(D) RADIO MISSIONS

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INTERNATIONAL VLBI SATELLITE (IVS)

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Abstract. IVS is under study in ESA as a second generation space VLBI observatory. The mission concept calls for a 25 m diameter radio telescope in space funded by the principal space agencies. Orbiting the Earth and observing in concert with the established ground-based VLBI arrays in Europe, USA, USSR and Australia, IVS will provide high quality images of galactic and extragalactic radio sources at wavelengths spanning the radio band from decimetres to millimetres with resolution as high as 10 micro arcseconds and sensitivity equal to those of ground-based images. New features of IVS compared to the first generation missions are: a more than order of magnitude increase in sensitivity; an order of magnitude increase in maximum angular resolution; extension of the wavelength range to the millimetre band; and the capability to operate as a stand-alone radio telescope enabling it to explore new frontiers in spectral line and microwave background research, in particular the distribution of galactic molecular oxygen and Compton scattering of the microwave background by foreground cluster gas.

1. Introduction

Radio interferometry plays a central role in high resolution imaging astronomy; instruments like the VLA and MERLIN have, for the last decade, provided images of a wide variety of cosmic objects from stars to quasars with the same detail as can be expected from the Hubble Space Telescope. But it is the Very-Long-Baseline Interferometry (VLBI) networks of telescopes spanning the globe which mark the greatest advance in angular resolution. Current global arrays with up to 18 elements and effective diameters of some 8000 km reach sub-milliarcsecond angular resolution and represent the largest telescopes which have ever probed the depths of the universe. Accompanying this advance has been an increase in the quality of the images, as characterised by their dynamic range, the ratio of the brightest to the faintest reliable features. This increase has come as a result of better aperture plane (or *uv* plane) coverage and improved image construction algorithms.

VLBI observations at high resolution have produced many important discoveries, including apparent superluminal velocities in quasars and radio galaxies, and highly collimated plasma jets in radio galaxies on scales of less than one parsec which are the bases of jets extending to several million parsecs. As the body of discoveries from VLBI has grown, it has become clear that in nearly every compact source observed at cm and mm wavelengths, there remains spatial structure which is unresolved with the best angular resolution achievable with antennas on Earth. To explore these structures in detail, substantially higher resolution, high quality images are essential. This can only be achieved through even longer baselines, which requires one or more interferometer elements in orbit observing in conjunction with Earth-based arrays.

Y. Kondo (ed.), Observatories in Earth Orbit and Beyond, 255–262.

TABLE I
IVS Design Goals

Telescope
diameter: 25 m
operating frequencies: 4.5–90 (220) GHz
symmetric Cassegrain design, focal ratio: 0.4
antenna efficiency (25 m): 0.5 at 43 GHz
surface error (25 m): ≤0.3 mm

Science instrument
set of super-heterodyne, dual-polarisation receivers, feeds, and coolers for:

frequency range (GHz)	amplifier	physical temp. (K)
4.5–8.5	HEMT	20
15–23	HEMT	20
42–60	HEMT	20
86–90	HEMT	20
(218–220	SIS	5)

stable total-power detectors
spectrometers (AOS or digital) for 42–60 GHz
2-way Ku-band phase transfer link
Ku-band science data downlink at 512 Mbits/s **Orbits**

It is proposed that IVS occupy three orbits during its lifetime:

Orbit 1: high inclination (~ 60°), apogee altitude ~ 20000 km, perigee altitude ~ 5000 km. This will allow images of unprecedented quality to be made with angular resolution 3 times greater than with Earth baselines alone (eg. 50 μas at 43 GHz).

Orbit 2: the apogee altitude is doubled to 40000 km to increase the angular resolution by a further factor of two (eg 25 μas at 43 GHz) while still providing good quality images. This orbit is the highest for which good quality imaging is possible with only one element of the VLBI array in space.

Orbit 3: the apogee altitude of IVS will be raised to at least 150000 km and perhaps considerably higher (depending on the constraints placed on the spacecraft design) in order to search for ultra-compact radio sources. The angular resolution in this orbit is, for example, $<3\mu$as at 90 GHz. Simple structural information (angular size, orientation, and strength) could be determined with such an orbit.

