MICROWAVE TECHNOLOGY INNOVATIONS IN ORBITING VLBI

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Abstract—The radio astronomical technique of very long baseline interferometry (VLBI) will soon be extended beyond the earth's surface by placing antennas and receiving systems in high earth orbit. Two such orbiting VLBI telescopes are expected to be in operation by 1995. The technical challenges of these projects have produced several interesting innovations in the microwave area, including designs of large, deployable antennas; designs of multifrequency feed systems; cryogenic low noise amplifiers; and methods of precise time synchronization with ground telescopes.

1 Introduction

Very long baseline interferometry (VLBI) is the radio astronomical technique in which a set of widely separated antennas forms an array of interferometers without any real-time connections among them. The antennas can then be located anywhere on the earth. The technique relies on having an ultra-stable oscillator (typically a hydrogen maser) at each station to ensure time synchronization, and on very high speed tape recording of the received (noise-like) signals to allow post-facto correlation (for a tutorial review, see [1]). Since the angular resolution of interferometers is inversely proportional to the antenna spacing, large spacings allow study of the finest details of radio sources. The largest spacings possible on the earth have now been achieved, and yet interesting features of some objects remain unresolved. There is thus considerable interest in extending the technique by placing one or more large antennas and appropriate receiving systems in earth orbit. Two such orbiting radio telescopes are scheduled to be launched in late 1994 and early 1995, one by Russia (called "Radioastron") and one by Japan (called "VSOP"). Various other countries are cooperating in these projects.

The fine details of radio source structure are often rather weak, so the largest possible gain-to-noise ratio (G/T) is needed. On the earth, reflector antennas of diameter 25 m to 100 m are usually used along with cryogenically cooled receivers achieving noise temperatures less than $(2\,\mathrm{K/GHz})f$ at frequency f. Frequencies of interest range from about 70 MHz to perhaps 280 GHz, and they include certain special frequencies where interstellar masers produce strong line emission on very small angular scales (e.g., OH near 1.67 GHz and H_2O near 22.2 GHz).

Orbiting VLBI presents many technical challenges, including several in the microwave area that form the subjects of this paper.

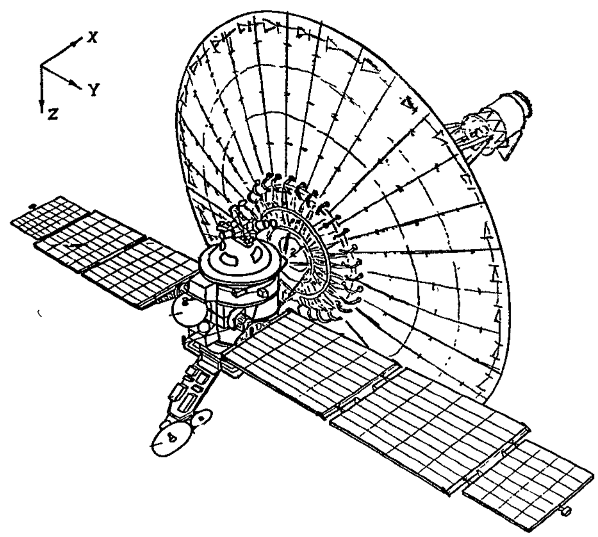

Figure 1: Radioastron satellite, deployed configuration

2 Deployable Reflector Antennas

An obvious challenge is the development of large but accurate deployable antennas. In space, it is at present not possible to duplicate the performance of state-of-the-art ground radio telescopes. For one thing, deployment of a 25-m diameter or larger reflector would be prohibitively expensive. Radioastron and VSOP will each deploy a reflector of about 10 m diameter, but their designs are very different. Radioastron will use a fixed central mirror of 3 m diameter surrounded by 27 foldable panels of 3.5 m radius (Fig. 1). VSOP will use a fabric-like mesh surface which is held in place by a tension truss of wires supported by six radially-telescoping tubes [2,3]. Each is expected to achieve a surface accuracy near 0.5 mm rms, allowing efficient operation up to the H_2O line frequency of 22.2 GHz.

