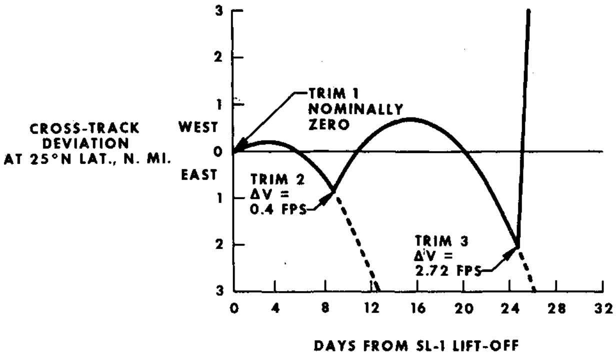

Fig. 3 SL-2 docked trim sequence for groundtrack control.

Once the groundtrack pattern was chosen, the selection of a set of 14 prime tracks from among the available tracks was undertaken. Since SL-2 preflight planning guidelines called for all U.S. passes (with some extensions into foreign areas), the analysis considered only the 32 tracks which included a portion of the U.S. A computerized scoring process was carried out. The tracks were ranked according to the number of sites within the U.S. and surrounding coastal areas which had the required sensor coverage. Seasonal conditions for these sites were also considered. Other details, such as instrument modes and sensor configuration conflicts, were not considered. The top-ranking 14 tracks and several alternates (ranking 15th through 19th) were selected as candidates for EREP passes on the SL-2 mission. The higher-ranking tracks passed over high site-density areas such as the Houston Area Test Site, the Atlantic Seaboard, and the Southern California-Phoenix area.

The final step consisted of fitting these tracks into the total Skylab-2 flight plan. First, the revolutions associated with each track which have proper sun angles for the U.S. portion were found. From Fig. 2, the ascending passes must occur in the first half of the mission, the descending passes in the second half. Because of flight plan conflicts (Earth resources is ranked behind other major experiment disciplines in priority on SL-2), not all of the 14 prime tracks were scheduled; two lower-ranking alternate tracks were inserted in the place of two prime tracks which interfered with other flight activities. The U.S. passes were extended into foreign areas whenever foreign sites in sufficient number were available within lighting and Z-LV constraints.

The EREP pass planning process for the later missions, SL-3 and SL-4, is similar, but these missions include some foreign passes, and SL-4 EREP passes are slanted somewhat toward completion of investigations which have unfinished tasks; this results in short "piece-meal" passes.

Real-Time Pass Planning

EREP pass planning is heavily affected by actual weather conditions; cloud cover adversely affects data acquired by the visible to IR range sensors, while the microwave instruments are not as sensitive to these conditions. The real-time pass planning procedure is essentially that discussed previously, except that cloud cover is considered, and instrument modes and configuration conflicts are considered in great detail.

Several days prior to any given mission day, the possible passes for that day are evaluated (based on the predicted cloud coverage) by using the interactive computer programs which were applied in the preflight planning; candidates are selected based on the task/site completion criteria as applied for the premission planning. Approximately 24 hr prior to the mission day, a prime pass or passes (not more than three) are selected and fitted into the flight plan for execution. If it were not for cloud cover, the pass would correspond to the one in the premission flight plan. However, based on simulation experience, actual cloud coverage results in changed EREP passes approximately 50% of the time, as well as reducing the number of sites acquired by approximately the same percentage. The EREP instrument on/off times are telemetered up to the OA at approximately pass time minus 12 hr and are based on later weather forecasts. At pass time minus 3 hr—too close to the pass to update the EREP time line—a GO/NO-GO decision is given based on latest weather.

Preliminary SL-2 EREP Results

Despite the systems problems encountered on the first manned Skylab mission, significant EREP data were taken. Because of the power, attitude maneuvering, and crew time limitations, the number of Z-LV passes accomplished was 11, rather than the planned 14. These passes consisted of data takes, averaging 13 min each, over most of the continental U.S., plus some coverage of the Pacific and Atlantic Oceans, the Gulf of Mexico, Mexico, and Central and South America. In addition, S193 (radiometer/scatterometer) and photographic data were acquired of a hurricane in the Pacific off the coast of Mexico. All six instruments and their related systems apparently functioned normally, and data for all disciplines, both applications and sensor development, were obtained.

Conclusions

Mission planning techniques have been developed to optimize the data return from the Earth Resources Experiments Package on Skylab. The techniques are designed to cope with a variety of missions, systems and weather constraints, and sensor development and science applications data requirements. The procedures have been computerized in an interactive real-time system for simulation and actual mission use. The planning techniques developed for Skylab are applicable to later generation orbital programs, both manned and unmanned, which involve the use of remote-sensing instrumentation for Earth resources.

