GLONASS and Radio Astronomy

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1. Introduction

Like many radio astronomers of my generation, I became involved in frequency protection because of GLONASS. I had begun studying OH masers in 1981. It was a very exciting time in maser research. The MERLIN interferometer at Jodrell Bank had just made the first maps of OH maser shells around OH-IR sources (Booth et al. 1981). The OH 1612-MHz maser is one of the few tools we have for studying these pulsating red giants, which are hidden from optical telescopes by the thick envelopes of gas and dust that they shed. Just one year later the Soviet Union launched the first satellites of their Global Navigation Satellite System GLONASS. The GLONASS satellites transmit one of their main navigational signals in a frequency band that directly overlaps the OH 1612-MHz rest frequency. As interest in OH-IR sources increased, so too did the number of GLONASS satellites, and so did the levels of interference to radio astronomy at 1612 MHz. By 1985 the interference had become a severe problem at radio observatories around the world, and the source of the interference had been clearly identified (Pankonin et al. 1985). A whole branch of radio astronomy was under threat (Cohen 2000).

My own research had moved on to OH megamasers. We were using a wideband acousto-optical spectrometer to search for the redshifted OH lines. The moment we took our first spectra with AOS we saw GLONASS (Figure 1). Compared with OH megamasers, the GLONASS signal was gigantic! Yet GLONASS was a military secret, and it was many years before IUCAF was able to establish a dialogue with its operators (Robinson 1999). Table 1 summarises some of the historical developments.

Table 1. Historical Landmarks

1968	Discovery of OH-IR sources (Wilson & Barrett 1968)
1979	OH 1612-MHz line given secondary allocation at WARC-79
1982	First GLONASS satellite launched (military); First OH megamaser discovered (Baan *et al.* 1982)
1983	Coordination of GLONASS begins
1985	Interference identified (Pankonin *et al.* 1985); IRAS catalogue published, with ~10^4 OH-IR candidates
1991	First IUCAF-GLONASS meeting
1992	Worldwide experiment to test possible solutions; Radio astronomy band made primary at WRC-92
1993	ITU-R WP7D reviews the joint experiment; GLONASS-IUCAF Agreement signed in Moscow
2006	Projected completion of clean-up plan

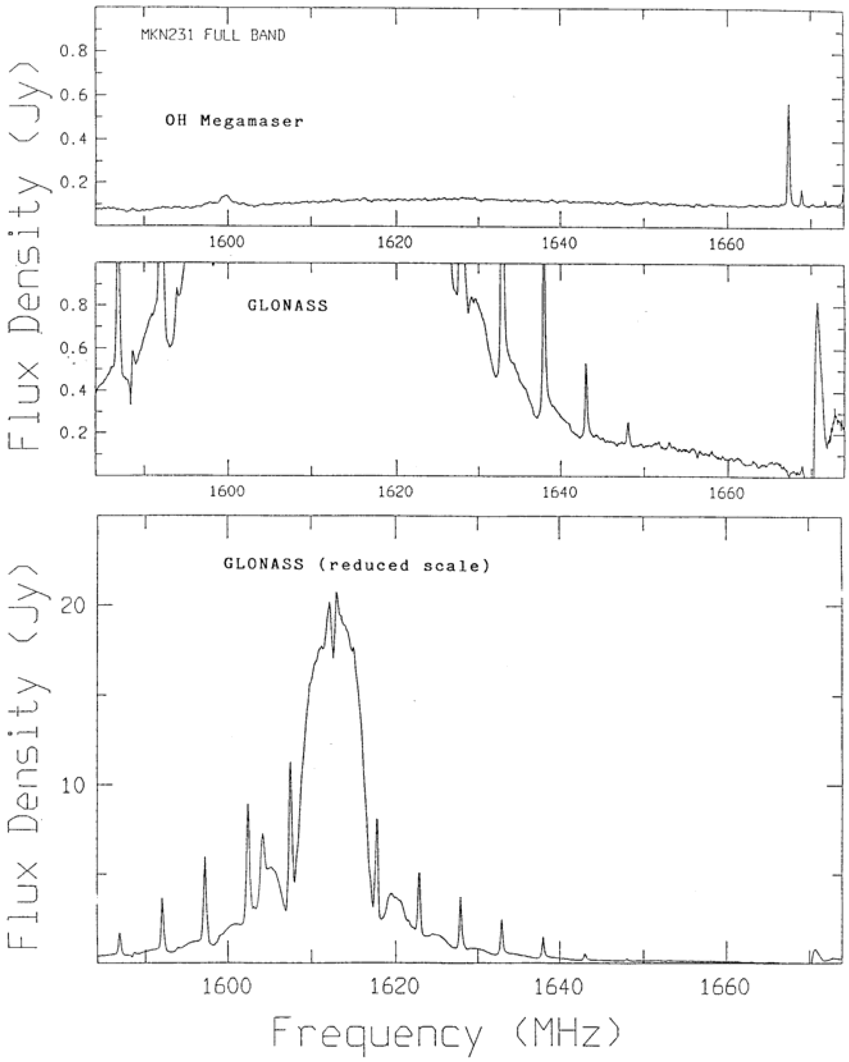

Fig. 1. Example of GLONASS interference in comparison with the OH megamaser emission from Markarian 231 at ~1600 MHz. The upper panel shows a GLONASS–free spectrum. The centre panel shows a spectrum with GLONASS interference plotted on the same scale, while the lower panel shows the same data plotted on a reduced scale. The spectra were taken at Jodrell Bank in 1986, with the 76-m Lovell Telescope and an acousto-optical spectrometer.