To the author's knowledge, the VSOP design is unique. Some details are shown in Fig. 2. A stable parabolic surface is formed by a system of fine- and coarse-adjustment cables made of Kevlar and Cornex, with their cross-

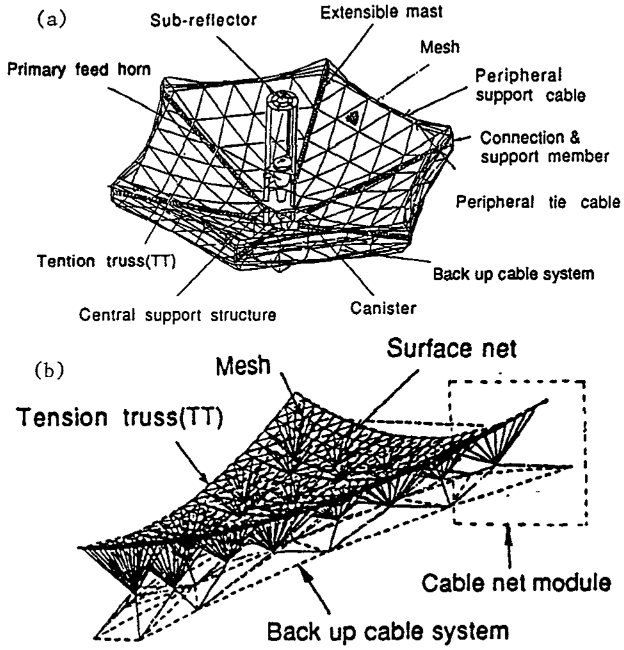

Figure 2: VSOP satellite: (a) general view, deployed; (b) 1/6 sector of cable mesh assembly. From [4].

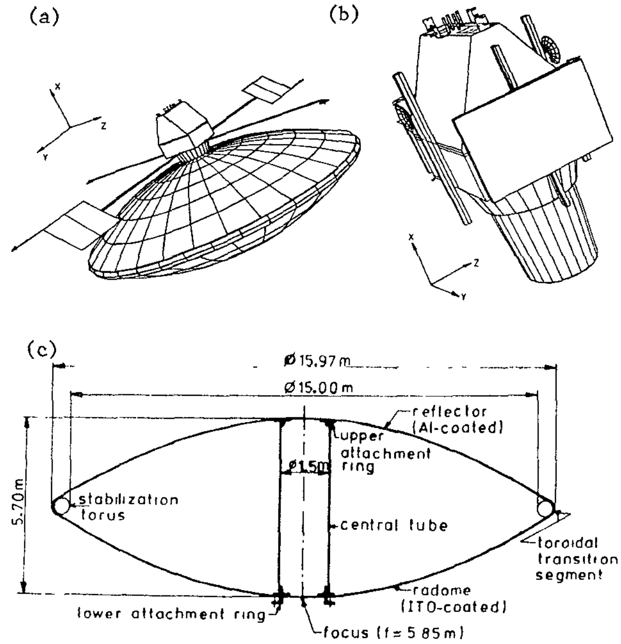

Figure 3: Quasat satellite: (a) deployed configuration; (b) launch configuration; (c) cross section of antenna structure. From [5].

sections chosen to produce the required stiffness. There are about 2500 cables in total. All of them are held in tension by six masts that extend during deployment, producing a statically determinate structure. Studies [3] have shown that the effects of the orbital environment on the materials, of deformations during stowage and deployment, of adjustment errors, and of thermal deformation will all be within the 0.5 mm rms tolerance.

Still another technique for placing a large antenna in space was studied for the Quasat project, which was a proposed VLBI satellite that did not receive funding beyond a Phase A study [4]. In this case, a design was developed for a 15 m diameter reflector using a thin, flexible membrane that could be folded into a small container during launch and inflated once in space, forming a lens-shaped closed surface that is metalized on one side to form a parabolic mirror and is dielectric on the other side to form a radome. With sun-induced heating, the special material involved becomes rigid after deployment. Based on scale-model studies, a surface error of 0.8 mm rms was predicted (Fig. 3).