Spaceborne Very-Long-Baseline Radio Astronomy Interferometry

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Introduction

In recent years, the techniques of very-long-baseline interferometry (VLBI) have made possible the observation of celestial objects at resolutions of 10^{-3} to 10^{-4} arcsec, or 3 to 4 orders of magnitude better than optical telescopes achieve. However, VLBI experiments have been performed on an ad hoc basis, there being no dedicated VLBI observatory.

VLBI methods may permit mapping of the Milky Way's small, active core on a scale of 1 a.u.; other galaxies could be mapped at a scale comparable to the Solar System. VLBI also offers such applications as: determining sky positions to 10^{-3} arcsec; measuring the length of the day to 10^{-4} sec; measuring global

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distances to a few centimeters; and synchronizing widely-separated clocks to a few nanosec.[1] Such capabilities would permit new tests of general relativity; enhanced detection of galactic motions and of planets of nearby stars; and direct measurement of continental drift and of variations in Earth's rotation and in the direction of its spin axis.[2]

Currently, the National Science Foundation is sponsoring construction of the Very Large Array (VLA), a dedicated synthetic aperture with resolution of 1 arcsec. There has been some discussion of a follow-on "super-VLA," or dedicated VLBI system, involving numerous ground-based radio telescopes. This Note describes an alternative: a space-based VLBI synthetic aperture system. It will be shown that space operations offer simpler data processing, improved astronomical image information, and capacity for system growth.

Principles of Aperture Synthesis and Radio Interferometry

A synthetic aperture is an array of antennas whose baselines (mutual separation vectors) are made to define a two-dimensional scan of the sky, in a plane normal to the line-of-sight to the radio source. In its simplest form, a synthetic aperture consists of a radio interferometer with variable spacing; the Earth's rotation produces one scan coordinate while the variable spacing defines the second. In VLBI, baselines span continents and cannot be varied; hence many radiotelescopes must participate, in order to synthesize a complete aperture. The principles of aperture synthesis by two orbiting satellites, free to translate with respect to each other, have been discussed by French et al.[3] In this mode, orbital motion defines one scan coordinate and the spacing (variable over thousands of kilometers) again defines the other. Hence, the simplicity of the variable-spacing radio interferometer is preserved.

In radio interferometry, two antennas receive the source signal (RF); the two received RF signals are coherent. At each receiver the RF is mixed with a reference frequency derived from a local oscillator (LO), the two LO signals being coherent. The resulting heterodyned signals (IF) then are also coherent and can be correlated to produce the interference fringe pattern. The IF frequency and bandwidth are typically > 1 MHz.

In movable two-element interferometers and other ground-based synthetic apertures, the LO signals are obtained from a single oscillator and transmitted by cable. Baselines up to 100 km have been achieved using radio-link interferometers, in which the LO signals are transmitted via microwave link.[4] The IF signals are returned to a central station, by cable or microwave link, for real-time processing.

In ground-based VLBI, however, the LO signals are derived from independent local, atomic oscillators driven by atomic clocks; the IF signals are tape-recorded for subsequent processing. Successful interferometry then requires that two conditions be met[1]: 1) the independent recordings must be synchronized to within $\delta t \leq 1/BW$ ($BW =$ bandwidth), or ≤ 1 μsec for $BW = 1$ MHz; and 2) the integration time (observation time) must be $\leq$ the LO coherence time, i.e., the two LO frequences must be stable to an rms phase shift of ≤ 1 rad over the integration time.

These requirements, together with the nonreal-time signal processing, lead to the signal processing time being rather longer than the observation time.

Prospects for VLBI

To perform aperture synthesis using ground-based VLBI, many baselines are needed. If n antennas participate, there are $n(n-1)/2$ independent baselines. A three-antenna system in the U.S. is undertaking observations regularly, and a few four-antenna experiments have been performed. In principle, $n \sim 12$ is possible since there are at least that many observatories with the necessary timing and recording equipment.

But it is difficult to coordinate a number of independent observatories in observing common sources at common frequencies, especially in view of the important noninterferometric work that they must perform. The international nature of such experiments constitutes another difficulty. Still another results from signal processing considerations: a ten day, twelve station experiment would require some six months of full-time computer processing.

The signal-processing difficulty can be circumvented by using communications satellites to return the IF signals for real-time correlation over the numerous baselines. The organizational problems may require construction of a dedicated international complex of observatories. Such an approach, however, is costly and may be difficult to organize or finance.