2. The GLONASS system

GLONASS employs a constellation of satellites in three orbital planes, with 8 orbital positions per plane. The orbital period is 11.294 hours, so that each satellite completes exactly two and one eight orbits per day. One of the main navigational signals is transmitted at one of 25 possible centre frequencies, given by ν = 1602.0000 + 0.5625 n MHz, where the channel number n ranges from 1 to 24, with channel 0 reserved for engineering tests. Channels 16-21 fall directly in the radio astronomy band 1610.6-1613.8 MHz, which is used to observe the OH 1612-MHz line.

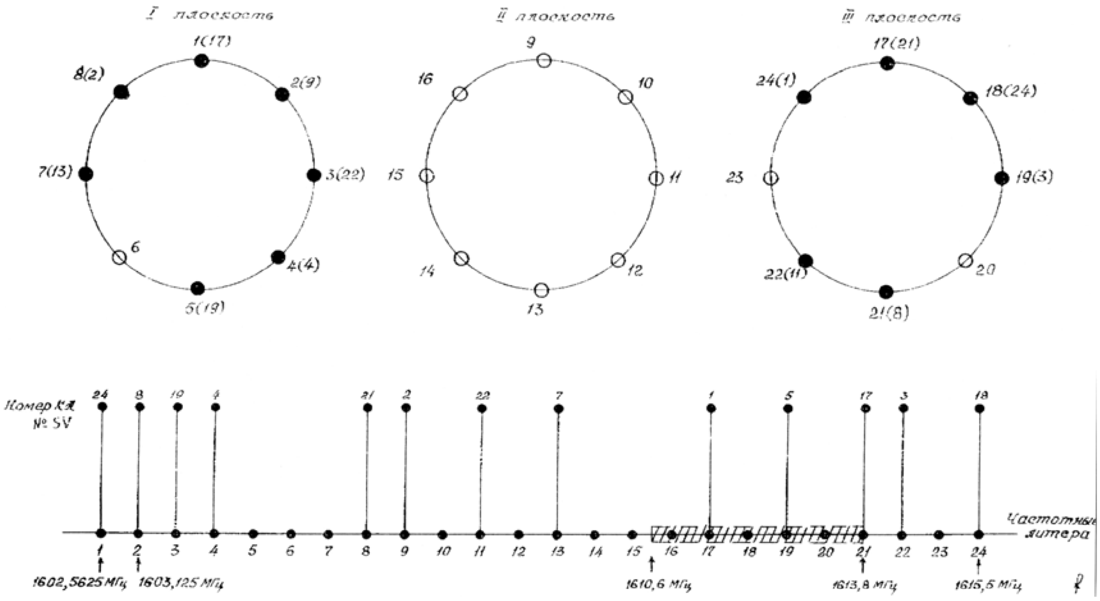

Fig. 2. GLONASS orbital occupancy and frequency plan in November 1992, at the time of the GLONASS-Radio Astronomy joint experiment.

The navigational signal is phase-modulated with a low-precision code switched at 0.511 MHz and a high-precision code switched at 5.11 MHz. The abrupt nature of the switching produces sinc-squared sidebands at both these frequencies. In addition there are “null spikes” that appear at the nulls of the 5.11-MHz pattern. Figure 1 shows the combined effect of several GLONASS satellites on radio astronomy data. The GLONASS emissions are picked up through far sidelobes of the radio telescope at ~0 dBi gain. The artefacts in the radio astronomical spectra have levels of ~5 K, that are equivalent to ~5 Jy for a 100-m telescope, but ~50 Jy for a 30-m telescope. The interference is spread over more than 100 MHz.

3. The joint experiment

The GLONASS administration was willing to help radio astronomy once the interference situation had been explained to them by IUCAF. They proposed a joint GLONASS-Radio Astronomy experiment to verify the levels of interference, and to test different ways of reducing the interference. The Soviets wanted the 76-m Lovell Telescope at Jodrell Bank to be the representative radio telescope for the experiment. They were keen to come to Jodrell Bank to witness the experiment, probably on account of the long historical association we have had with Soviet space scientists and radio astronomers. At an IUCAF meeting in Manchester I agreed to coordinate the experiment. My first move was to widen the experiment and bring in other observatories. In the event 12 radio observatories in 8 countries participated.

