FIRST FGAN/MPIfR COOPERATIVE DEBRIS OBSERVATION CAMPAIGN: EXPERIMENT OUTLINE AND FIRST RESULTS

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ABSTRACT

A high performance bistatic 24 hour debris observation campaign (COBEAM–1/96) has been prepared and conducted, which uses FGAN's recently improved TIRA L–band system as the primary transmitter/receiver and the world largest steerable radio telescope as a secondary receiver with very high sensitivity. Due to the close location of the two systems (21.4 km), a large shared observation volume is ensured (more than 200 km height extent, centered at h = 850 km). COBEAM–1/96 was successfully conducted in November 1996. First analysis of the 150 GB of data collected revealed detection thresholds according to about 2 cm sized objects at TIRA and to less than 1 cm at the Effelsberg telescope.

1. INTRODUCTION

Current models for the estimation of the space debris population density and its potential hazard to space activities suffer from considerable uncertainties in the 1...50 cm size regime due to the lack of sufficient measurement data. Only a few dedicated radars worldwide are capable to detect objects of centimetre size or smaller in LEO. In recent years concepts were developed and implemented at the Research Establishment for Applied Science (FGAN) in the frame of ESA/ESOC study contracts, to modify FGAN's Tracking and Imaging Radar (TIRA) system in order to be able to efficiently observe the mid–size debris population. By a first 24 hour staring campaign in December 1994 the principal suitability of the TIRA L–band radar and the developed concepts was demonstrated. Careful data analysis revealed that TIRA should be capable of detecting down to 2 cm sized objects at 1000 km range taking into account all proposed modifications (Ref. 1).

Due to the severe restrictions for an active sensor system like the TIRA L–band radar (losses in transmit/receive duplexer, limited cooling of the large monopulse feed horn receiver system,...), a higher sensitivity may currently be achieved only with the help of a secondary passive sensor with a large aperture and cryogenic cooled receivers. The close location of the world largest steerable radio telescope at Bad–Münstereifel–Effelsberg, operated by the Max–Planck–Institute for Radio Astronomy (MPIfR), Bonn, to FGAN's TIRA system is unique in Europe and offers promising conditions for debris observation in LEO with high sensitivities.

In November 1995 FGAN's proposal was agreed upon by MPIfR, to perform a 24 hour cooperative beam–park campaign in 1996 (COBEAM–1/96) using the Effelsberg 100 m telescope as a secondary receiver. Two initial test experiments on receiver compatibility and direct pulse transmission to Effelsberg revealed the principal feasibility of COBEAM–1/96 (Ref. 2).

In preparation of COBEAM–1/96 a completely new data collection concept had to be developed and various tests and calibration experiments had to be performed in order to guarantee the maximum possible outcome of the 24 hour campaign. Some of the details are described in section 2.

In section 3 a short summary of COBEAM–1/96 itself will be given, which was successfully conducted on 25/26 November 1996.

Development of a suitable data processing system and analysis of the collected data (about 150 GB) started early this year and is still going on. An overview of the processing approach will be given in section 4 together with a brief summary of the results achieved so far.

Finally an outlook will be provided, summarizing the neccessary further steps and ongoing work with respect to the COBEAM–1/96 data analysis.

2. COBEAM PREPARATION

This section describes the preparation phase of COBEAM–1/96. A completely new data collection concept for this bistatic radar experiment had to be developed (subsection 2.1) and various techniques had to be investigated and tested in order to guarantee basic functionality, relative/absolute calibration, maximum sensitivities, and verification of relative/absolute pointing accuracies of both systems (subsection 2.2).

2.1 Development of the data collection systems

Besides high sensitivities, beam–park campaigns for the measurement of debris population densities by radar require coverage of observation volumes which are as large as possible with respect to space, time, and range rate. The angular extend is usually defined through the 3 dB width of the cone–shaped beam, whereas its range extend is selectable for the transmit/receive system (TIRA, typically 600...4000 km range window) but fixed through the overlap region of the two beams for the secondary receiver (Effelsberg telescope) for a given observation geometry. Since range rates of artificial Earth satellites fall into the interval -8...8 km/s, the receivers should cover a bandwidth of at least 200 kHz, allowing also pulse compression. The duration of a beam–park experiment should exceed 24 hours, so that Earth rotation cycles the observation volume through at least one closed right ascension ring.

Analog systems, which allow realtime processing of receiver signals with characteristics mentioned above, are usually expensive and rather inflexible with respect to the adjustability of processing parameters like range gate shift and Doppler filter width. A different approach was therefore chosen here: After quadrature demodulation in the intermediate frequency (IF) stage of each receiver channel, the video inphase and quadrature phase signals are continuously sampled by a twin A/D converter with 500 kHz sampling frequency (which is more than twice the usable bandwidth of the L–band radar). A/D outputs stemming from inside the selected range window are written to harddisk. Processing and analysis of the data is performed off–line by software means (see section 4).

In view of COBEAM–1/96 various other requirements had to be fulfilled by the data collection units (DCU):

- Short development time, cheap and easy available components,
- 5 separate, compact and portable units: 2 for the telescope left– and right–handed circular polarized receiver channels (LCP, RCP) and 3 for TIRA's sum ($\sum$) and transverse and elevation difference channels (Δ_H, Δ_V),
- modular, reusable units for easy exchange of hardware and software components,
- modules for synchronization of all units at the two sensor stations,
- modules for control and monitoring of the complete data collection process and for rudimentary online visualization (quick–look) of selected parts of the data stream.

A block diagram of the DCU hardware concept is shown in figure 1. Each unit basically consists of a SUN SPARC station with a 90 MHz twin CPU and SBUS twin A/D converter board, which offers 16 MB user–interruptable onboard RAM and 2 analog as well as 4 TTL input channels, all synchronously sampled via internal or external clock. For data storage up to 5 conventional 9 GB harddisks can be mounted.

