains to be addressed.

RF Metrology

The architectural concept uses RF measurements of the gain and phase of the elements to make the final sub-wavelength corrections needed to form the beam with the required accuracy. Two approaches were considered for this, both based on making “in-band” measurements of RF signals from the beacons. The first was to use PN-coded signals in a manner similar to GPS. The second was to use a constant CW tone and measure the phase. The second approach was selected, as the PN-coded system did not provide any significant advantage in performance, and is more complex. Techniques using measurement of the phases of RF signals for accurate position determination are well understood (it was the basis of the OMEGA global navigation system), and require simple hardware and signal processing, suitable for integration into an embedded processor.

Assessment of Error Sources in RF Metrology

Two significant error sources are present in the RF-metrology system. The first is the stability (especially phase noise in the 100 Hz-10kHz range) of the oscillators in the elements and the second is the changes in the apparent phase center of the element due to inter-element mutual coupling. A breadboard was used to assess the impact of the former, and numerical modeling was used to assess the latter.

The breadboard used two stable beacon signals to measure and predict the future performance of an inexpensive mass-produced oscillator. Preliminary analysis (Figure 3) shows that a simple linear predictor using the last 0.3 seconds of data can remove the errors in frequency sufficiently well that the residual error is less than 5 ppb, corresponding to a phase error of 1.8° over 0.1 second.

A numerical method of moments-modeling of the interaction of dipoles over ground screen (a “worst-case” with a lot of interaction) was used to determine the sensitivity of the phase measurement. This data (Figure 4) shows that knowledge of the spacing to within 1% and the angular orientation to within 1^{o} is sufficient to calculate the mutual interaction effects to within a few degrees-of-phase error.

RF Link and Communication-Rate Budgets

RF links are used to distribute the transmit pulse to all the elements, and to perform spatial combining on the received signals. The RF-metrology system also uses RF signals from the beacons to the elements. RF-link budgets were computed based on a transmit/receiver distance of 1 to 100m, assuming isotropic antennas at both ends of the link and a link frequency of 2.5 GHz. In both directions, the goal is that the SNR be high enough that the noise contribution from the link is insignificant. A 100 mW transmitter will provide a 44-dB SNR in a 10-MHz radar bandwidth at the farthest distance. A significant finding from this analysis is the large dynamic range resulting from element displacement from nominal, particularly at short ranges. This effect will drive the overall layout of beacons, combining points, and elements.

The dataflow model was used to estimate the number and type of data items that would need to be transmitted among the elements. The embedded control and model algorithms require data only from adjacent elements, due to the strongly banded diagonal structure of the interaction matrices (both structural and electromagnetic). Using an assumption of a 1-millisecond update rate, these data volumes correspond to rates of several tens of kbit/second. These rates are well within the capability of off-the-shelf technology.

E. SIGNIFICANCE OF RESULTS

This task developed a set of baseline requirements for radar antennas to bound the area of investigation for modeling and conceptual design. These requirements are not necessarily reflective of any current or proposed mission requirements, but span the likely set of requirements over the next 10-15 years. Particularly interesting is that the architecture developed in this work may facilitate the use of novel lightweight structures (e.g. inflatables) being developed by others, since it can compensate for the lack of stiffness in these structures.

The preliminary analysis and modeling indicates that the metrology and calibration performance required can be met by a combination of currently available inexpensive optical sensors and simple radio-frequency phase-and-amplitude measurements. An unexpected result of this analysis was that knowledge of the orientation of the antenna elements may be a significant driver for the performance metrology system, due to the mutual coupling of adjacent elements, which affects the radiated pattern and apparent phase center.

Laboratory test data using breadboard components and a simple measurement algorithm indicates that inexpensive mass-produced oscillators have sufficient phase and frequency stability, and that simple algorithms will track and predict the variations.

F. FINANCIAL STATUS

The total funding for this task was $140,000, all of which has been expended.