The experiment was carried out from 23.00 UT November 19th 1992 (02.00 November 20th Moscow time) to 19.50 UT November 21st 1992 (22.50 Moscow time). During the experiment 13 GLONASS satellites were operating. Initially the frequencies were as shown in Figure 2. During the experiment 9 satellites were moved in frequency and/or their navigation signals were switched off, while 4 satellites remained unchanged. Three frequency configurations were tested:

1. Central frequencies of navigation signals removed from the radio astronomy band (1610.6-1613.8 MHz);
2. Central frequencies of navigation signals restricted to frequency channels 12 or lower;
3. Central frequencies of navigation signals restricted to frequency channels 6 or lower.

Twelve radio astronomy observatories participated, as listed in Table 2: 10 made radio astron-omical measurements, while 6 measured the satellite transmissions directly and monitored the times of the satellite manoeuvres. Some observatories also took measurements before the official start of the experiment and during the restoration of the GLONASS system immediately after the experiment. The Jodrell Bank measurements were witnessed by the GLONASS chief engineer, Valery Tubalin, and by Slava Slysh.

Data from the participating stations were sent to Jodrell Bank during the exp-eriment by fax and by email. Dr. Tubalin was particularly impressed with the qual-ity of the monitoring data from the Leeheim tracking station in Germany, which gave

Table 2. Radio telescopes that participated in the joint experiment.

Observatory	No. of hours	No. of sources	Type of observation	Bandwidth
Jodrell Bank (UK)	104	21 13 sat.	Spectral line autocorrelator and acousto-optical, plus satellite monitor	5.0 and 1.25 MHz 90 MHz
Arecibo (USA)	15	8	Spectral line	20.0 and 2.5 MHz
Effelsberg (Germany)	24	1	Spectral line	25.0 and 6.25 MHz
Hartebeesthoek (South Africa)	24	10	Spectral line	5.12, 2.56, 1.28 and 0.64 MHz
Leeds University (UK)	60	13 sat.	Satellite navigation messages	
Leeheim (Germany)	60	13 sat.	Satellite measurements and monitor	100.0 and 3.2 MHz
Nançay (France)	100	40 13 sat.	Spectral line plus radio interference surveillance	1.6 and 6.4 MHz
NRAO Greenbank (USA)	57	9	Spectral line plus satellite measurements	5.0, 2.5, 1.25 and 0.625 MHz
Parkes (Australia)	39	112	Spectral line	8.0 and 0.5 MHz
Penticton (Canada)	170	2	Spectral line plus satellite measurements	2.0 MHz 50.0, 20.0, 4.25, 0.25 and 1.25 MHz
VLA (USA)	6	4	Interferometer, Phased Array	6.25 and 1.56 MHz
Westerbork (Netherlands)	83	8	Interferometer	5.0 MHz

gave precise spfd values for each satellite. At the end of the experiment data from all the participating observatories were sent to Jodrell Bank for evaluation. Figure 3 gives an example of data from the VLA, showing how GLONASS interference affects synthesis imaging. The source should appear as a single point at the centre of the field, but it is hidden by the artefacts produced by imaging the radio interference. Figure 4, which is based on Jodrell Bank data, shows that although the GLONASS satellites transmit only on one circular polarization (RHC), radio astronomical spectra are equally affected in both circular polarizations, since the GLONASS signals arrive through many different sidelobes. The only polarization selectivity comes when GLONASS is in the main beam (RHC) or seen directly by the feed in the "spillover ring" at an angular separation of 100° (LHC).

As had been agreed, I sent a preliminary report on the experiment to the GLONASS administration within 2 months. This was probably the toughest deadline of my career. The joint experiment was subsequently evaluated by ITU-R Working Party 7D in April 1993. Working Party 7D recommended firstly that the GLONASS frequency configuration 2 from the experiment (n ≤ 12) be adopted as soon as practicable and noted that this could be achieved by reuse of frequencies on opposite sides of the same orbit. The full WP7D report is given in Appendix A.