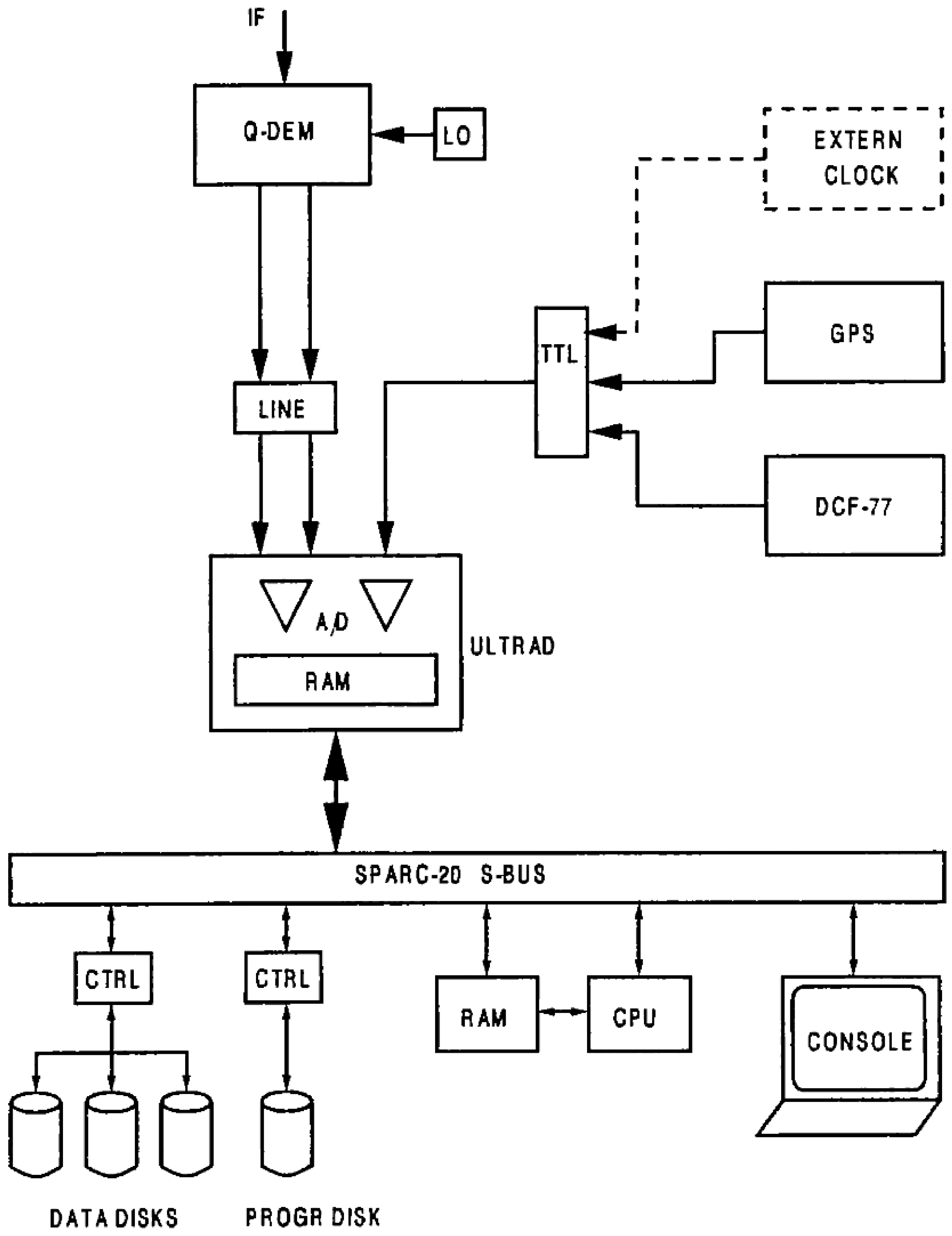

Figure 1. Basic components of the DCU hardware.

Synchronization of the 5 DCUs is provided by continuous sampling of a DCF–77 time telegram (absolute time), a GPS receiver time signal (accurate second), and by assessment of the transmit pulse start times via tracking of TIRA's transmit pulse.

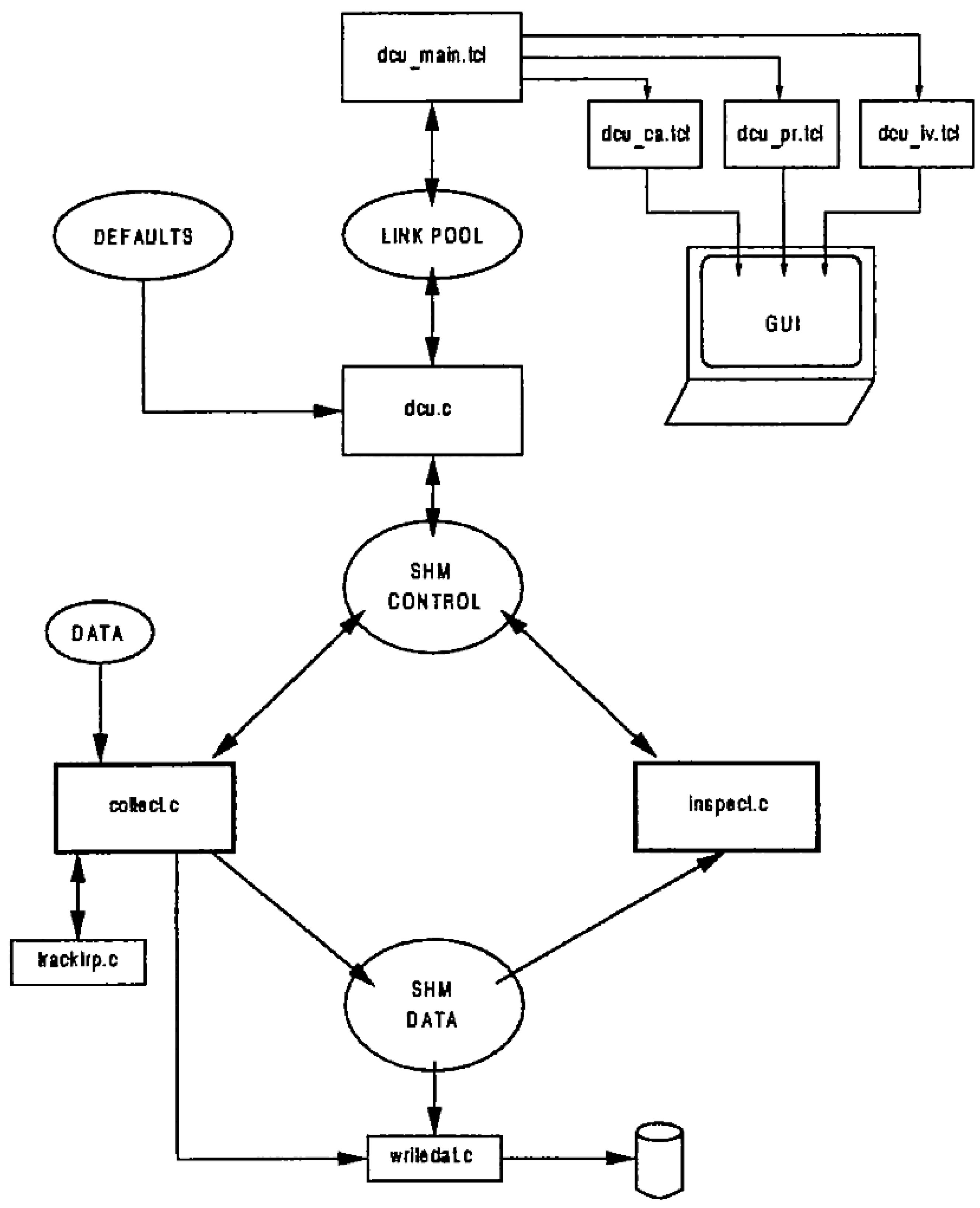

Figure 2. Main components of the DCU process software.