G. PUBLICATIONS AND PRESENTATIONS

[1] James Lux, “Clusters in Space”, *Proceedings*, ClusterWorld Expo, April 5-8, 2004, San Jose CA

[2] James Lux, et al. , “Distributed Metrology and Control for Large Radar Apertures”, accepted for IEEE 2005 Aerospace Conference, March 2005, Big Sky, MT

H. REFERENCES

[1] ESTIPS database at http://estips.nasa.gov/ (last accessed Dec 2003)

[2] Elliott, R.S., "Mechanical and electrical tolerances for two-dimensional scanning antenna arrays", IEEE Trans on Ant and Prop, v6, n1, Jan 1958, pp114-120

[3] Bracewell, R.N., "Tolerance Theory of Large Antennas", *IRE Transactions on Ant. and Prop.*, vTBD, n1, pp49-58, Jan 1961

[4] Lo,Y.T., "A Mathematical Theory of Antenna Arrays with Randomly Spaced Elements", IEEE Trans on Ant & Prop, pp257-268, May 1964

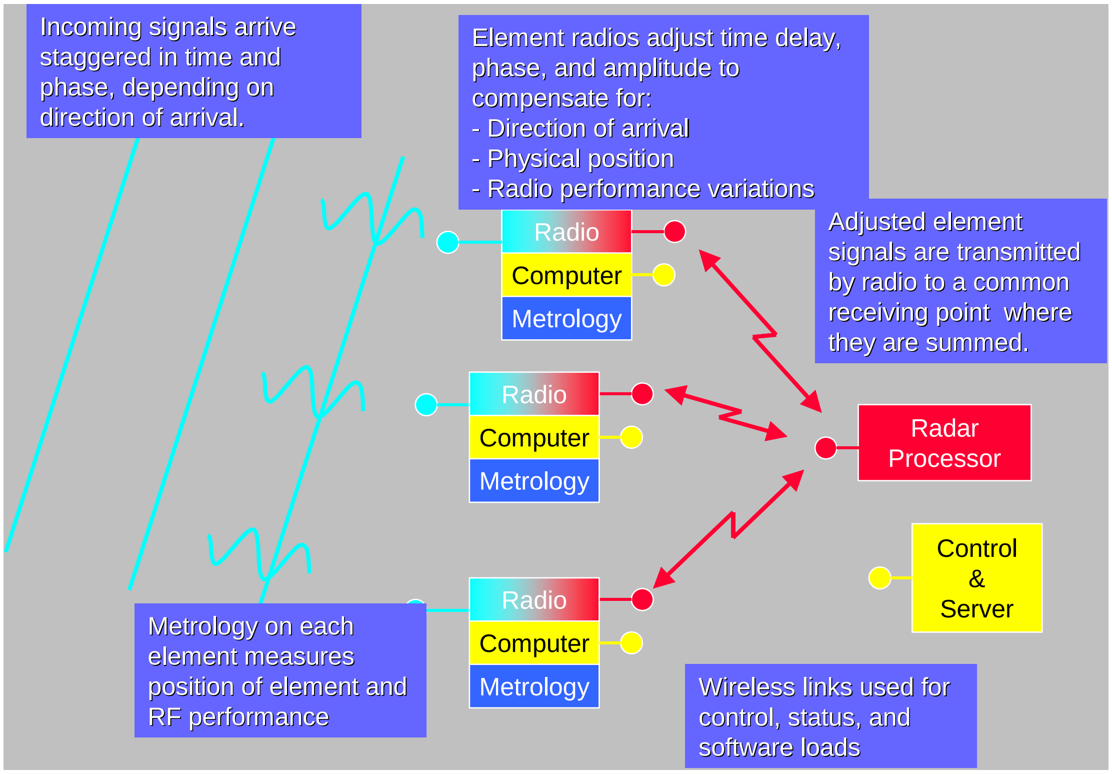
[5] Duren, R., *et al.*, "Metrology, attitude, and orbit determination for spaceborne interferometric synthetic aperture radar", *SPIE AeroSense Conference on Acquisition, Tracking, and Pointing XII*, April 1998

[6] Tibert, G., *Deployable Tensegrity Structures for Space Applications*, Doctoral Thesis, Royal Institute of Technology, Stockholm, Sweden 2002,

[7] Kusters, J.A., et al. , “A No-drift and less than 1x10^{-13} Long-term Stability Quartz Oscillator Using a GPS SA Filter”, *Frequency Control Symposium, 1993, 47th., Proc of the 1994 IEEE Intl.*, 1-3 June 1994, pp 572-577

I. FIGURES

Figure 1: Conceptual Design



Incoming signals arrive staggered in time and phase, depending on direction of arrival.