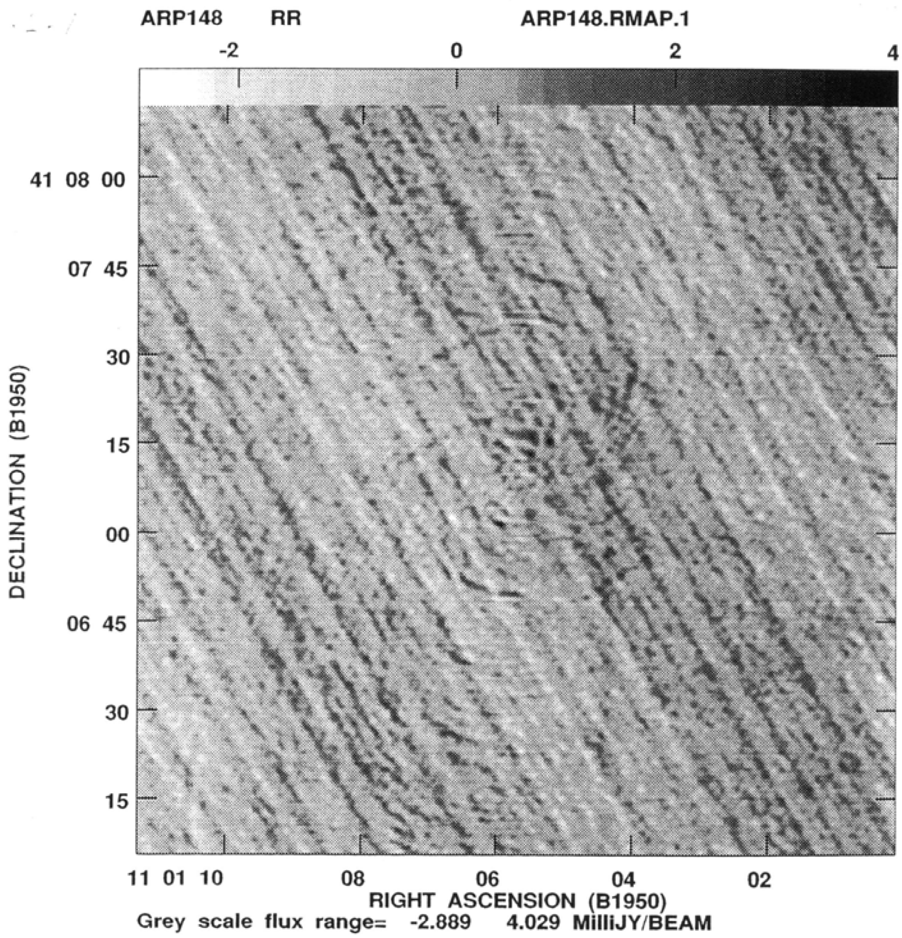

Fig. 3. Results from the VLA during the joint experiment, showing imaging artefacts due to GLONASS interference (courtesy of Vivek Dhawan).

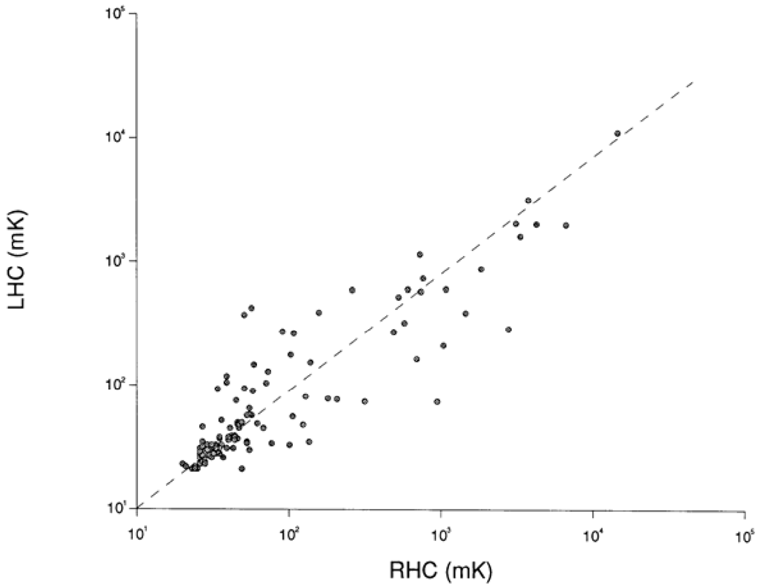

Fig. 4. Effects of GLONASS on spectra of LHC and RHC polarizations show no systematic difference, even though GLONASS transmits RHC. The data shown here are the rms noise levels of spectra taken at Jodrell Bank using the Lovell Telescope and a 1024-channel autocorrelator interference.

4. The GLONASS - IUCAF Agreement

In September 1993 the GLONASS administration reached a bilateral agreement with the Australian administration, and as a show of good faith changed the frequency plan of GLONASS without warning. Satellites with frequency channels between n=16 and n=21 were moved out of the radio astronomy band, as in phase 1 of the joint experiment. By good fortune, Jodrell Bank was observing OH at the time, and we were able to thank the Russians within a matter of days for reducing our interference levels. The political importance of this was vital when IUCAF went to Moscow at the end of October 1993 for further negotiations.

The IUCAF delegation was headed by Willem Baan, and the GLONASS delegation was headed by General Vladimir Durnev (although Col. Viktor Gorev led the actual negotiations). The meeting reached an historic agreement, the full text of which is reproduced in Appendix B. The agreement sets out a step-by-step plan to achieve compatibility between GLONASS and radio astronomy. The first steps follow phases 1, 2 and 3 of the joint experiment, with satellite frequencies being moved further and further away from the radio astronomy band. Future steps include the fitting of filters to satellites to suppress the GLONASS sidebands.