The concept for the DCU control and monitoring software had to take respect to the limited realtime capabilities of the Solaris operating system. Communication between the three independent main programs (for configuration, data collection, and online data processing and visualization) is ensured via shared memory blocks. A graphical user interface (GUI, implemented in Tcl/Tk) provides user interaction and rudimentary online visualization of a small part of the total data stream. A principal block diagram is shown in figure 2.

2.2 Functionality tests and calibration

Various techniques have been considered and tested in order to guarantee basic functionality, relative and absolute calibration, maximum sensitivities, and verification of relative and absolute pointing accuracies of both systems. Especially relative pointing accuracy is crucial since it greatly influences the observation volume as seen by the telescope (an azimuth squinting angle of more than 0.5 deg of either system would mean that the telescope beam 'sees' nothing since not illuminated by the transmitter beam). Pointing accuracy verification and absolute/relative calibration was performed by three types of experiments:

1. Joint measurements of several radio stars (point sources) with and without compensation of Earth rotation; gives measures of absolute pointing accuracy,
2. joint observations of different sized calibration spheres; TIRA tracking the spheres over complete passes, the telescope beam staring to predefined rendevouz positions; gives precise cross sections through the telescope's beam pattern, useful for calibration,
3. joint calibration sphere beam-park experiments at precalculated orbit positions; relative pointing accuracies are derived from comparison of the time instances of peak signal returns.

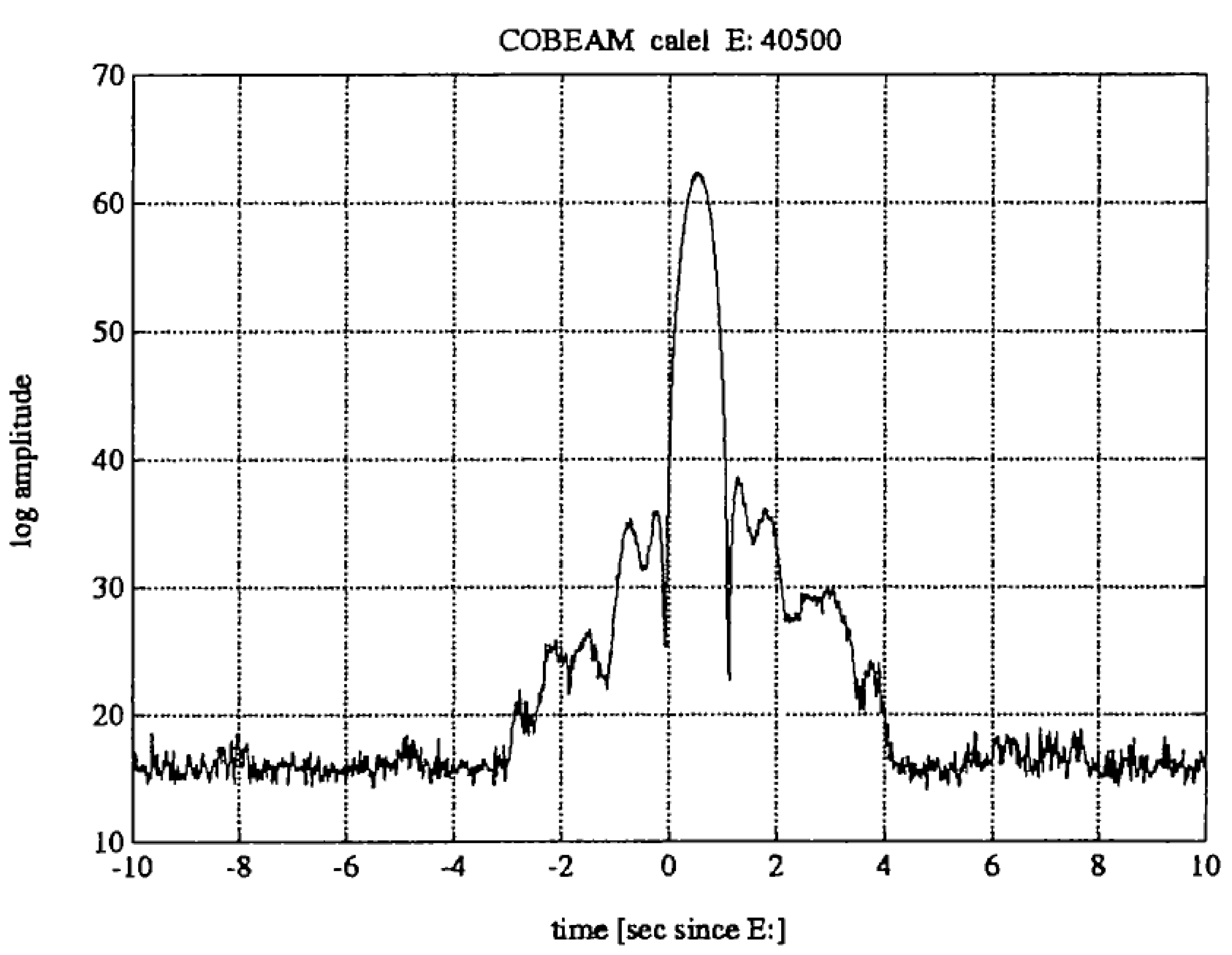

Figure 3. Beam–park amplitude signature of a 20 cm calibration sphere at Effelsberg LCP receiver channel

Figure 3 shows the amplitude signature of a 20 cm calibration sphere crossing the telescope beam at about 1100 km range. The antenna pattern is clearly visible, even higher order sidelobes are well above noise, which indicates the very high sensitivity of the telescope system. Elaborate analysis of the mainlobe width and comparison with the exact value provided by MPIfR confirms the desired pointing accuracy to within 1/100 degree. From the known L–band radar cross section (RCS) of the sphere, both systems can be absolutely calibrated.

