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APPLICATIONS OF RADAR TO SPACECRAFT AND SPACEFLIGHT

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INTRODUCTION

The advent of space programs such as Gemini, Apollo, and Surveyor have established radar as an essential part of spaceflight. Some of the applications of radar in these programs closely resemble prior radar applications in aircraft. However, several new and unusual applications are either in the planning stage or under development.

Prior to the Gemini Program, the principal use of radar was as a tracking aid. In the Mercury Program, the spacecraft carried only "S" and "C" band beacons which worked in conjunction with cooperative ground based radar. The Gemini Program, however, has used a radar-computer combination to achieve rendezvous of two orbiting spacecraft. The Surveyor moon landing vehicle utilizes a Doppler radar as a landing aid.

In the Apollo Program, present plans are to equip the Lunar Excursion Model (LEM) with both a rendezvous radar and a Doppler landing radar system. Experiments which are presently in the planning stage include side-looking radar systems, scatterometers, non-cooperative radar systems, and high resolution altimeter and velocity sensors.

PRESENT APPLICATIONS

Applications of radar in spaceflight to date consist principally of spacecraft rendezvous and spacecraft landing applications. In the following paragraphs, each of these applications will be explained in relation to its use in spaceflight.

RENDEZVOUS APPLICATIONS

The evolution of radar systems in manned spaceflight began with the rendezvous requirement. Suffice it to say that the basic technique of achieving a rendezvous is first to have two spacecrafts in different circular orbits around a referenced body such as the earth. Because the orbital velocity in an inverse function of the distance from the center of the referenced mass, and the diameter of the inner circle is smaller, the inner spacecraft will complete an orbit quicker than the spacecraft in the outer orbit. At a predetermined relative range or angle between spacecraft, the inner spacecraft is injected into an elliptical orbit which will intersect the outer circular orbit. A change in velocity, or delta V correction, is given to the inner spacecraft, which will change the circular orbit to the intersecting transfer ellipse orbit. The amount of delta V correction is dependent on the accuracy of the range or angle information. The fuel consumption or required fuel weight, which should be minimized, is a function of the number of delta V corrections required to complete a rendezvous. As the terminal phase is approached it is necessary to have range rate information because it becomes difficult to visually judge closing rates with reference objects. Essentially then, a rendezvous radar must have these characteristics; very accurate range and/or angle information at long ranges (midcourse corrections) and range rate information at short ranges. The circular

orbits used for this particular technique are commonly called concentric trajectories. The methods to achieve rendezvous for both the Gemini and Apollo missions are essentially the same.

The monopulse angle tracking technique is considered to be the most accurate method of achieving high angular accuracy. The Gemini Radar System employs an antenna with pseudo-phase monopulse cooperative tracking system, while in the Apollo Program the LEM Rendezvous Radar uses an amplitude-comparison monopulse cooperative tracking system.

LANDING AID APPLICATIONS

The first space application of radar as a landing aid was by the Russians in the Luna series of unmanned soft moon-landing vehicles. While no detail of the mechanization of this system is available, it is generally believed that it was a Doppler system similar to that used by the United States Surveyor unmanned moon landing-craft. The Apollo LEM vehicle will also make use of a Doppler system as a landing aid.

In the applications of the radar, velocity and altitude data are used to update inertial data as the spacecraft approaches the Lunar Surface. This is generally in the 1,000 to 40,000 feet altitude range. In this range, a combination of velocity and altitude data obtained by the radar is used in conjunction with inertial data and a computer to compute an optimum trajectory for landing. The computer then guides the spacecraft into this optimum trajectory by firing a descent or control engine.

Below 1,000 feet the spacecraft may be controlled to a landing solely by the radar system, or an astronaut may take control. In the Surveyor, the radar system continues to guide the spacecraft to a soft landing, with the radar actually providing a signal which will shut off the descent engine at an altitude (14 feet) which will allow the vehicle to safely free fall to the Lunar surface.

The Apollo LEM vehicle will be guided to a hover at approximately 100 to 200 feet altitude. Below this point, inertial data which has been updated by the landing radar will be used to bring the spacecraft to a safe landing.