Strictly speaking the GLONASS-IUCAF agreement is not a coordination agreement, since those can only be reached by administrations. Nevertheless the agreement with IUCAF, squarely based on the results of the joint experiment, has served as a model for coordination agreements subsequently reached between GLONASS and many other administrations.

Fig. 5. Willem Baan signing the GLONASS-IUCAF accord in Moscow, 4th November 1993. Jim Cohen and John Ponsonby from the IUCAF delegation are standing behind. General Vladimir Durnev, head of the GLONASS delegation, is seated holding his papers; the lady is Nina Labusova, the translator.

5. Current Status and Prospects

GLONASS has followed the step by step plan agreed in Moscow. Since 1993 there have been no satellites with a centre frequency in the radio astronomy band. Since 2000 there have been no satellites with their main emissions in the radio astronomy band. The last launch was on 1st December 2001. We have yet to see evidence of filters fitted on new satellites, but IUCAF has been reliably informed that the next launch will include a satellite fitted with filters.

Unfortunately the situation is now complicated by newcomers, notably Iridium. A new GLONASS administration is in place. IUCAF is gathering information on current levels of interference from GLONASS, with a deadline 1st Nov 2002. This will form the basis for further negotiations and a possible further joint experiment.

6. References

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Appendix A: Technical Evaluation of the GLONASS-Radio Astronomy Joint Experiment by Working Party 7D (Radio Astronomy) of ITU-R.

Documents Radiocommunication Study Groups Period 1990-1994	<u>Document 7D/TEMP/17-E</u> 5 April 1993 <u>English only</u>

<u>Working Party 7D</u>

PREMLIMINARY DRAFT REPORT

EVALUATION OF THE JOINT GLONASS-RADIOASTRONOMY EXPERIMENT

The members of Working Group 7D of the Radiocommunication Sector (formerly CCIR) have considered the observatory reports on the Joint GLONASS – Radio Astronomy Experiment held 20-22 November 1992. Reports considered in detail were those for single dish observations from Arecibo, Dominion Radio Astrophysical Observatory, Effelsberg, Jodrell Bank, Greenbank 140 ft, and Parkes, the interferometric data from the Very Large Array and Westerbork Synthesis Radio Telescope, and monitoring data from the Leeheim Station.

On the basis of the available data, the members of Radiocommunication Sector WP 7D conclude that:

1. GLONASS emissions display broad sidebands with frequency structure of widths 0.511 and 5.11 MHz due to low precision and high precision navigation code modulations, together with narrow monochromatic spikes which occur in the nulls of the 5.11 MHz sidebands. During the experiment accurate power flux densities were measured for all satellites by the Leeheim monitoring station. An example of these data is shown in Figure 1.

2. During the Joint Experiment GLONASS satellite transmissions were restricted in frequency to centre frequencies outside the radio astronomy band 1610.6 – 1613-8 MHz (phase 1), to centre frequencies ≤ 1608.75 MHz (phase 2) and to centre frequencies ≤1605.375 MHz (phase 3). During phases 2 and 3 of the experiment the interference levels suffered by radio astronomy observatories in the band 1610-6 – 1613.8 MHz were reduced by more than 20 dB. This effect is illustrated by Figure 2.

3. During phases 2 and 3 of the experiment useful data were obtained for most observations of strong Galactic 1612 MHz OH-IR sources, which generally have narrow bandwidths (≤500 kHz). The usefulness of the observational data depends on the strength of the source, as well as the spectral profile of its emissions.

4. Observations of weak Galactic 1612 MHz OH-IR sources produced some useful data during phases 2 and 3 of the experiment. The usefulness depends on the proximity of occupied GLONASS channels to the radio astronomy band, the frequencies of the narrow spikes in the GLONASS sidebands relative to the frequency of the astronomical source, and the spectral structure of the emissions from the source. The success rate was higher in phase 3 of the experiment.

5. Observations of broadband Galactic and extragalactic sources (bandwidths ≥ 1 MHz) were strongly affected by emissions from GLONASS satellites with centre frequencies above 1605.375 MHz. The usefulness of these data is low due to the weakness and spectral width of the emissions from the astronomical sources.

6. The narrow monochromatic spikes which occur in the nulls of the GLONASS 5.11 MHz sidebands were detected over a wide range of frequencies. In particular they were detected in the 1660 – 1670 MHz radio astronomy band at power flux densities exceeding the thresholds for harmful interference to spectral line measurements. These spikes may mimic astronomical signals from narrow band maser sources.

7. During phase 3 of the experiment the power flux densities of emissions from individual GLONASS satellites in the radio astronomy band 1610.6 – 1613.8 MHz were below the thresholds for harmful interference to spectral line observations using long baseline and very-long-baseline interferometers. Some useful data were also obtained using long baseline interferometers during phase 2 of the experiment.