3. EXPERIMENT CONDUCTION

The principal geometry of COBEAM–1/96 is sketched in figure 4. In the determination of optimum observation parameters a compromise between several conflicting requirements had to be found. The height of the crossing point of the two line–of–sights (centre of observation volume, COV) was the only parameter fixed in an early phase to h_{COV} = 850 km, in order to cover the orbital region which is assumed to be highly populated by coolant droplets leaking from members of the Russian RORSAT reactor family.

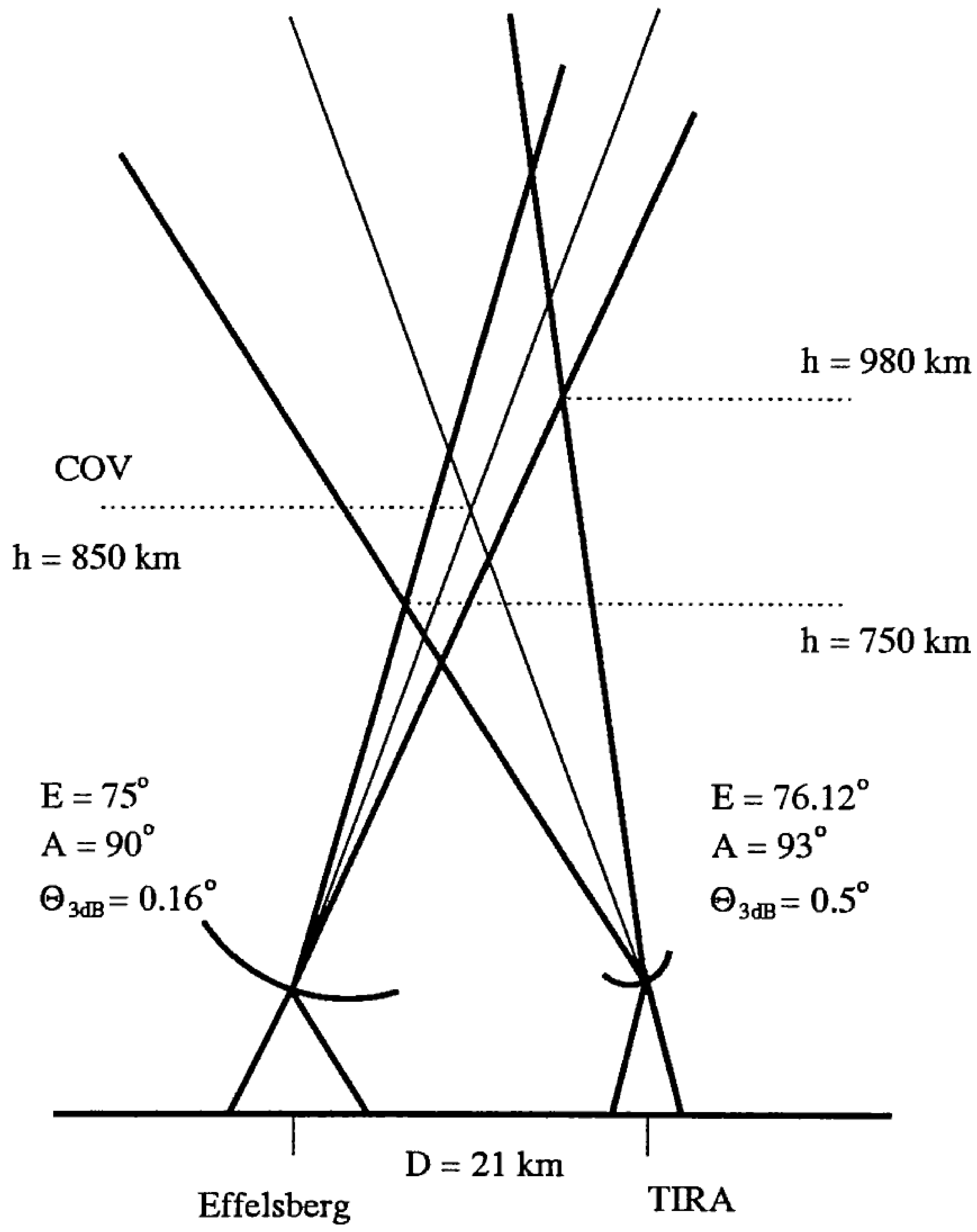

Figure 4. Principal COBEAM–1/96 geometry

Thorough analysis (see also Ref. 3) revealed, that the range margins of the beam overlap region are nearly independent of the azimuth positions for moderate to high elevation angles. This suggested to set the Effelsberg telescope azimuth angle to 90 degrees (East) with an elevation of 75 degrees. In this constellation an unambiguous relationship between a target's Doppler frequency and its orbital inclination is given, an information which otherwise would not be obtainable by the telescope since it has no monopulse receivers.

Category	Parameter	TIRA	Effelsberg
centre of observation volume	height h_{COV}	850 km	850 km
	range R_{COV}	875 km	880 km
	elevation E_{COV}	76.12°	75.0°
	azimuth A_{COV}	93.0°	90.0°
antenna beam	3 dB beam width	0.5°	0.165°
transmitter	frequency f_t	1.333 GHz	
	polarization	RCP	
	peak power P_t	1.6 MW	
	pulse length τ_t	1 ms	
	pulse period length T_t	27 ms	
receiver	channels	LCP: $\sum$, Δ_H, Δ_V	LCP, RCP
DCU data window	range R	575...1175 km	705...1055 km
	range rate D	-11...11 km/s	-11...11 km/s
Tracking filter data window	range R	800...950 km	
	range rate D	-0.556...-0.444 km/s	

Table 1: COBEAM–1/96 observation parameters and radar settings

With the corresponding pointing angles for TIRA an altitude overlap of more than 200 km results. The relevant observation parameters and radar settings which were finally agreed upon are summarized in table 1.

COBEAM–1/96 has been successfully performed in November 1996 (330 11:30 - 331 12:30 UT), yielding in total about 150 GB of data in the five receiver channels plus about 1 GB in TIRA's conventional tracking filter (TF), which was operated in parallel, and some additional hundred MB of data from calibration measurements directly before and after the campaign.

4. DATA PROCESSING AND FIRST RESULTS

4.1 Target search filter processing

As pointed out in section 2, the chosen approach of storing the complete unfiltered raw data to disk and processing them off–line by software means allows for quite flexible detection strategies. In contrast to an analog hardware filter concept, it is possible to adaptively change processing parameters or even reprocess the data with changed and refined sets of algorithms. Range–adapted incoherent multi–pulse integration (the number of echoes of an object crossing the beam on the average linearly increases with range) can be applied, and unavoidable range gate straddling and Doppler filter scalloping losses may be widely reduced by using sophisticated filtering algorithms.