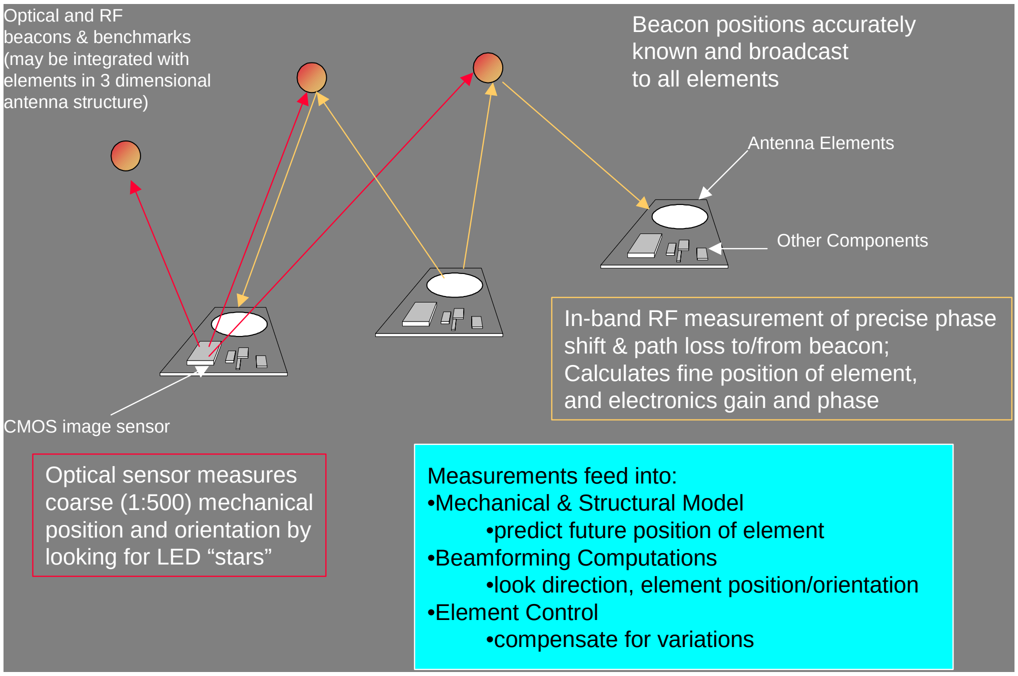
Element radios adjust time delay, phase, and amplitude to compensate for:
- Direction of arrival
- Physical position
- Radio performance variations

Adjusted element signals are transmitted by radio to a common receiving point where they are summed.

Metrology on each element measures position of element and RF performance

Wireless links used for control, status, and software loads

Figure 2: Metrology Concept


Optical and RF
beacons & benchmarks
(may be integrated with
elements in 3 dimensional
antenna structure)

Beacon positions accurately
known and broadcast
to all elements

Antenna Elements

Other Components

In-band RF measurement of precise phase
shift & path loss to/from beacon;
Calculates fine position of element,
and electronics gain and phase

CMOS image sensor

Optical sensor measures
coarse (1:500) mechanical
position and orientation by
looking for LED “stars”

Measurements feed into:
- Mechanical & Structural Model
  - predict future position of element
- Beamforming Computations
  - look direction, element position/orientation
- Element Control
  - compensate for variations

Figure 3: Breadboard test shows residual frequency error of 5ppb

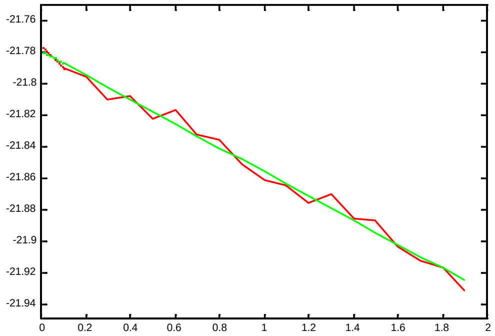


Figure 4: Modeling shows <1° phase error for 1% position uncertainty