In order to reduce the interference experienced by the radio astronomy service due to GLONASS emissions, the members of Radiocommunication Sector WP 7D recommend that:

1. As an urgent first step, the GLONASS system be confined to the lower twelve frequency channels of the present configuration (centre frequencies ≤1608.75 MHz). This may be achieved by the reuse of frequencies by satellites on opposite sides of the same orbit.

2. As a second step, the twelve frequency channels of the GLONASS system be shifted down in frequency to channels six and lower (centre frequencies ≤ 1605.375 MHz).

3. As soon as practicable, the GLONASS system employ filtering above the first sideband of the highest frequency channel used.

4. Radio observatories continue to monitor the effects of GLONASS emissions in the radio astronomy bands, in order to assist in the evaluation of changes made to the GLONASS system.

5. IUCAF representatives and the GLONASS administration continue their efforts to find an equitable solution to the interference problem.

The following members of Working Party 7D participated in the evaluation:

Willem Baan (Arecibo Observatory, USA), Yuri Borodaenko (Russian Space Agency, Russia), R. James Cohen (University of Manchester, Jodrell Bank, United Kingdom), Robert Cooper (Radiocommunications Agency, United Kingdom), Tomas Gergely (National Science Foundation, USA), Hans Kahlmann (Netherlands Foundation for Research in Astronomy, The Netherlands), Robert S. Roger (Dominion Radio Astrophysical Observatory, Canada), Klaus Ruf (Max Planck Institut für Radioastronomie, Germany), A. Richard Thompson (National Radio Astronomy Observatory, USA), John B. Whiteoak (Australia Telescope National Facility, Australia).