Lifetime
≥ 3 years operations, ≥ 6 years consumables

A successful proof-of-concept of orbiting VLBI was carried out by a JPL-led international team in the period 1986–1988 using the 4.9 m antenna on the US Tracking and Data Relay Satellite (TDRS) with antennas in Australia and Japan (see R. P. Linfield, these Proceedings). This put the technical feasibility of orbiting VLBI beyond doubt, and demonstated clearly that many radio sources possess structure on interferometer baselines as long as 2 Earth diameters at frequencies of 2.3 and 15.0 GHz.

Two first-generation orbiting VLBI missions have been approved for launch in the 1993–5 period: RADIOASTRON (USSR) and VSOP (Japan), both carrying 10 m diameter antennas. RADIOASTRON (N. S. Kardashev, these Proceedings) will be launched into a highly eccentric orbit with an apogee altitude of at least 75000 km, VSOP (H. Hirabayashi, these Proceedings) into a lower orbit with apogee altitude 20000 km.

A new mission, International VLBI Satellite (IVS), is currently undergoing an Assessment Study in ESA supported by the Soviet Academy of Sciences and NASA/JPL. It is a second-generation mission carrying a 25 m diameter antenna and capable of more than an order of magnitude improvement in sensitivity and angular resolution over the two earlier missions (and more than 200 in sensitivity compared to TDRSS). It is well-matched to the ground VLBI arrays in both sensitivity and wavelength coverage.

2. Mission Description

IVS mission is intended to be a major radio telescope orbiting the Earth. In VLBI mode it will observe together with the ground-based VLBI arrays in Europe, USA, USSR, and Australia (see Figure 1). IVS will also operate as a stand-alone antenna enabling it to explore new frontiers in spectral line and microwave background research. Table I summarises the design goals.

Compared to its precursor VLBI missions, RADIOASTRON and VSOP, IVS will have:

- 20 times greater sensitivity (larger collecting area reflector, wider data downlink bandwidth, decreased receiver temperatures, and ability to increase the integration time by phase referencing),
- 10 times greater maximum angular resolution,
- higher observing frequencies and,
- accurate orbit determination, allowing phase referencing and astrometric observations to be done.

The mission will provide a space-based VLBI element equivalent in sensitivity and frequency range to an element in one of the modern generation of ground-based synthesis arrays (eg the VLBA, the US dedicated VLBI array). At its most sensitive, IVS will reliably detect a 1 mJy radio source in 5^m integration time, and 80 μJy if phase referencing allows a 12^h integration time.

IVS will also be a major advance as a single-dish spectroscopy instrument for O_2 in the 48-60 GHz band. Its sensitivity for extended sources of O_2 will exceed

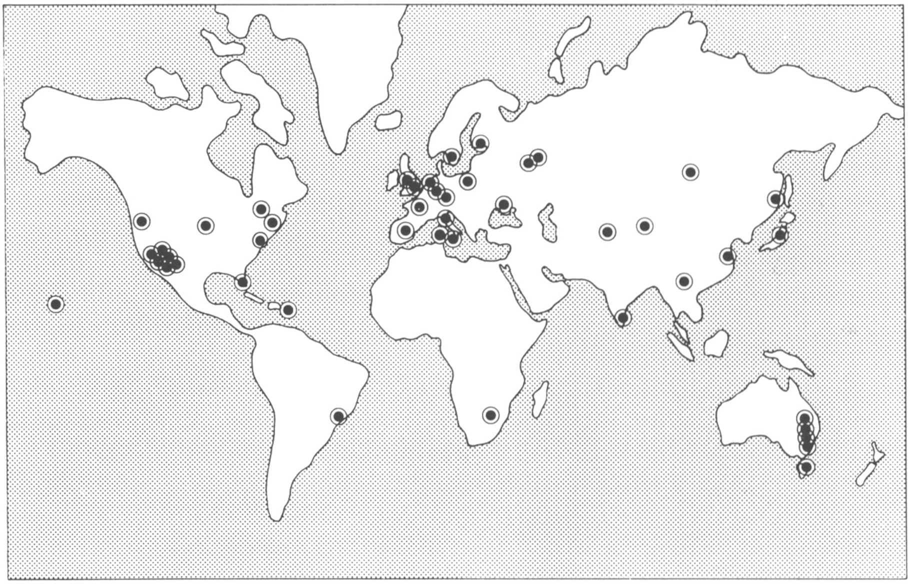

Fig. 1. The global net of VLBI antennas. Forty-four major VLBI stations expected to be operational by 1995. The radio telescopes are located in Australia, Brazil, Canada, China, England, Finland, France, W-Germany, Italy, Japan, the Netherlands, Poland, South Africa, Spain, Sweden, USA and USSR.

that of FIRST, LDR and SWAS (observing at 425 GHz or 487 GHz) by at least an order of magnitude. For point source detection of O_2, IVS will be comparable in sensitivity to the 8 m FIRST.