Development of the COBEAM data processor started end of 1996 by rearranging and adapting most of the modules already used for the 1994 campaign. The code was ported to C and some new modules and options were added. Basically new is the processor's capability to perform incoherent multi–pulse integration over a set of different pulse numbers simultaneously. In the first run power–of–two integration lengths (up to 64 pulses for TIRA and up to 32 for the telescope data) were used. In which of the integration ring buffers the best target return occurs depends on several factors: the target dwell time (the time it resides inside the beam) which itself depends on range and on the angular position where it crosses the beam, the target's reflexion characteristics (which in most cases however can be assumed to be non–fluctuating for small objects at L–band wavelength due to volume scattering tendency), and the modulation of the echo amplitude by the antenna far field pattern.

A block diagram highlighting the basic functions implemented so far is shown in figure 5. In the current, still experimental state of the data processor output data files are produced at all intermediate stages so that reprocessing can occur in case of failures or necessary parameter modifications without having to rerun the complete process.

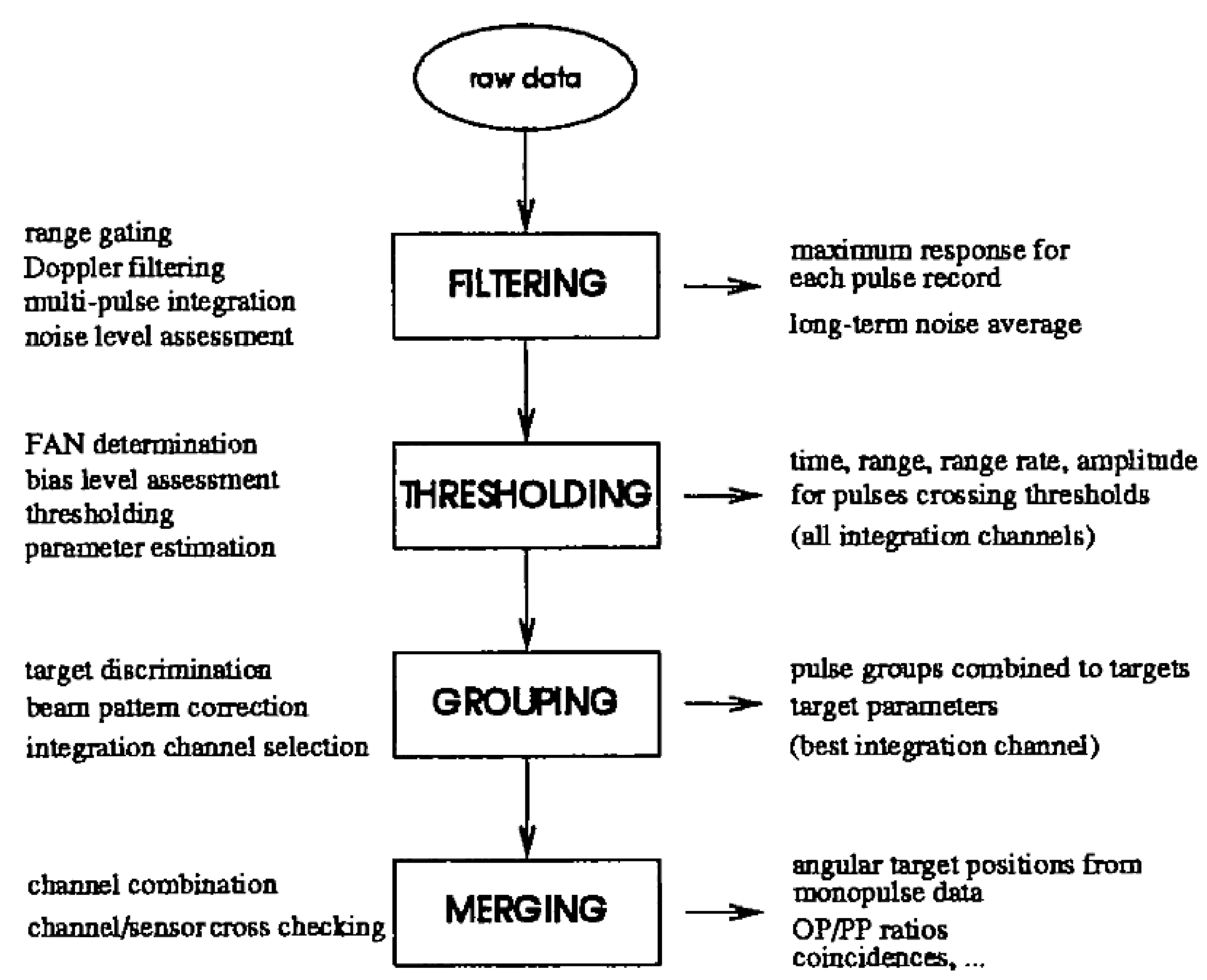

Figure 5. Block diagram of the COBEAM search filter processor in its current state

The initial, most time consuming module mimics the conventional matched filter processing. Range gates are extracted at positions shifted by 1/5 pulse width and Doppler filtered by a 2048–point zero–padded FFT. This gives average straddling losses (target echo not fully contained in the gate) of about 0.45 dB and average scalloping losses (target Doppler not centered in filter channel) of only 0.1 dB. Multi–pulse incoherent integration is performed in parallel for N = 2^i (i = 0, 1, 2,...) pulses with the help of integration ring buffer arrays which are intermediately stored to disk to allow continuation across raw data file borders. Together with the maximum signal's (noise or target) amplitude and time–frequency position in each pulse record, the module also outputs a long–term noise average estimate.

Discrimination between noise and target pulses is performed in the thresholding module. The false alarm number (FAN) is calculated from the actual processing parameters and the desired false alarm rate of 1 per 10 hrs according to the theory outlined in Refs. 4 to 6. Corresponding bias levels are assessed for each integration length assuming mostly linear detector characteristics. (A test run on a large part of the data had shown that the threshold settings better conform to linear than to quadratic detector theory). For each pulse period for which the threshold is exceeded in at least one of the integration buffers, time, range, range rate and amplitude are recorded (for all integration channels).

In the third module, detections which belong to the same target are grouped and target parameters are carefully assigned. This process is currently not fully automated, especially for fluctuating objects or rather short detections manual interaction is required. Echo amplitudes are rescaled with respect to the beam pattern characteristics and RCS–to–size conversion is performed (currently simply according to the Rayleigh rule).