A preliminary design has also been developed for a much larger and more accurate deployable reflector. A proposed future orbiting VLBI satellite called "IVS" [5] would use a 20- to 25-m diameter reflector consisting of solid panels similar to Radioastron's. A surface accuracy of 0.3 mm rms would feasible, supporting observations at frequencies approaching 100 GHz. Such specifications are not achievable in the mesh-surface or inflatable technologies. This satellite would be large and massive, and would require the world's largest rocket (the Russian "Energia") to put it into a useful orbit.

3 Feeds

Another challenge involves the design of feeds for these deployable reflectors. Observations are needed over a wide range of frequencies, and the space installation requires that any band switching involve no mechanical motion. For compatibility with ground telescopes, circular polarization of high accuracy is desired.

An especially novel design has been developed for Radioastron [6,7]. It allows efficient illumination from the prime focus in four bands centered at 0.33, 1.6, 5.0, and 22 GHz in such a way that all feeds are concentric and connected to separate receivers. Both circular polarizations are supported.

For each band, the radiator consists of a circular ring two wavelengths in circumference connected to two coaxial ports via a directional coupler, as illustrated in Fig. 4. Signals at the ports correspond to traveling waves on the ring in opposite directions, and these couple to radiation in each sense of circular polarization. A half-power beamwidth of about 65 deg is obtained, suitable for prime-focus illumination of a parabolic reflector. Because of the empty space inside the ring, an additional feed for a higher frequency can be installed there with only small interaction between it and the first feed. The Radioastron design uses three such concentric rings to cover the 0.33, 1.6, and 5.0 GHz

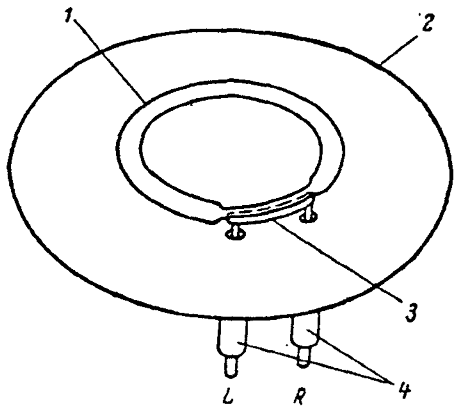

Figure 4: One element of the Radioastron ring feed. 1=ring resonator, 2=ground plane, 3=coupler, 4=coaxial ports. From [6].

bands, along with a conventional conical horn for the 22 GHz band that fits inside the innermost ring.

4 Receivers

The design of state-of-the-art low noise receivers for use in space is also interesting. Through at least 50 GHz, the best noise temperatures are provided by HFET amplifiers operated at cryogenic temperatures as low as 15 K [8]. Due to weight and power constraints, the presently planned VLBI satellites will cool their amplifiers only to about 80 K. Efficient thermal design is important, and the effects of radiation (high electron and proton flux) on the HFET devices is of some concern [9].

VSOP will have single-channel receivers at 1.6, 5.0 and 22.3 GHz, although only the 22.3 GHz amplifier will be cooled. Radioastron will have two-channel receivers (both circular polarizations) at the four bands mentioned earlier. The six amplifiers for the three higher bands will be cooled to 80 K, with one pair being usable at a time.

The microwave low-noise amplifiers are under development in Finland (22.3 GHz), Germany (5 GHz), and Australia (1.6 GHz) for Radioastron and in Japan for VSOP. Although cryogenically cooled HFET amplifiers are in wide use on ground radio telescopes, it is believed that these are the first such amplifiers to undergo full space qualification.

5 Time Synchronization

Finally, a major difficulty in orbiting VLBI is the need to synchronize the timing of local oscillators on the satellite with those in ground radio telescopes. It is at present not practical to include ultra-stable oscillators on the satellite, and so both Radioastron and VSOP will rely on the uplinking of a timing reference from an earth station. It is very difficult to do this with the desired precision, typically several psec (0.5 radian at 22 GHz), considering that the satellite is moving rapidly in an imperfectly-known orbit, and furthermore that the signal must pass through the turbulent troposphere and ionosphere. The techniques that have been worked out to accomplish this make no attempt to achieve absolute synchronization to better than several μs; for this we will rely on post-facto astronomical calibration. Instead the objective is to achieve high stability of the timing over time scales from milliseconds (the on-board phase locked loop time constant) to hours (the duration of contact with a single earth station). This requires a two-way link so that propagation effects can be measured and corrected on the assumption of reciprocity, along with calculated adjustments for known non-reciprocal effects.