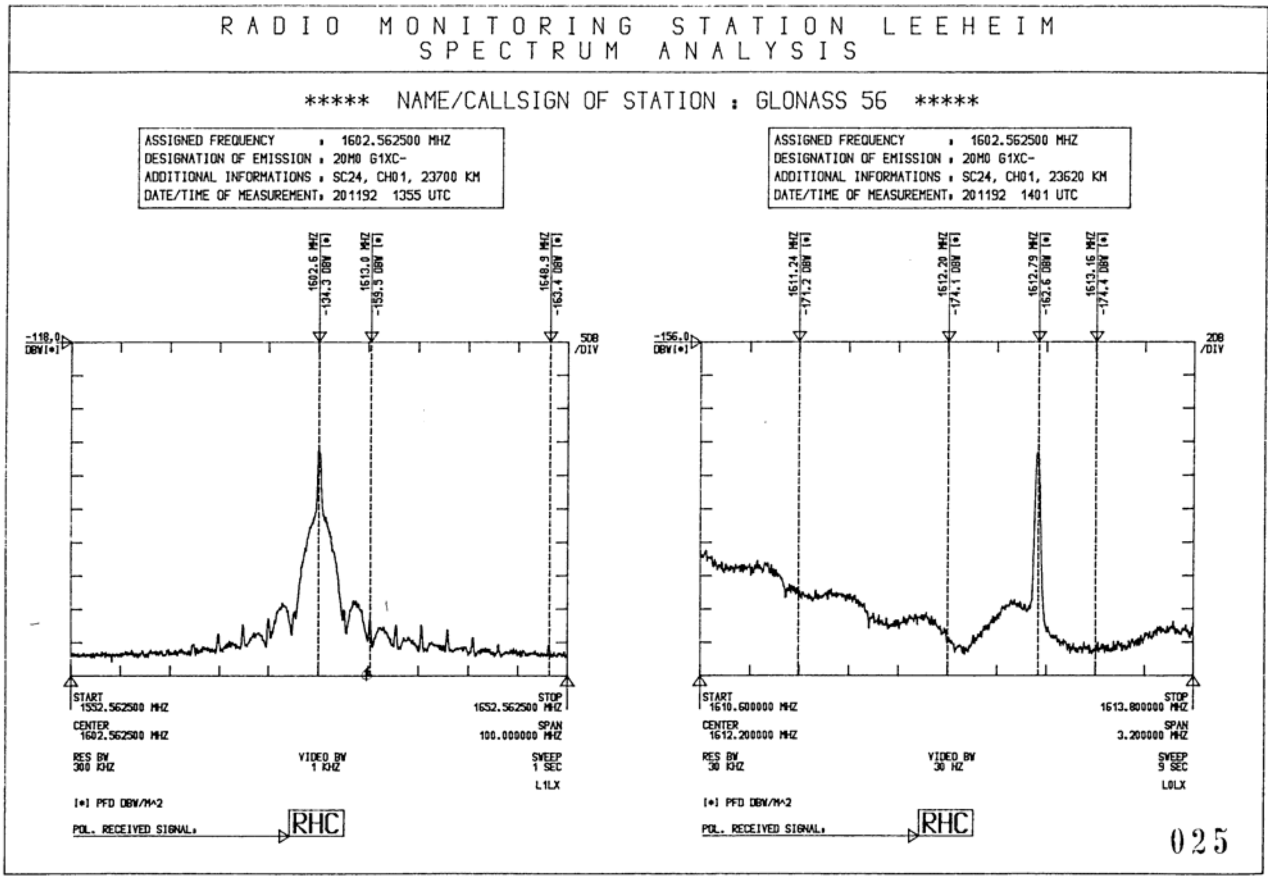

Figure 1. Power flux density of emissions from GLONASS spacecraft number 24 as measured by the Leeheim Monitoring Station during the joint experiment. The left hand panel shows measurements made over a 100 MHz bandwidth centred on the assigned frequency of the satellite emissions, with a resolution bandwidth of 300 kHz. The centre frequency of the satellite emissions was 1602.5625 MHz in this case. The right hand panel shows the power flux density falling in the radio astronomy band 1610.6 – 1613-8 MHz, measured with a resolution bandwidth of 30 kHz. The peak pfd level of the emissions in the radio astronomy band is –212 $dBWm^{-2}Hz^{-1}$, which lies well above the threshold for harmful interference to single telescope spectral line measurements (-238 $dBWm^{-2}Hz^{-1}$), but below the threshold for harmful interference to very-long-baseline interferometry (-208 $dBWm^{-2}Hz^{-1}$), as given in Recommendation 769, Tables 2 and 3.