Merging of data from the different receiver channels is provided by the fourth module. E.g. the three TIRA channels ($\sum$, Δ_V, Δ_H) are combined here to provide monopulse angles and OP/PP RCS ratios are calculated from the Effelsberg polarization channels. Cross checks between the two sensor detections are also performed at this stage.

4.2 Results achieved so far

A first processing run was performed on the COBEAM data with the processor descripted above, concentrating on the two most important receiver channels, TIRA's sum ($\sum$) and the telescope's left–handed circular polarized channel (LCP). The initial filter module which is most time–consuming takes about 10 to 20 days of processing time for each channel on an otherwise idle SPARC station, depending on the processing parameters and the selected range window.

Combining noise averages, bias level settings, and the assessed RCS calibration values, the detectable object sizes at R = 1000 km are determined to be 2 cm for the TIRA sum channel with 64 pulses integrated and 0.9 cm for the Effelsberg LCP channel with 32 pulses integrated.

In the following some of the results obtained so far will be described.

Figure 6 shows hourly detection rates versus altitude (30 km bins) for the total populations seen at the TIRA sum (solid line) and Effelsberg LCP channels (dashed line). Lower and upper bins have been disregarded since they might contain several target echoes not totally included inside the range window borders. Displayed altitude ranges are 640...1120 km for TIRA and 710...1010 for the Effelsberg data. Both distributions are strongly peaked at 900 km, additional peaks in the TIRA sum data at about 600, 800, and 1100 km will have to be verified and explained by deeper analysis.

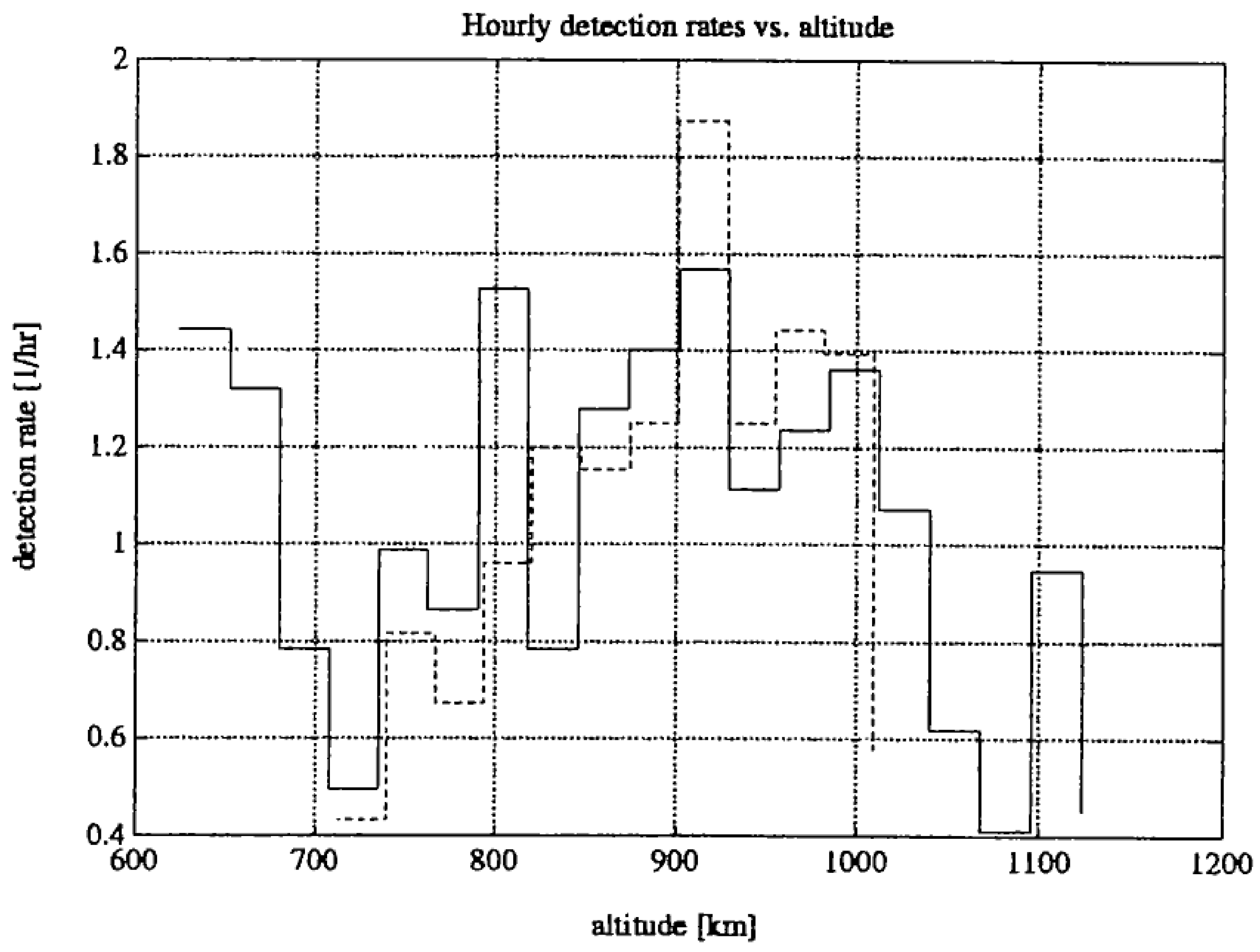

Figure 6. Detection rates vs. altitude for TIRA sum channel (solid) and Effelsberg LCP channel (dashed), 30 km altitude bins.

Hourly detection rates versus range rate (only detections in -2...2 km/s interval) are plotted in figure 7 for the same altitude ranges as in figure 6. Through deeper analysis, peaking of the Effelsberg LCP distribution around 1 km/s can be shown to result from the 1...2 cm size population not detectable by TIRA.