A major concern in these applications is the validity of lunar reflectivity models. The assumed lava-like lunar surface has dielectric properties which necessitate a mean value correction of radar penetration (the altimeter beam) below the actual surface. The rough surface increases the scattering and hence, lessens the reflected return in a manner similar to absorption material. A reflected wave along the nadir has specular return and the combination of specular and rough surfaces presents a lunar reflectivity model which necessitates serious consideration of terrain bias errors in using the radar information.

Another consideration is the efficient utilization of rf power output versus audio susceptibility to acoustical noise (vibration) and mixer noise. For example, if the Doppler velocity sensor is frequency modulated, the use of a system based on higher-order Bessel functions, such as the first or third, would decrease the susceptibility in the low frequency spectrum. However, the efficiency of the power output is reduced from a zero-order Bessel function system such as unmodulated CW. Therefore, the need for low power systems in spacecraft, while desirable, creates problems in system design.

Another problem with radar altimeters is proper position of the spacecraft. Under normal aircraft flight-paths, a Doppler radar system is alined in one position. A spacecraft such as the LEM varies its attitude in all axes (yaw, pitch, and roll). As a result, the zero Doppler regions have to be considered as a constraint to a spacecraft trajectory. This event occurs when a radar beam and the flight path form a 90° angle as implied in the basic Doppler expression $fd = (2V/\lambda) \cos \theta$, where V is the line of flight velocity, θ is the relative depression angle, and λ is the wavelength.

EVALUATION

Evaluation of radar systems for spacecraft generally makes use of many of the techniques used to evaluate aircraft radar systems. Boresight ranges are utilized to determine the static angular accuracy of rendezvous radars. Spacecraft effects such as near-field effects or multipath reflections are measured on a boresight range by mounting mockups of the spacecraft on a positioner. Flight tests are used for dynamic evaluation.

In the development of the Gemini rendezvous radar, the wide beam-widths of the interferometer antenna lead some to believe that a horizontal boresight range might yield questionable results because of ground reflection and multipath problems. So a vertical boresight was performed by mounting the radar on a specially prepared stand on the ground. This stand was made of absorptive material which minimized reflections. An aircraft containing the transponder was then flown back and forth over this test stand. This test was performed at the White Sands Missile Range where accurate tracking of the aircraft could be obtained. Optical data were then compared to radar data for angular accuracy. A comparison of this data with boresight data from a horizontal range showed good results.

In the Surveyor program, a balloon was used to hoist a scale model of the Surveyor vehicle to a height of 1,000 feet. The vehicle was then dropped and a large parachute deployed to slow the descent of the vehicle to that expected on the lunar surface. The descent engine was then fired and controlled by the radar-inertial system until the vehicle landed. This test was performed at a specially prepared test site at Holloman AFB, New Mexico, where precise optical tracking data could be obtained.

In the Apollo LEM vehicle, the radar rendezvous and landing systems will be evaluated by both boresight tests and flight tests. Both systems will be evaluated statically on boresight ranges. The landing radar will be evaluated by mounting it in both a helicopter and high performance jet aircraft. These aircraft will then fly those portions of the LEM landing trajectory which are within their respective flight capabilities. This test will also be performed at the White Sands Missile Range where accurate optical tracking data can be obtained.

The rendezvous mission cannot be easily simulated by aircraft because of the velocities and distances involved.. The rendezvous radar, however, has an additional requirement to track the lunar orbiting command and service module while parked on the Lunar surface. This situation will be simulated by flying an aircraft containing the cooperative radar system transponder over the rendezvous radar mounted in a LEM mockup on the ground. This test will also be performed at the White Sands Missile Range where optical data can be obtained for comparison with the rendezvous radar data.

FUTURE APPLICATIONS

Radar has many valuable attributes, most of which have been associated with guidance and navigational capabilities; however, perhaps the most exciting potential capability of all is the utilization of radar as a sensor in geoscience research for Earth, Lunar, and Martian applications. The utilization of radars in this manner has improved very rapidly since 1945, particularly in connection with side-looking imaging systems. In the future, the union of this new technology with that of an even newer one, manned orbiting spacecraft, promises to open up new opportunities and possibilities for scientific and practical resource-oriented studies of the earth.