3. IVS Science

The angular resolution and greatly increased sensitivity of IVS combined with its imaging capability will open up exciting new opportunities in cosmology as well as galactic and extragalactic astronomy, including:

– the mechanisms of relativistic energy generation, transport, collimation, and dissipation in the nuclei of radiogalaxies and quasars (see Figure 2), an independent determination of the cosmic distance scale using H_20 masers (see Figure 3), and the radio emission mechanisms in stellar objects in the galaxy. For most of these studies, an imaging capability is essential.

– On these small scales, changes in radio structure are to be expected in response to surges in the energy release processes, proper motion of the emitting regions at relativistic speeds along jets, and evolution of the emitting regions themselves. Tracing these changes in both galactic and extragalactic sources through repeated multi-frequency imaging in total intensity and polarisation will be one of the pri-

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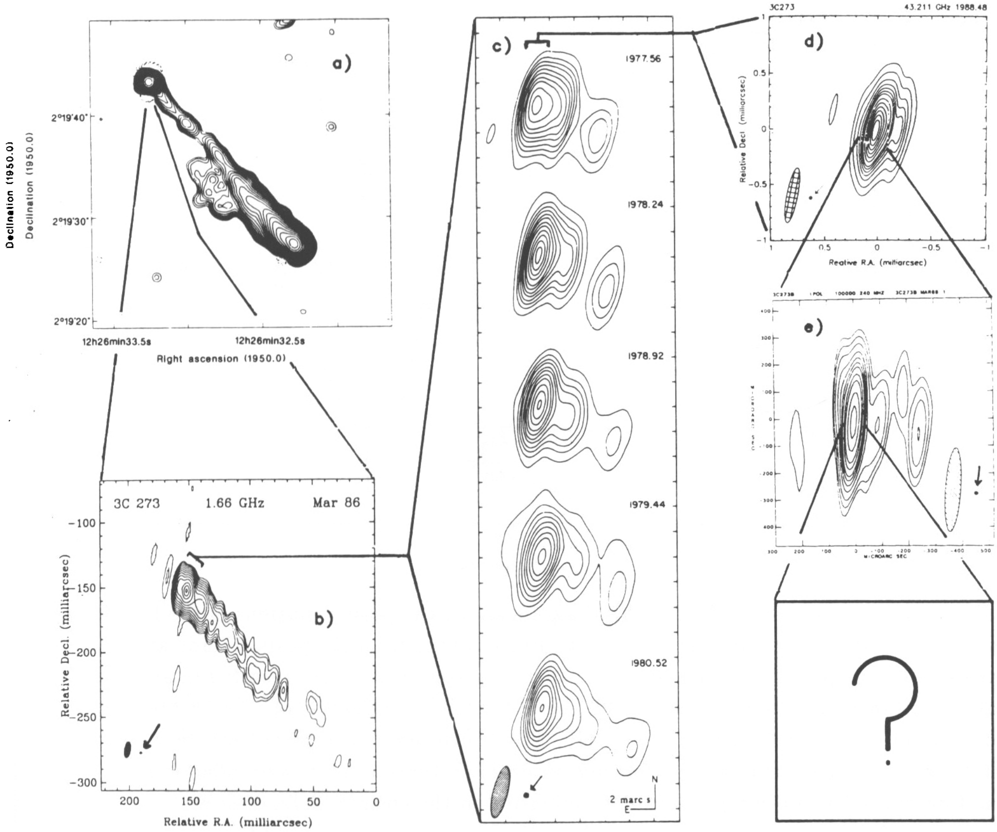