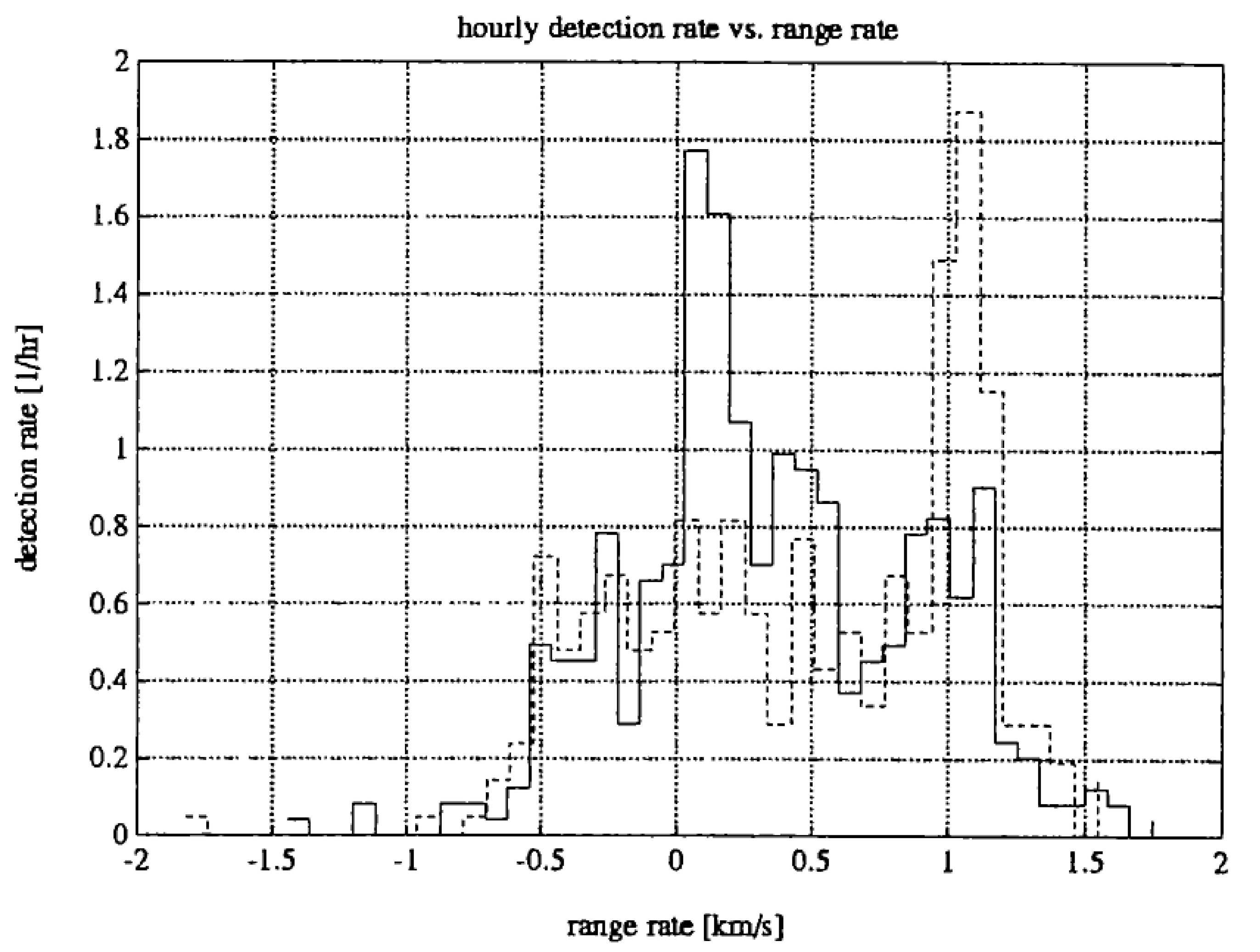

Figure 7. Detection rates vs. range rate for TIRA sum channel (solid) and Effelsberg LCP channel (dashed), 0.08 km/s range rate bins.

The non–homogenous distribution of hourly detection rates over time is clearly visible in figure 8. The distinct peaking at non–evenly spaced intervals might indicate that the observation volume crossed debris swarms concentrated in certain inclination bands. This has to be verified, however. Missing values between hour 3 and 6 in the Effelsberg distribution are due to a data gap caused by technical problems.