TYPES OF NATURAL RESOURCE SENSORS

In general, there are two types of resource sensors. "Passive" sensors, such as aerial photography, and thermal infrared and microwave scanning and spectrometer systems, depend respectively upon reflected solar energy or upon radiation emitted from terrestrial objects; while "active" sensors such as radar depend upon transmitted and received signals as their source of information. Each sensor records within a relatively narrow energy band of the electromagnetic frequency spectrum; consequently, each obtains different information about objects and/or phenomena which reflect or emit energy in that band.

In the area of "active" sensors, multi-frequency polypolarized coherent, imaging, side-looking radar systems have been proposed for spacecraft use in support of the natural resource sensor program. These radars may penetrate soils and other materials, depending on the wavelength used. They will also be polarization-sensitive to natural orientations of trees, rocks, crystals, bedding planes and so on. These radar systems are all-weather instruments, and share with infrared and passive microwave systems the ability to obtain images at night or in the long Arctic winter.

When a number of these sensors are used in concert, they give data no individual part of which is diagnostic, but which together may be unmistakable. This concept, for which R. N. Colwell[1] (1963) uses the phrase "multiband spectral reconnaissance", is the key to using spacecraft as an observation platform in studies of earth resources. For efficient diagnosis of the earth's landscapes, a variety of sensors will be required, precisely as sensing of the ills of man may require the use of stethoscope, electrocardiogram and X-ray.

With combinations of sensors on orbiting spacecraft, it whould be possible to:

1. Image continuous swaths tens to hundreds of miles wide.
2. Obtain physical data about objects or phenomena at any time of day or season.
3. Monitor conditions that change with time.

The capabilities will enable continuous imagery to record transitions which take place over such long distances that similar coverage by conventional aerial photography would require weeks or months.

Finally, there is a very great advantage, in that radar is an all-weather sensor capable of penetrating the thickest clouds experienced on earth, thus, by continuous surveillance, it can simultaneously provide information on a multitude of geoscience problems, no single one of which might justify radar on a spacecraft, but which collectively make it a most attractive natural resources sensor.

NEW SIDE LOOKING RADAR CAPABILITIES

NASA is supporting feasibility studies at the University of Kansas, GIMRADA, Ohio State University, the Army Waterways Experiment Section, and a number of other institutions which are devoted to evaluating sophisticated multi-frequency, multi-polypolarization, coherent imaging systems for geoscience purposes. These studies rest on experience with multi-spectral photography (Colwell et al) and multi-band infrared imagery (Holter and Legault[2]) which strongly suggests that a four or five-frequency system will give a substantial information gain over a single frequency. In the same manner, the use of multiple polarization rests on the knowledge that many objects in nature (trees, crops, rocks, soils) are anisotropic in their dielectric field, crystal orientation, bedding, foliation, and so on; hence potentially separable by combining frequencies and polarizations. As a result of the studies, these institutions have recommended the use of coherent synthetic aperture radars on spacecraft to provide imaging in three frequencies, centered at 0.5, 2, and 8 GC. Images will be produced with direct and

cross polarization at each frequency, and displayed in congruent geometry to aid geoscience interpretation. Radar altimeter-scatterometers were also recommended at 0.4 GC and 8 GC.

FUTURE RADAR ALTIMETER APPLICATIONS

Along with imaging radars on manned spacecraft, there is anticipated a significant series of roles for radar altimeters, particularly in sea-state sensing and profiling the Antarctic continent.

Radar altimeters were developed prior to 1941. Both military and commercial versions have now been refined considerably in both size and accuracy. In this paper altimetry is given a broader definition since it is used for a downward-pointing radar illuminating a relatively wide area to obtain information on altitude and on the scattering properties of the surface within 45° to 60° of the vertical. Pulsed and frequency-modulated altimeters have been used widely for altitude measurement. For measurements of scattering-coefficient, pulsed and narrow-beam continuous and Doppler wide beam continuous altimeter systems have been used.

Radar altimeters at orbital altitude are coarse resolution instruments in area, for they average over tens of square miles, but they can be very accurate over the sea. Over the land, their precision is less. They may also be used as scatterometers to measure the back-scattering coefficient as a function of viewing angle (0_o vs θ).

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