Fig. 2. 3C273, the "classical" quasar. 3C273, imaged at different angular resolutions from 408 MHz to 100 GHz. (a) MERLIN at 408 MHz showing the core (to the NE) and the 21 arcsec long jet which coincides with the optical jet. (b) VLBI at 1.66 GHz on a scale 250 times smaller than panel 'a'. (c) a series of VLBI images at 5 GHz on a scale a further factor of 4 smaller than panel 'b'. The changes in angular position of some of the features over the course of several years imply linear velocities in the plane of the sky well in excess of the speed of light. This "superluminal" motion is usually interpreted in terms of relativistic bulk motion close to the line of sight towards the observer. (d) the first image obtained of 3C273 at 43 GHz on a scale 10 times smaller than panel 'c'. (e) the first image at 100 GHz showing that the "core" at 43 GHz is in fact composed of a number of features. In panels b to e, the synthesised beam of the ground VLBI network used to produce the image is shown together with the IVS beam (indicated by an arrow) at the same frequency. **References**: (a) Davis et al. 1985 Nature, 318,343; (b) Unwin and Davis 1988 Proc. IAU 129, 27; (c) Pearson et al 1981 Nature 290, 365,; (d) Krichbaum et al, submitted; (e) Baath et al, submitted.

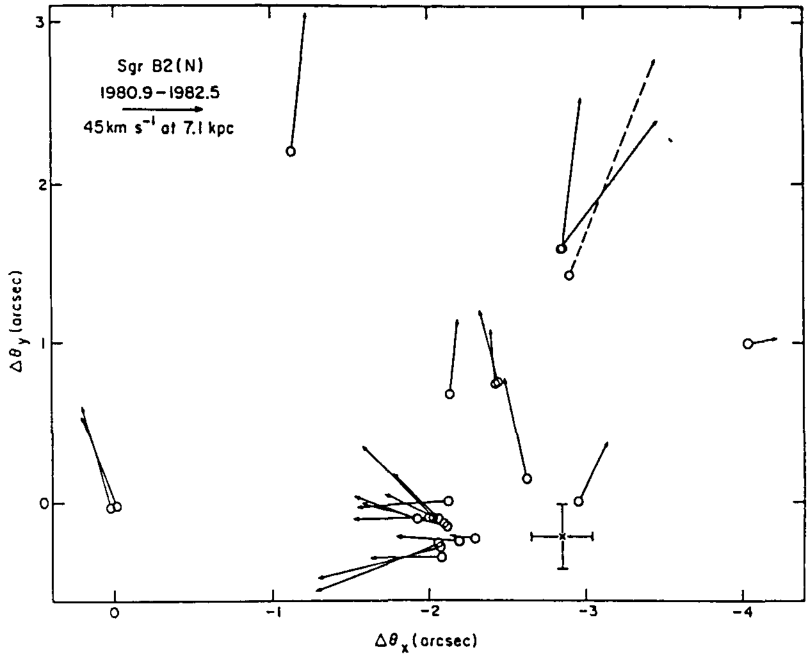

Fig. 3. Sgr B2(N) 1980.9-1982.5. This diagram shows the proper motions of the H_2O maser spots. The maser spots appear to be expanding outward from the position indicated by the cross. A least squares fit of a uniformly expanding spherical source resulted in an estimate of the distance to the source (within 0.3 kpc to the Galactic Center) of 7.1 ± 1.5 kpc. (Figure from Reid et al.: 1988, Astrophys. J. 330, 809). Such maser complexes will be observable in nearby galaxies. Measurement of their internal motions and/or their galactic rotational motion will allow an independent determination of the cosmic distance scale.

mary tasks of IVS. This should provide unique information on the structure, the kinematics, the magnetic field, and the thermal electron distribution in a wide variety of astrophysically important objects on linear scales of great interest. Many of the changes have timescales of several years, and therefore an operational lifetime of at least three years (with consumables for six or more years) is essential in order for the scientific potential of IVS is to be fully realised.