A Spaceborne Synthetic Aperture

The synthetic aperture diameter is the maximum allowable separation of the orbiting antennas, which is set by requirements of line-of-sight visibility.[3] The time for aperture synthesis then is (max separation)/(drift rate). When observing a source away from the orbit plane normal, the synthetic aperture is not circular but elliptical; if the source is in the orbit plane, the aperture is seen on edge. Hence, for full sky coverage, the selected orbit has inclination 45°, so that nodal precession permits the largest possible line-of-sight angle (45°) of the synthesized aperture to an arbitrarily located source.

Figure 1 shows, as a function of orbital altitude for a 45° orbit, the payload capacity of the Space Shuttle,[5] nodal precession period, maximum line-of-sight separation, and proposed drift rate. This last quantity is given by (max separation)/(precession period)$\cdot\frac{1}{8}$, such that an aperture is synthesized for a 45° nodal precession. Thus, orbits up to 600 naut mile appear feasible, with associated aperture synthesis times of ~ 15 days and separations of over 4000 naut mile (8000 km). Resolution of an interferometer is $\lambda/3D$ ($D =$ separation); hence, resolutions of 3×10^{-4} arcsec are possible at $\lambda = 3$ cm, equal to the best obtained in VLBI to date.

To observe faint sources, large antennas are desirable. Two proprietary concepts for large space-deployable paraboloids are the Flex-Rib of LMSC,[6] used on ATS-F, and the Expandable Truss of General Dynamics.[7] The latter appears preferable since it can be packaged when furled to fill the Shuttle's cargo bay efficiently; apertures up to 200 ft can be thus accommodated, with weight up to 4000 lb.

The pointing accuracies of the orbiting antennas then are set not by the synthetic aperture resolution, $\sim 10^{-3}$ arcsec, but by the resolution of the individual antennas, ~ 1 arcmin. Hence pointing and attitude control requirements are readily met.

Since the system operates in a line-of-sight mode, LO signal generation and IF signal processing can avoid the complexities of Earth-based VLBI systems in favor of the simpler methods of radio-link interferometry.[4] In particular, it is possible to use space-qualified quartz oscillators[8] with frequency stabilities of 2 parts in 10^{11} instead of the hydrogen masers, 100 times more stable, used in Earth-based VLBI.

In principle, one could synthesize an LO signal at one antenna or element, transmit it via microwave link to the other element, amplify the received signal, and use it directly as the LO. In practice the resulting LO signals will lack coherence due to unknown orbit perturbations and ionospheric effects. But a

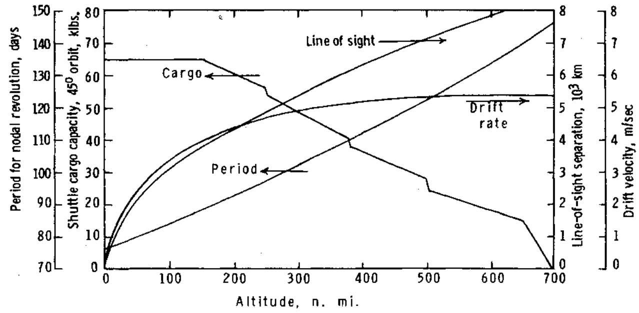

Fig. 1 Performance characteristics of an orbiting VLBI system.

stable transponder on the second element can return the transmitted signal to the first element for comparison. An integration time of 1 sec or less then suffices to determine the phase shift rate (Doppler shift) between transmitted and received LO signals. This information, retransmitted to the second element, then can insure coherence of the two LO signals. The IF signal from the second element can also be transmitted to the first element, corrected for phaseshift in the same way, and correlated in real time.

Thus, coherence times of $\sim$ 1 sec will suffice; the quartz oscillators previously noted will permit rms phase errors of $< 10^{-2}$ rad per GHz. Moreover, orbit determination or on-board ranging can insure knowledge of the separation to a fraction of a kilometer, for the time delay needed for synchronization of the IF signals in processing. This approach offers solutions to the problems of synchronization, phase stability, and signal processing.

System Growth

An orbital VLBI system could be built in stages, to match the available budget and to support a phased experiment program.

First, a single antenna would be orbited. It would be a major radio telescope in its own right, providing experience in space operations of such a structure. It could also serve as one element of an interferometer, the other element being Earth-based, thus meeting the 1970 recommendation of the Space Science Board for use of a satellite for VLBI.[9] This would permit precision orbit determination, for geophysical and geodetic applications.

Next, the second antenna would be orbited, completing the basic system, which would be used in source mapping at extreme resolution. However, it probably would have limited usefulness for astrometry or source position determination. These latter applications require precision determination of the phase of the interference pattern, a quantity difficult to measure directly. But it can be measured, using a second antenna at each interferometer element, to observe a bright source (such as quasar 3C 273) as a phase reference.