A simplified block diagram of the signal processing involved is shown in Fig. 5. Generally, the astronomical signal is converted to baseband and digitized on the satellite; ultimately, this digitized signal will be cross-correlated with similar signals from ground radio telescopes. It is necessary to know the time at which each sample was taken to a small fraction of the reciprocal bandwidth, and also to know the net phase of local oscillators used in the frequency conversion to a small fraction of a cycle. However, absolute knowledge of these quantities is not needed if they are sufficiently stable, since the offsets can be determined by a signal-searching process during correlation. To obtain the high stability, a two-way microwave link is established. An uplink timing reference signal is used to synthesize all signals on the satellite, including a similar timing signal that is returned on a downlink. The earth station measures the two-way delay to psec precision, corrects for its own motion during the two-way time, and assumes that half of the result is the uplink time. This establishes the time on the satellite relative to a stable clock at the earth station. The two-way delay measurements are recorded as a time series, forming a continuous record of the effects of satellite motion and of the propagation medium. From this a correction is derived to the "time" of each data sample recorded by counting simply counting them.

There are two major problems with this procedure: (1) the assumption of reciprocity may be violated, especially if the uplink and downlink carrier frequencies are different, due to such effects as multipath and ionospheric dispersion; and (2) unless the link signals are quite complicated, the measured time is highly ambiguous (e.g., simple sinusoids have an ambiguity of one cycle). In practice, nonreciprocal effects must be minimized by design, including the choice of high and close frequencies for the links. Effects of the ionosphere can be corrected to first order if a separate measurement of the total electron content along the link path is available. The ambiguity in time can be acceptable if it results in an error that remains constant over the contact time (hours); this is possible if continuous contact can be maintained at sufficiently high signal-to-noise ratio (no dropouts). For a more detailed discussion, see [10].

Radioastron and VSOP will each use simple timing links with quasi-sinusoidal signals in each direction. The fre-

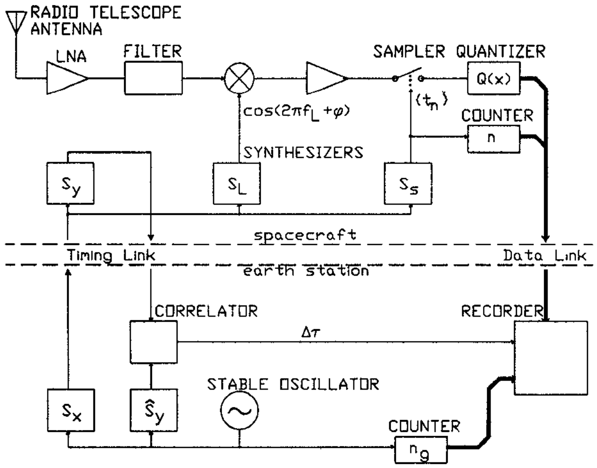

Figure 5: Simplified block diagram of orbiting VLBI signal processing, showing the separate functions of the satellite and earth station, including the two-way timing link. From [10].

quencies selected for the up- and downlinks are respectively 7.2 and 8.47 GHz for Radioastron and 15.3 and 14.2 GHz for VSOP. (For VSOP, the 14.2 GHz carrier will be modulated with the digitized astronomical signal, so the timing downlink involves extraction of the carrier at the earth station. For Radioastron, the data is transmitted separately at 15 GHz.) In order to minimize the size of the timing corrections required, the earth stations now being designed for these missions will continuously adjust the phase of the uplink signal so as to compensate for the satellite's motion; in this way, the signal phase received at the satellite will be nearly constant at the nominal frequency. This compensation cannot be perfect, however, because the orbit is not expected to be known in real time to better than about 1000 m in position and 10–100 cm/sec in velocity.

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