– One of the most important goals for the 48–60 GHz receiver on IVS is the search for interstellar molecular O_2 which is impossible to carry out from the ground due to atmospheric shielding. Oxygen is more abundant in the universe than all the other heavy elements combined. The evolution of initially diffuse cold interstellar gas to the point of star formation is controlled by the conversion of atomic oxygen into molecular compounds. IVS will be used to measure the distribution and excitation of molecular oxygen (O_2) in interstellar clouds. The transitions which occur near 60 GHz are ideal for this investigation because they sample every N quantum level in the rotational ladder of O_2 (see Figure 4), thus yielding unambiguous information

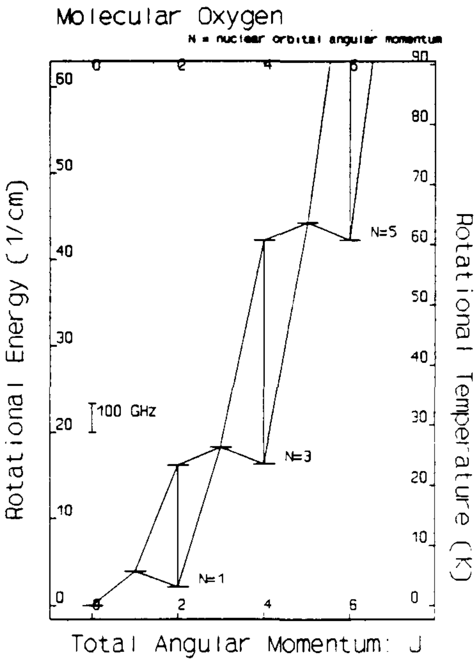

Fig. 4. Rotational energy level diagram of O_2.

on the excitation of the molecule. The lowest transitions, like transitions of CO, are expected to be detectable in most of the molecular clouds of the Galaxy.

– Compton scattering of the Cosmic Background Radiation (CBR) by hot gas associated with galaxy clusters distorts the spectrum of the CBR. This so-called Sunyaev-Zel'dovich effect has been detected at 20 GHz towards three clusters from the ground. However the sensitivity of ground-based observations of this effect is limited primarily by atmospheric noise. IVS with stable sensitive receivers will be a powerful instrument for measurement of the microwave decrement, allowing observations of many clusters in a modest amount of time. Combined with X-ray data, such observations provide an independent measurement of H_0, and the radial velocities of clusters with respect to the CBR.

4. IVS Payload

IVS will be a radio telescope in space that with many of the features and most of the flexibility of a ground-based radio observatory. It will be capable of making almost any observation that is possible from the ground, but its position in space will be exploited to make observations that are not possible from the surface of the Earth. Since IVS functions like a typical ground-based radio observatory, and also has many similarities with a communications satellite, the science payload is conceptually straightforward and the technology is largely in hand.

The payload is to consist of a 25 m diameter microwave antenna, a dual polarisation 4(5)-band receiver at the feed point consisting of low-noise amplifiers and phase stable frequency down converters to produce IF signals, data digitisation equipment for the VLBI observations and the equipment associated with the 48–60 GHz single-dish operation. Stable total power detectors are necessary for observations of the microwave decrement at $\nu \geq 22$ GHz.

The main element of the IVS payload is the 25 m diameter reflector which should be capable of operating fully illuminated with good efficiency at 43 GHz. The Dornier inclined panel concept developed for FIRST is being investigated for IVS. This a solid-panel flower petal arrangement, deployable in space with, for IVS, a 5 m central section and 10 m long petals. The performance at shorter mm wavelengths will also be investigated. Such an antenna will require a large volume fairing such is provided by the payload container attached to the Energia booster (see Section 5).

The receivers are super-heterodynes that select, translate in frequency, digitise, format and relay the astronomical signals to the ground. The signals received on the ground can either be processed immediately in a digital spectrometer, for stand-alone measurements, or recorded on magnetic tape for subsequent processing at a VLBI processing centre. A possibility for stand-alone observations would be to have an on-board spectrometer and memory so that observations could be made with bandwidth wider than that of the link, or when out of view of a ground station.

In its VLBI observational mode, IVS will have the capacity to operate simultaneously any four receivers and relay the received signals via a digital link directly to the telemetry stations on the ground. Typically, simultaneous observations would be conducted in two frequency bands in both hands of circular polarisation.

5. International Collaboration on IVS

The model assumed for the Assessment study is as follows:

– ESA payload module and critical sub-systems including antenna, attitude and orbit control, and link equipment – ESA or NASA DSN data downlink reception and phase link – ESA Science Operations Centre – Soviet service module (standard space platform) – Soviet launch (Energia) – Soviet flight operations control – National agencies for the scientific instrument (e.g. receivers) – National agencies for VLBI data reduction facilities