Thus, the next stage in system growth would add another antenna at each element, with the element LO generator serving both antennas. Precision astrometry could then be conducted, as well as tests of general relativity involving gravitational bending of electromagnetic waves.

Finally, even higher resolution might be required. This could be achieved by improvements in paraboloidal surface shaping, permitting operation at shorter wavelengths, or by using higher orbits for longer baselines. With $\lambda = 1$ cm in geosynchronous orbit, resolution exceeds 10^{-5} arcsec, still limited by diffraction and not by interplanetary scintillations.[10]

Conclusions

A system such as the one described would offer many advantages. As a dedicated system, it would supplant present-day ad hoc VLBI experiments. As a space-based system, it would permit complete aperture synthesis by two elements, avoiding the administrative difficulties of many antennas in different nations, as required by an Earth-based dedicated system. Real-time signal processing would simplify experiments and permit adaptive use. State-of-the-art technology in structures and electronics would keep costs down, and the system could be built up in phases matched to science budgets and experiment programs.

References

[1] Kellerman, K. I., "Intercontinental Radio Astronomy," *Scientific American*, Vol. 226, No. 2, Feb. 1972, pp. 72–83.

[2] Counselman, C. C., "Very-Long-Baseline Interferometry Techniques Applied to Problems of Geodesy, Geophysics, Planetary Science, Astronomy, and General Relativity," *IEEE Proceedings*, Vol. 61, No. 9, Sept. 1973, pp. 1212–1225.

[3] French, F. W., Rodman, A. K., and Huguenin, G. R., "A Synthetic Aperture Approach to Space-Based Radio Telescopes," *Journal of Spacecraft and Rockets*, Vol. 4, No. 12, Dec. 1967, pp. 1649–1656.

[4] Elgaroy, O., Morris, D., and Rowson, B., "A Radio Interferometer for Use with Very Long Baselines," *Monthly Notices of the Royal Astronomical Society*, Vol. 124, No. 5, 1962, pp. 395–403.

[5] "Space Shuttle System Summary," SSV73-45(R), July 1973, Rockwell International Space Division, Downey, Calif.

[6] "Space Erectable Large Aperture Reflectors," LMSC-A946613, March 16, 1969, Lockheed Missiles and Space Co., Sunnyvale, Calif.

[7] Hamilton, E. C. and Fager, J. A., "Large Erectable Antenna for Space Application," NASA-CR-102522, Sept. 30, 1969, General Dynamics—Convair Aerospace Div., San Diego, Calif.

[8] Ehrlich, E., "The Role of Time-Frequency in Satellite Position Determination Systems," *IEEE Proceedings*, Vol. 60, No. 5, May 1972, pp. 564–571.

[9] "Priorities in Space Science and Earth Observations," 1970, U.S. Space Science Board, NASA.

[10] Hilgeman, T., Favale, A., and Savet, P., "Introduction to LORI, Grumman's Long-Baseline Orbiting Radio Interferometer," RM-547, July 1972, Grumman Aerospace Co., Bethpage, N.Y.

Comet Encke Flyby—Asteroid Rendezvous Mission

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Introduction

THE scientific interest in comet and asteroid missions has been growing steadily over the past several years. This is due, in large part, to the activities of the NASA-sponsored science working groups and study panels.[1–3] The discovery this year of comet Kohoutek and the flurry of activity focused on observing this comet has certainly raised the level of interest. A final factor is the advent of advanced propulsion technology, particularly solar electric propulsion (SEP), which will make possible future rendezvous, docking, and even sample-return missions to small-body targets.

The current consensus among scientists and mission planners is that comet Encke will be the primary target of early cometary exploration in the 1980 decade.[4] A two-mission sequence is planned which encompasses a flyby of Encke at its 1980 apparition (perihelion passage) to be followed by a rendezvous in 1984. Several preliminary design studies of the flyby mission are now underway. These studies are expected to provide the necessary tradeoff data from which NASA can make a more definitive selection of mission/spacecraft mode and science payload, should the flight project be approved. The three principal mission modes under consideration are: 1) a short (90 day) ballistic transfer utilizing a modified Helios spacecraft with encounter near Encke's perihelion at a flyby speed of 7–9 km/sec; 2) a short ballistic transfer utilizing a modified Pioneer-Venus spacecraft with encounter 16–26 days before perihelion at a flyby speed of 18–26 km/sec, and possibly retargeted after Encke encounter to flyby the asteroid Geographos; and 3) a long (650 days) low-thrust transfer utilizing a 10–15 kw SEP spacecraft with encounter 20–30 days before perihelion at a slow flyby speed of 4–5 km/sec and possibly pretargeted to flyby an asteroid prior to Encke encounter.

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