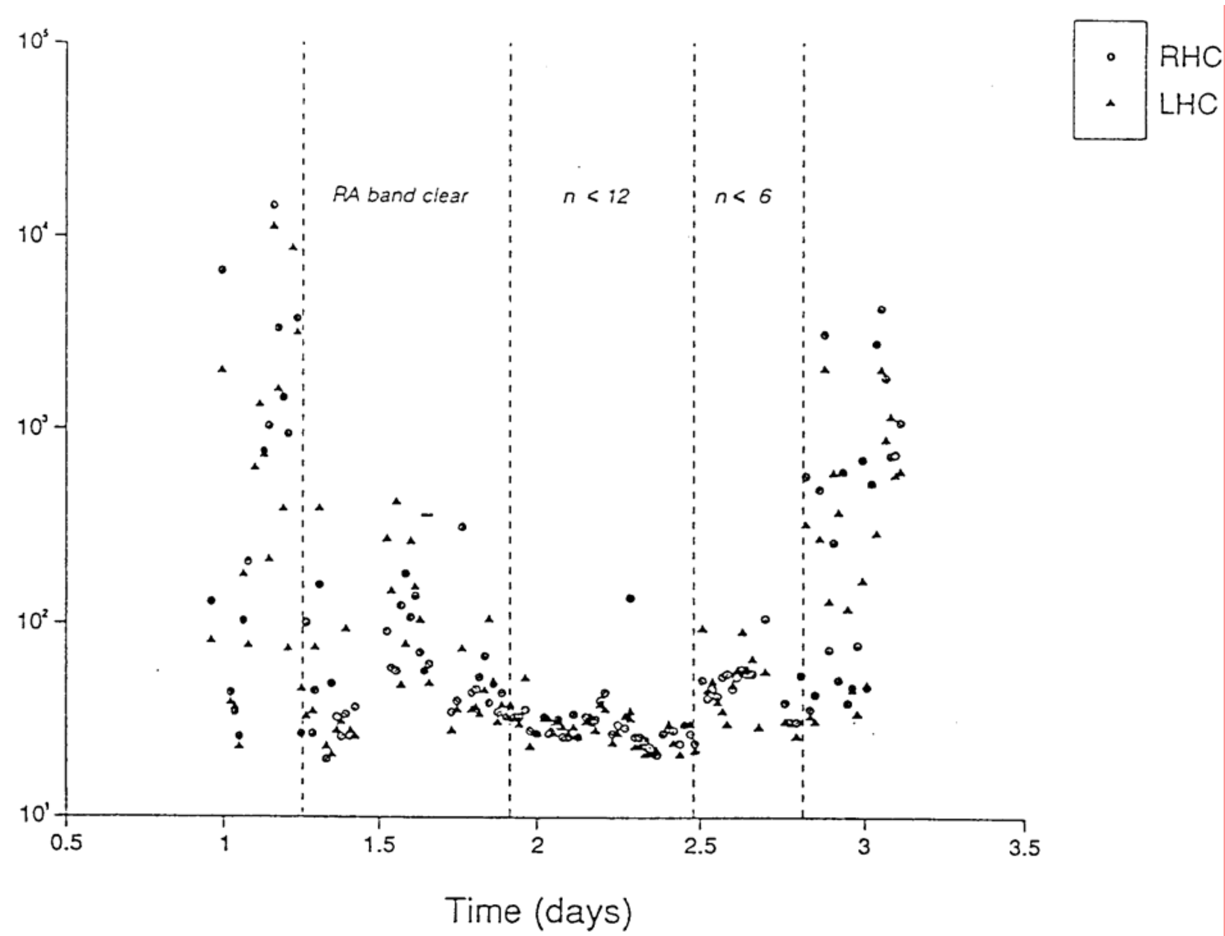

Figure 2. The effects of the GLONASS emissions on radio astronomy spectral line measurements are shown as a function of time during the course of the joint experiment. The measurements were made at Jodrell Bank, with a resolution bandwidth of 17.3 kHz and an integration time of 1200 s. The quantity RMS3 is the rms noise level in the measurements after subtracting a third order polynomial baseline. The rms noise was measured across those parts of the radio astronomy band believed to be free of spectral line emission from the astronomical source. Data for LHC and RHC are shown separately. The different phases of the experiment are indicated by the dashed vertical lines. Phase 2 corresponds to $n \leq 6$. The rms noise decreased by 20 dB during phases 2 and 3 of the joint experiment. Note that the receiver noise increased by 3 dB when the galactic centre was observed at times 1.5 – 1.7 day and 2.5 – 2.7 day, so the rms noise values at these times were also increased by 3 dB.

Appendix B: GLONASS-IUCAF Agreement
(presented to WRC-93 as document CMR-93/43-E)

AGREEMENT

between the GLONASS Administration and IUCAF concerning frequency usage by GLONASS-M and the Radio Astronomy Service

The delegation of the GLONASS Administration and the delegation of the Inter-Union Commission on Frequency Allocations for Radio Astronomy and Space Science (IUCAF), meeting in Moscow on 2-4 November 1993,

Considering

- the conclusions of their meetings in Moscow in October 1991, June 1992 and November 1993;

- the results of the Joint GLONASS-Radio Astronomy Experiment in November 1992, and the technical evaluation of the experiment by Working Party 7D of the Radiocommunication Sector of the ITU in April 1993;

- the organizational and technical measures implemented by the GLONASS Administration in September 1993;

- the bilateral agreements reached in September 1993 between the administration of the Russian Federation and the administrations of Australia and Japan, and the summary record of the meeting in October 1993 between the administrations of the Russian Federation and the United States of America;

and noting

- the impact of the GLONASS-M satellite system on radio astronomical measurements in the bands 1610.6-1613.8 MHz and 1660-1670 MHz, and the continuing implementation of the GLONASS-M satellite system; and

- the technical difficulties in achieving electromagnetic compatibility between the GLONASS-M system and the Radio Astronomy Service;

agree that:

1. the GLONASS Administration shall continue to exclude the main emission of the 1M02G7X class (GLONASS: narrow band) from the band 1610.6-1613.8 MHz, and from 1999 will exclude the main emission of 10M2G7X class (GLONASS-M: broad band);

2. during the period 1994-1998 filters will be installed on the newly developed GLONASS-M spacecraft to reduce the levels of out-of-band emissions in the frequency band 1660-1670 MHz below the levels specified in CCIR Report 224;

3. the GLONASS Administration undertakes to communicate to IUCAF any changes in the orbital parameters and frequencies of the GLONASS system, as soon as practicable, in order to assist in the planning of radio astronomy observations to avoid the interference caused by GLONASS.

4. IUCAF undertakes to communicate information on the GLONASS system to the radio astronomy community, to advise the radio astronomy community on optimal times to observe, and to coordinate further joint experiments as needed to evaluate the compatibility of the GLONASS system with the Radio Astronomy Service. The coordination will be done by the IUCAF coordinator at Arecibo Observatory in the first instance;

5. GLONASS Administration undertakes to investigate the optimal assignment of frequencies among the GLONASS-M satellites, within the constraints of existing technical limitations, so as to minimize the impact on the radio astronomical observations;

6. the GLONASS administration agrees to investigate the ways of reducing out-of –band emissions in the frequency band 1610.6-1613-8 MHz to the levels indicated in CCIR Report 224, and to communicate their proposed solution of this problem at a future meeting;

7. a solution of the interference problem caused by the main emission of class 10M2G7X and out-of-band emissions of GLONASS transmitters in the frequency band 1610.6-1613.8 MHz will be achieved only if the frequency plans of the GLONASS-M systems are modified. IUCAF agrees to assist in the coordination of the necessary changes with the interested administrations and with the ITU.

Both delegations believe that the implementation of the above agreements is a sufficient basis to achieve compatibility between the GLONASS system and the Radio Astronomy Service, and that coordination between GLONASS, GLONASS-M and the Radio Astronomy Service is possible. This information shall be communicated to the ITU and to interested administrations within one month.

The agreement is written in Russian and in English, and both versions have equal standing. The agreement will come into force at the moment of signing.

On behalf of the GLONASS Administration	On behalf of IUCAF
General Vladimir I. Durnev	Dr Willem A. Baan
Head of GLONASS delegation	Head of IUCAF delegation

Moscow, 4th November 1993