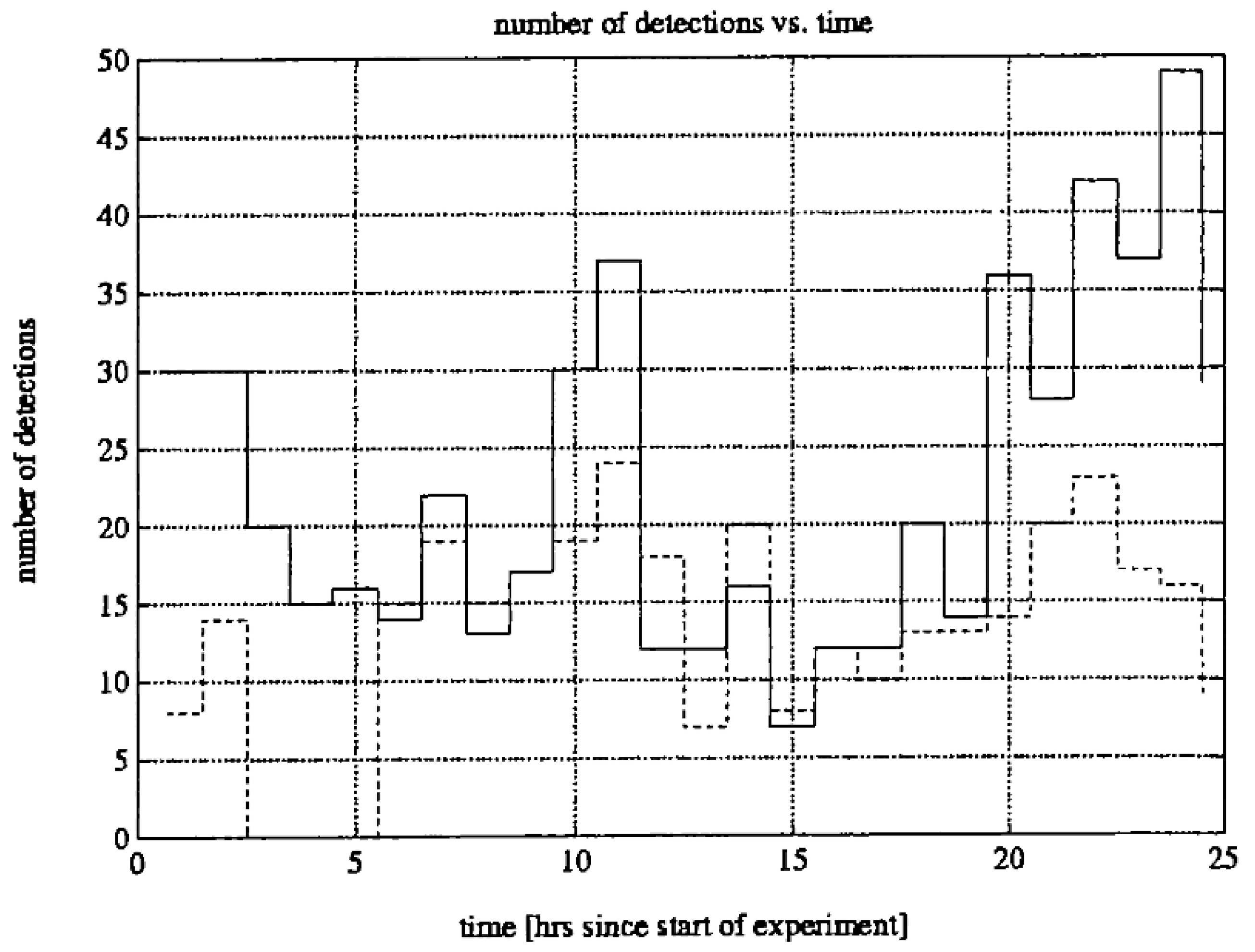

Figure 8. Number of detections vs. time for TIRA sum channel (solid) and Effelsberg LCP channel (dashed).

Finally, cummulative hourly detection rates are plotted against object diameter in figure 9. To be comparable, only detections from the overlap altitude window (750...980 km) have been taken into account. Remember however, the larger 3 dB beam of TIRA (0.5 deg.), but the higher sensitivity of the Effelsberg system. First comparisons with MASTER model predictions (see Ref. 3) reveal, that both distributions are slightly underpredicted at the lower size ends and moderately overpredicted at larger sizes.

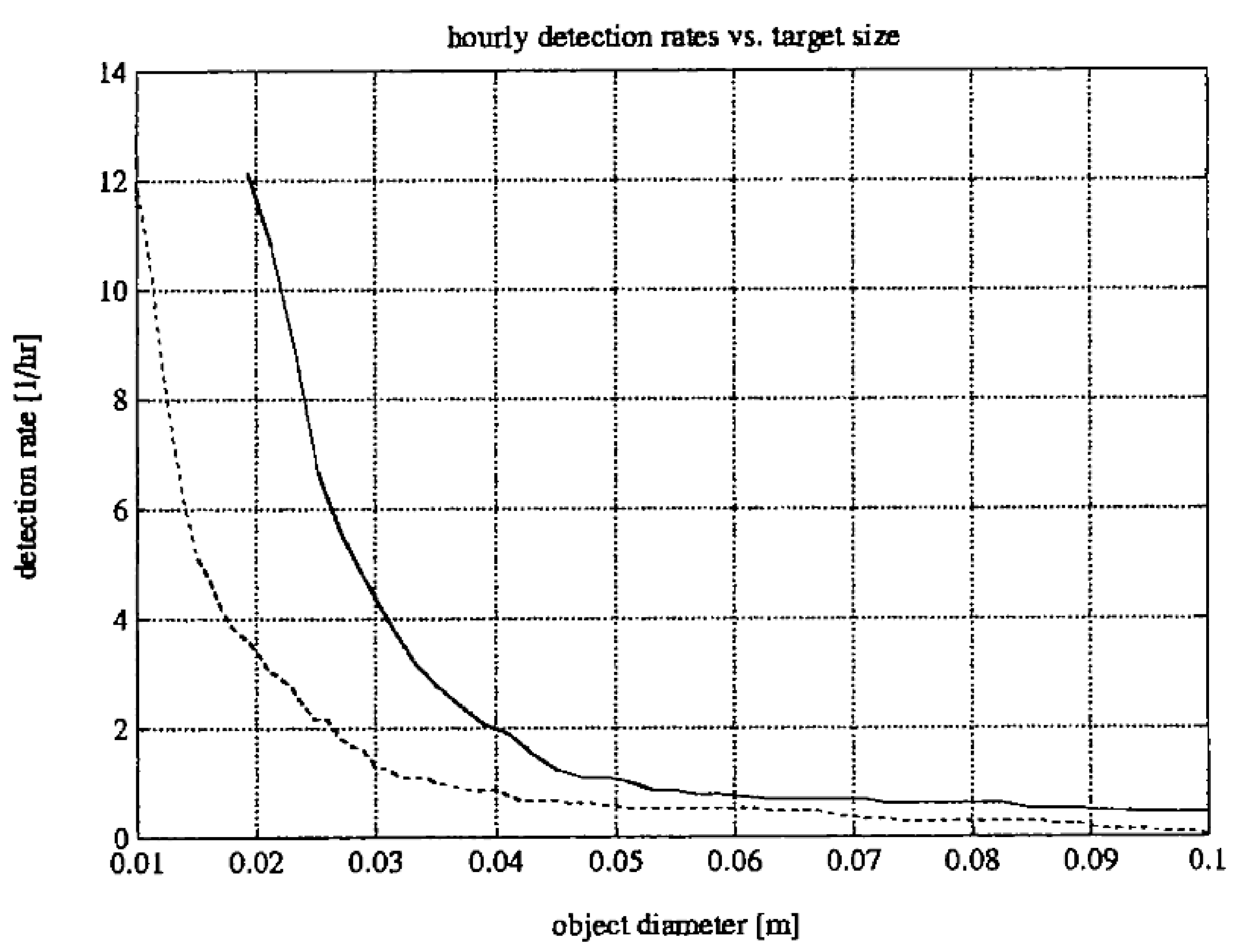

Figure 9. Cummulative detection rates vs. object diameter for TIRA sum channel (solid) and Effelsberg LCP channel (dashed) in overlap altitude window.

5. SUMMARY AND OPEN ISSUES

COBEAM–1/96 presents a major step in Europe towards the ability to observe the debris population down to the 1 cm size limit by radar. In addition to its high sensitivity, the experiment is characterized by a remarkably large observation volume due to the close location of the two sensor stations. The data collection and processing concepts have proven to work in principle, although several improvements seem worth to be considered. First analyses of part of the collected data seem to give reasonable results which will have to be verified and further enhanced. Key issues in continuation of the COBEAM data processing will be:

- Processing of the TIRA elevation and transverse angular difference channels to assess monopulse angle information (for > 2 cm objects detected at TIRA),
- processing of the Effelsberg RCP channel data to determine OP/PP RCS ratios,
- derivation of 'pseudo–inclination' from target Doppler at both sensors and comparison with inclinations from TIRA monopulse data,
- analysis of the TIRA tracking filter data, cross–checks among the receiver channels of each station and between the combined results of both sensors,
- TLE catalogue cross–checks,
- more detailed comparisons with MASTER model predictions,
- eventually reprocessing with refined parameters and improved range and range rate estimation modules.

6. ACKNOWLEDGEMENTS

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